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Some new LDPC-coded orthogonal modulation schemes for high data rate transmissions in navigation satellite systems

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Abstract

In this paper, we design some new LDPC-coded orthogonal modulation (OM) schemes for high data rate transmissions (HDRT) in the navigation satellite systems. We analyze their error-performance utilizing soft-decision bit metrics and compare them with those of L61 and L62 signals in the quasi-zenith satellite system (QZSS) for centimeter-level augmentation services (CLAS). Compare to the L62 signals of QZSS, both schemes have higher data rates (14.6% increase) and essentially the better error performance at high SNR region. At the region where frame error rate (FER) = 10^{-3}, one of the proposed schemes has better error performance of 1.4 dB in terms of carrier-to-noise ratio (C/N_0).

Keywords: Navigation satellite systems; High data rate transmissions; Centimeter-level augmentation services; Low density parity check codes; Orthogonal modulation

1. Introduction

A satellite navigation system is closely related to the real life of users who need location information and related services. Recently, some communication systems based on the new/existing navigation satellite systems are being considered for precise point positioning (PPP) services and public safety services [1,2]. Some typical examples of existing signals are Galileo E6 and QZSS L6 signals [3,4]. These augmentation signals transmit a large amount of positioning information at high data rate and serve to calculate the more precise location of the receiver.

Japan's QZSS L6 signals were designed for real-time centimeter-level augmentation services (CLAS) [5,6]. It provides with PPP service using satellite navigation signals at a high data rate. The [246, 214] Reed–Solomon (RS) code over GF(2^8) is used as a high code rate FEC for QZSS L6 signals. The encoded bits are concatenated with the preamble 32 bits, and they form a L6D navigation message of 2000 coded-bits, transmitted by QZSS-1 star satellites, which is called the L61 signal. The L62 signal, mainly transmitted by the QZS $2 \sim 4$ star satellites, contains both 2000 coded-bit L6D navigation message and 2000 coded-bit L6E navigation message interleaved. Therefore, the data rates of the L61 signal and the L62 signal are 2000 and 4000 coded-bits/s, respectively. For modulation after FEC, the encoded bits are mapped into sequence of modulation symbols. Here, every consecutive 8-bit of the encoded bits is mapped into an integer value in the range between 0 and 255. Therefore, 2000 (or 4000, resp.) coded-bits/s is converted into 250 (or 500, resp.) symbols/s [5,6].

The code shift keying (CSK) is a well-known high-order orthogonal modulation that can increase the data rate without losing synchronization performance, thus being a suitable signal candidate for the GNSS applications [7]. It utilizes the orthogonality of distinct phases of a pseudo-random noise (PRN) code, and modulates symbols onto some distinct phases of the same PRN code. It is reported also that CSK may have some inherent capability of combating against spoofing [8]. Currently, CSK modulation is applied to the QZSS L6 signals in operation [6].

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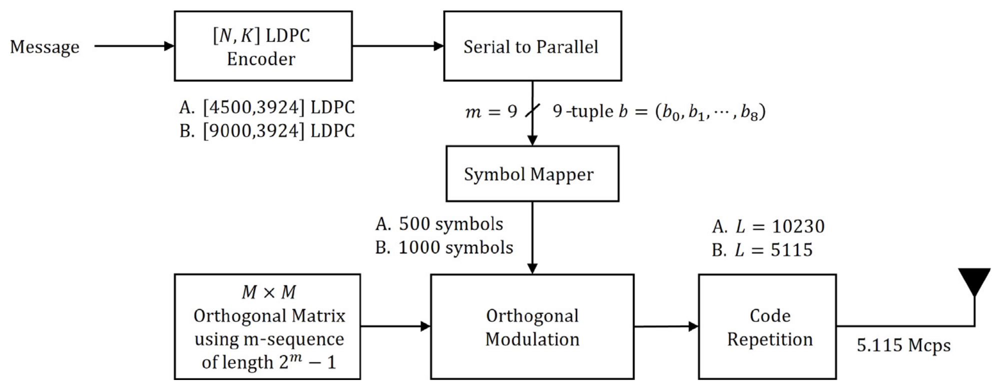


Fig. 1. Proposed LDPC-coded orthogonal modulation schemes.

CSK modulation can be regarded as an orthogonal modulation (OM) since the different phases of the PRN code are usually considered to be orthogonal. An alternative way of OM is to use distinct orthogonal codes for different symbols. As a result, this type of OM can be used for DS/CDMA systems, since it makes efficient use of the frequency spectrum and each signal can be transmitted robustly against noise, reducing inter-signal interference [9]. A famous candidate for the set of orthogonal codes comes from the Hadamard matrices of various types: Walsh–Hadamard type [10] or m-sequence type [11]. Authors of [10,11] indicated that an orthogonal modulation with a set of orthogonal codes from certain Hadamard matrices can be a better choice than CSK with a single PRN code (as in QZSS L6) in terms of the receiver complexity.

LDPC codes [12] can be good candidates for an FEC of satellite navigation systems. Two half-rate LDPC codes are concatenated and used as FEC in GPS modernization L1C signals in CNAV2 message structure of data rate around 100 sps [13]. These have lengths 1200 and 548, respectively. Authors of [14] have analyzed their coding gains and concluded that some single LDPC codes of an overall length 1748 would have been much better. Recently, LDPC codes are also adopted for an advanced FEC of 5G NR [15]. In this paper, we use both high rate and low rate LDPC codes in the proposed schemes.

High data rate transmissions in navigation satellite systems for various augmentation services have to be studied. In this direction, Peña et al. [16] proposed some LDPC-coded CSK modulation schemes. They made some comprehensive analysis on various decoding algorithms paired with different types of channel codes with 1/2 code rate, LDPC and RS, so that the overall data rate spans from low to high level. Andreotti et al. [17] analyzed schemes that use the BICM-ID method to decode a system applied the CSK modulation method with convolutional codes and turbo codes as FEC. These papers applied FEC with a relatively short-length and around half-rate, similar to the existing navigation satellite signals for open service. On the other hand, the CSK modulation for high data rate transmissions (HDRT) in satellite navigation systems has been studied recently. Cho et al. [18] proposed an RS-coded orthogonal modulation scheme for HDRT in satellite navigation systems, but analyzed the performance by hard decision decoding.

In this paper, we design some new LDPC-coded OM scheme for HDRT in navigation satellite systems. We analyze their error-performance utilizing soft-decision bit metrics and compare them with those of L61 and L62 signals in QZSS for CLAS. Compared to the L6 signals of QZSS, one of our proposed schemes has higher data rates (14.6% increase) and better error performance about 1.4 dB at FER $= 10^{-3}$.

Section 2 describes the proposed LDPC-coded orthogonal modulation scheme for HDRT. Some simulation results are described in Section 3. Section 4 concludes this paper.

2. The proposed LDPC-coded orthogonal modulation schemes

We propose two LDPC-coded orthogonal modulation schemes for HRDT in the navigation satellite system. The proposed schemes use two different binary LDPC codes as FECs and the orthogonal modulation with the same parameters for high data rate as shown in Fig. 1.

Our proposed schemes consider the same chip rate of 5.115 Mcps as QZSS L62 signal, and a frame of 3924 bits of message data without any preamble bits. Preamble bits do not need to be considered since we take orthogonal modulation using orthogonal codes of length only 512 [10], instead of CSK using PRN codes of length 10 230 in QZSS. The amount of data bits is increased from 3424 (QZSS L62) to 3924, which corresponds to 14.6% increase in the data rate.

Orthogonal modulation using codes of length 512 (which is much shorter than 10 230 as in CSK of QZSS) not only makes preamble codes unnecessary, but also gives one additional advantage. Since we fix the transmit chip rate, we are able to repeat the orthogonal code for each symbol at the end. Two schemes are different in the number of repetitions and the code rate. Scheme A repeats $\lceil \frac{10230}{512} \rceil = 20$ times for 500 symbols from the LDPC code of rate $0.872 = 3924/4500$, while Scheme B repeats only $\lceil \frac{10230/2}{512} \rceil = 10$ times for 1000 symbols from the LDPC code of rate $0.436 = 3924/9000$. Therefore, Scheme A focuses on the gain of the repetition, while Scheme B focuses on the gain of the lower rate LDPC code.

As shown in Fig. 1, the output of the LDPC encoder is mapped to the sequence of symbols, where each symbol corresponds to m bits for the encoder. There are many different

Index	0	1	2	⋯	$M-2$	$M-1$
$c_{\#0}$	0	0	0	⋯	0	0
$c_{\#1}$	0	$c(0)$	$c(1)$	⋯	$c(M-3)$	$c(M-2)$
$c_{\#2}$	0	$c(M-2)$	$c(0)$	⋯	$c(M-4)$	$c(M-3)$
⋮	⋮	⋮	⋮	⋮	⋮	⋮
$c_{\#(M-1)}$	0	$c(1)$	$c(2)$	⋯	$c(M-2)$	$c(0)$

Fig. 2. $M \times M$ Orthogonal matrix using m-sequence of length $M-1$.

schemes for this, for example, the interleaved symbol maps or some straight symbol map, etc. Over the AWGN channel, the result will not be much different [9,17], and thus, we simply choose the straight simple map of converting the m consecutive bits of codewords to decimal numbers. That is, for example, since $m = 9$, we have 000000001 $\leftrightarrow$ 1, 100000000 $\leftrightarrow$ 256, 000011100 $\leftrightarrow$ 28, etc.

We applied cyclic-type Hadamard codes [11,19] using an m-sequence to generate orthogonal matrix as shown in Fig. 2. This type of Hadamard codes can reduce the computational complexity of the correlator at the receiver [11]. Here, an m-sequence $c(0), c(1), \ldots, c(M-2)$ of length $M-1 = 2^m - 1 = 511$ and all its cyclic shifts are used in this orthogonal matrix in addition to the all-zero left-most column and the top row. There are many different m-sequences of length 511 but their theoretical performance in the orthogonal modulation may not be much different, because it depends only on their orthogonality of the rows of the orthogonal matrix.

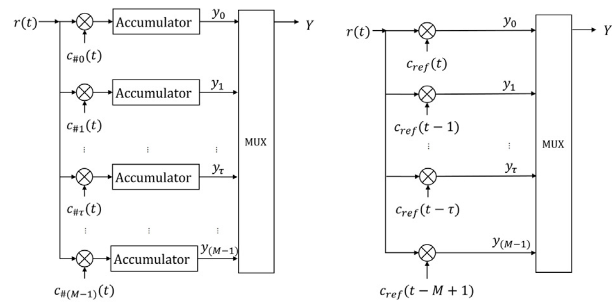
3. Performance of the proposed schemes

In this section, we show the performance of our proposed Schemes A and B as shown in Fig. 1. First, we want to show the performance of Scheme A in comparison with the existing RS-coded CSK modulation scheme (QZSS L62) as well as some other hypothetically intermediate scheme using the LDPC-coded CSK modulation. Performance between RS codes and LDPC codes, and those between CSK modulation and orthogonal modulation will be individually compared. Second, we compare the performance of Scheme A and Scheme B. Scheme B lowers the code rate of LDPC and halves the number of repetition compared to Scheme A, so we expect to get some gain at the same chip rate.

3.1. Receiver for the proposed schemes

The receiver of the proposed schemes consists of four parts. Among them, we explain the correlator and the bit likelihood ratio (LR) calculator.

The correlator for orthogonal modulation is shown in Fig. 3(a). The correlation values are calculated for each of the received signal $r(t)$ and M orthogonal signals in bipolar form, and are accumulated in an accumulator by the number of repeated transmissions. MUX collects accumulated correlation values and outputs $Y = (y_0, y_1, \ldots, y_{M-1})$. In the case of CSK modulation, a correlation operation is performed with M reference PRN codes, c_{ref}, shifted by $\tau(= 0, 1, \ldots, M-1)$ and $r(t)$ as shown in Fig. 3(b).



(a) For orthogonal modulation (b) For CSK modulation

Fig. 3. Correlator in receiver.

Table 1
Simulation parameters of FECs.

	RS/GF(2^8)		RS/GF(2^9)		LDPC
	# Symbols	# Bits	# Symbols	# Bits	# Bits
K	2 × 214	3424	428	3852	3852
N	2 × 246	3936	492	4428	4428

When a binary LDPC code is applied as an FEC in DSSS system, a calculation of LR value for each bit is required from the output of the correlator. With the correlator output Y, the each bit LR value is calculated as [16,17,20]:

$$LR(b_k) = \frac{P(b_k = 0|Y)}{P(b_k = 1|Y)} = \frac{\sum_{i=0,b_k=0}^{M-1} exp(\frac{y_i}{\sigma^2})}{\sum_{i=0,b_k=1}^{M-1} exp(\frac{y_i}{\sigma^2})}, \tag{1}$$

where $0 \leq k \leq m-1$.

3.2. Simulation results

First, we aim to compare and analyze the performance of the proposed Scheme A with three comparison techniques. These are QZSS L62, modified L62 and LDPC coded CSK modulation schemes. For the modified L62, we consider the same number of symbols as L62, but the number of bits per symbol is increased so that the total navigation message is 428 more bits (12.5% increase), which is compared with the LDPC-coded CSK scheme in the same way. The parameters of these schemes are shown in Table 1, and the block diagrams of the proposed schemes and the block diagram of the schemes for comparison are shown in Figs. 4, 5 and 6, respectively. The proposed LDPC codes are generated by the PEG algorithm and used the degree distribution of base graph 2 in 5G NR LDPC codes [21,22]. The experiments assume AWGN channel and BPSK modulation. RS codes and LDPC codes are decoded using Berlekamp–Massey and sum–product decoding with max 50 iterations, respectively.

Since a useful measure of a receiver's performance is the carrier-to-noise ratio (C/N_0), it is necessary to compare them in this point of view. We assume that the data rate of each signal is to transmit a codeword length N of symbol (or coded bit) per second, that is, N sps. Then C/N_0 [dB-Hz] is calculated as [16,23]:

$$C/N_0 = E_b/N_0 + 10log_{10}(c_{rate}) + 10log_{10}(r_{chip}) + 10log_{10}(m) - 10log_{10}(L), \tag{2}$$

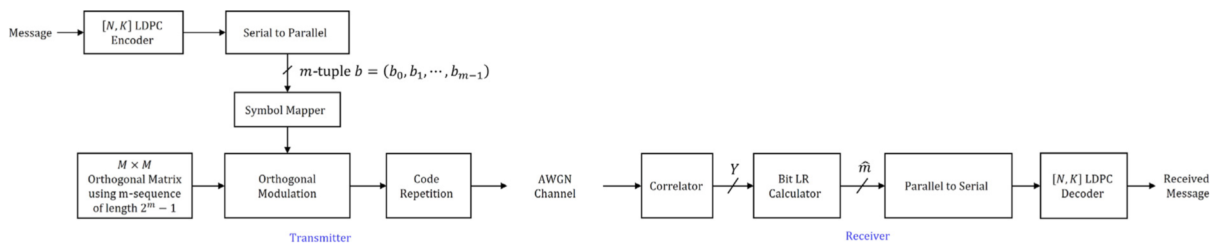


Fig. 4. LDPC-coded orthogonal modulation scheme (proposed).

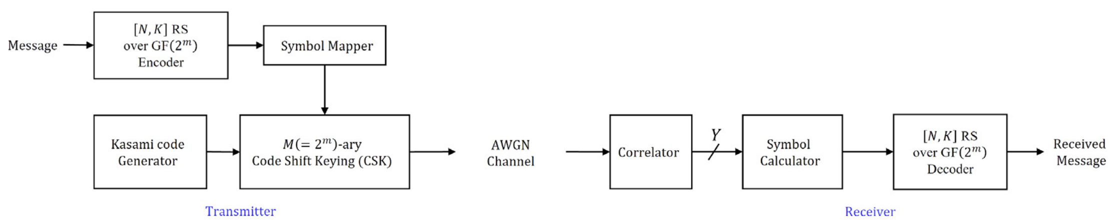


Fig. 5. Reed–Solomon-coded CSK modulation scheme (QZSS L6).

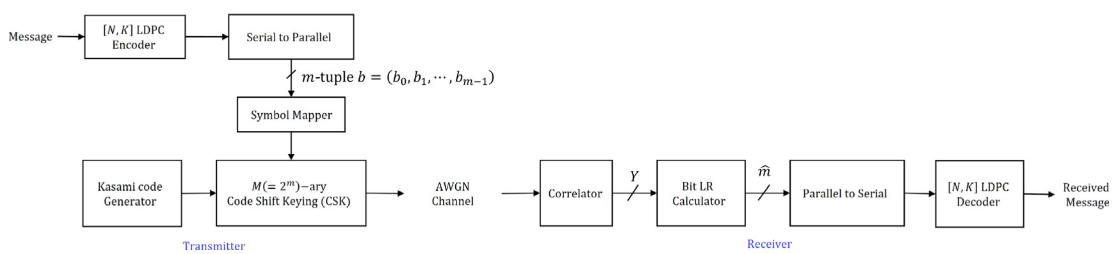


Fig. 6. LDPC-coded CSK modulation scheme (for comparison).

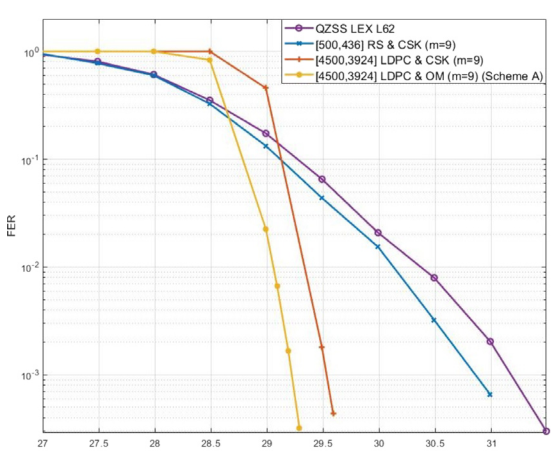


Fig. 7. Comparison of the proposed Scheme A and the other schemes.

where c_{rate} is the code rate, r_{chip} is the chip rate, m is the number of bits per symbol, and L is the length of PRN code per symbol.

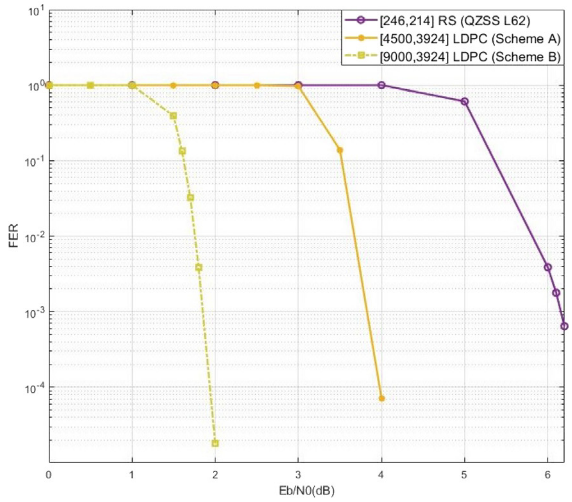
Fig. 7 shows the performance of the considered schemes. Compared to the L62 scheme, the $[492, 428]$ RS-coded CSK modulation with $m = 9$ shows worse performance about 0.3 dB. It is considered that this is due to the codeword length difference from the viewpoint of C/N_0. The scheme with the $[4428, 3852]$ LDPC code and CSK modulation($m = 9$) shows better performance compared to L62 by 1.2 dB, despite of the longer codeword length. In the case of the proposed Scheme A, it is also a 1.4 dB performance improvement than QZSS L62 scheme at FER $= 10^{-3}$. According to the simulation results, it can be seen that the data transmission rate is increased and performance is improved by high-order modulation. Also, it can be confirmed that improved signal performance is achieved through application of OM instead of CSK and application of LDPC codes instead of RS codes.

Fig. 8 shows the performance of Scheme A and Scheme B. It can be seen that this is different from the result we expected. In terms of E_b/N_0, Scheme B with a long LDPC code shows good performance, but in terms of C/N_0, Scheme A shows good performance. Based on this result, it can be seen that the performance degradation that occurs when the PRN code length per symbol is shortened has a greater effect on the receiver side than the performance improvement of the long FEC.

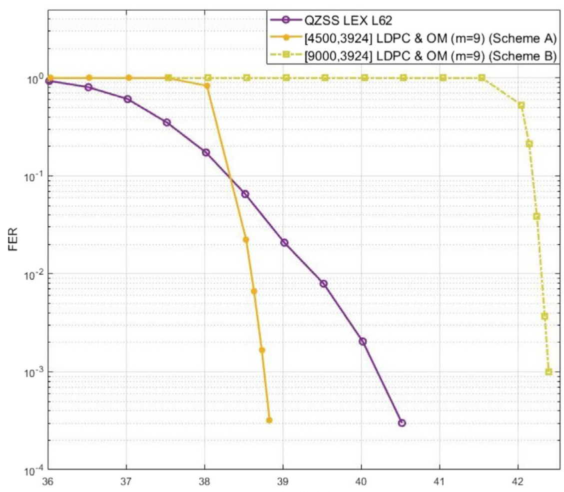
Additionally, we compare the performance of our proposed Scheme A by applying the similar parameters as the QZSS L61 signal as shown in Fig. 9. Compared to QZSS L61, the proposed Scheme A with similar parameters shows 1.4 dB improved performance at FER $= 10^{-3}$.

4. Conclusions

In this paper, we proposed two LDPC-coded orthogonal modulation schemes for HDRT and compared their performance with some other similar schemes. Both have the same



(a) FEC and BPSK modulation



(b) FEC and orthogonal modulation

Fig. 8. Comparison of the proposed schemes.

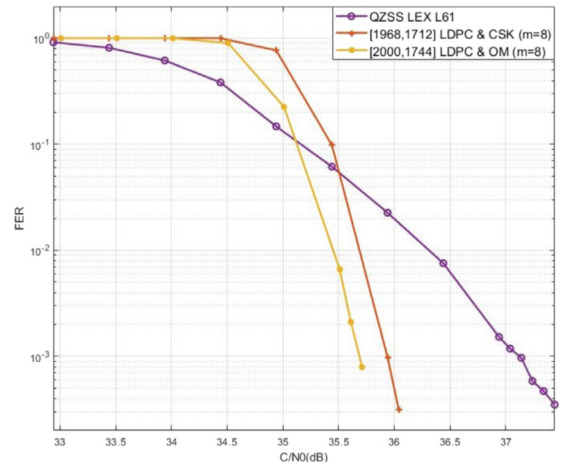


Fig. 9. Performance of the proposed scheme with L61 parameter.

data rate of 3924 bps (which is 14.6% better than those of QZSS L62) and the same chip rate of 5.115 Mcps as those of QZSS L62. The difference is in the choice of FEC code rate and the repetition numbers as shown in Fig. 1.

In the mean time, we also compare the performance of two types of FECs: RS codes and LDPC codes. We compare also the performance of two orthogonal modulation schemes: CSK modulation with long PRN code and orthogonal modulation followed by repetition with very short orthogonal codes from some Hadamard matrix.

We conclude that both schemes are essentially better than the QZSS L62. Both schemes have higher data rate and the error performance curves with much steeper slopes than those of QZSS L62, which implies that they are eventually better in high SNR region. At the region where FER $= 10^{-3}$, the proposed Scheme A has better error performance about 1.4 dB in terms of C/N_0. It is to be noted that all these were achieved by some simply designed LDPC codes using PEG. We believe that there is still some room for the improvement in the optimization of LDPC design.

Declaration of competing interest

The authors declare that there is no conflict of interest in this paper.

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