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Some new RS-coded orthogonal modulation schemes for future GNSS

Hyunwoo Cho[a], Hong-Yeop Song[a,*], Jae Min Ahn[b], Deok Won Lim[c]

[a] *Department of Electrical and Electronics Engineering, Yonsei University, Seoul, Republic of Korea*
[b] *Department of Electrical and Radio and Information Communications Engineering, Chungnam National University, Daejeon, Republic of Korea*
[c] *Satellite Navigation Team, Korea Aerospace Research Institute, Daejeon, Republic of Korea*

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Abstract

Considering the availability of the global navigation satellite system (GNSS) signals and the increase in its data rate in the future, this paper proposes some new Reed-Solomon coded (RS-coded) orthogonal modulation schemes using the Hadamard codes, as an alternative to the RS-coded code-shift-keying (CSK) modulation in the Quasi-Zenith Satellite System L-band experimental (QZSS-LEX) signals. The simulation result of the proposed schemes shows that, though the frame size and hence the data rate is increased with much reduced complexity in the receiver, the bit error rate performance of RS-coded orthogonal modulation is slightly better than or comparable to the QZSS-LEX.

Keywords: Global navigation satellite system; Reed-Solomon codes; Orthogonal modulation

1. Introduction

The evolution and growth of the positioning, navigation, and timing (PNT) market demand the service relying on GNSS signals with much improved accuracy. Some several services (e.g. satellite-based augmentation system services, Galileo Commercial Services) may rely on huge and massive data volumes with low latency. Therefore, the navigation data component such as increased data rate and improved availability should be considered [1].

On the other hand, the data rate increase is a difficult task since GNSS systems use direct-sequence spread spectrum (DSSS) technique. For DSSS/BPSK signals, the data rate increase requires the chip rate increase or the truncation of the pseudo noise (PN) sequences. In case of the truncation, the orthogonality property decreases and it could result in the performance degradation. Neither of these options is desirable. Therefore, an appropriate option is to implement some higher order data modulation. The CSK modulation is a good alternative to the BPSK modulation [2,3], and is adopted by QZSS-LEX. Here, the CSK modulation is combined with Reed–Solomon (RS) codes in order to achieve the increased data rate [4].

Recently, the orthogonal modulations based on various types of Hadamard codes have been proposed as some alternative schemes of CSK modulation. Among these, those based on the cyclic Hadamard codes using the m-sequences are known to have much simpler computational complexity than CSK modulation [5].

In this paper, we propose two RS-coded orthogonal modulation schemes using the Hadamard codes based on m-sequences. For this, we have to design some new RS codes suitable for the orthogonal modulations: one over GF(2^8) and the other over GF(2^9). The orthogonal modulations are selected accordingly to have orders 8 and 9, respectively. Two proposed schemes have the same overall speed of chip rate that is 5.115 Mcps but differ in many aspects: (1) one has similar structure as QZSS-LEX L62 and the other as QZSS-LEX L61; (2) the RS code over GF(2^8) is 16-error-correcting while those over GF(2^9) is 32-error-correcting; (3) the number of input data bits is $1,744 \times 2 = 3,488$ bits for the first scheme and 3,924 bits for the second. We will show the performance of these two systems as well as QZSS-LEX L62 in Section 3.

We will briefly introduce RS codes, Kasami codes, two modulation schemes of interest, and QZSS-LEX message structure in Section 2. We propose two different RS-coded orthogonal modulations, one of order 8 and the other of order

* Corresponding author.
E-mail addresses: hyunwoo.cho@yonsei.ac.kr (H. Cho), hysong@yonsei.ac.kr (H.-Y. Song), jmahn@cnu.ac.kr (J.M. Ahn), dwlim@kari.re.kr (D.W. Lim).
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9, and compare their performances with that of QZSS-LEX in Section 3. Finally, Section 4 concludes the paper.

2. Preliminaries

2.1. Reed-Solomon codes

The (N, K) RS code $\mathbf{C}$ has the maximum distance separable (MDS) property, and therefore, its minimum distance D satisfies

$$D - 1 = N - K,$$

and hence, it has the t-error-correcting capability where $t = (N - K)/2$ [6,7].

Suppose we need an RS code over $GF(2^8)$ with 16-error-correcting capability. Then, $N = 2^8 - 1 = 255$ and $2t = 32 = D - 1 = N - K$, and hence, $K = 223$. Therefore, the $(255, 223)$ RS code of length 255 over $GF(2^8)$ is defined as a BCH code with the generator polynomial $g(x) = (x - \alpha^1)(x - \alpha^2) \cdots (x - \alpha^{32})$.

Usual practice is to use the non-binary RS code over $GF(2^r)$ of length N as a binary code of length Nr by mapping each non-binary symbol (over $GF(2^r)$) into a binary vector of length r using some fixed correspondence. QZSS-LEX signals [4] use such a binary RS code of length $255 \times 8 = 2040$.

2.2. Kasami codes

Kasami code is known as one of the important classes of PN sequences, and some truncated small set Kasami codes are used in QZSS-LEX signals as PN code for CSK modulation [4].

The small set of Kasami codes are generated easily using two linear feedback shift registers of length n as described in [8] for any even integer n. The non-trivial correlation values are known to be three-level: $-1, -2^{n/2} - 1, 2^{n/2} - 1$ [8].

2.3. Modulation schemes

The CSK modulation is designed to increase the data rate of a band-limited spread spectrum signal without affecting the PN code property [2].

The CSK modulation maps a symbol into a cyclic phase of a given PN code. When the PN code has length N, it has N distinct cyclic phases, and therefore, N different modulation symbols can be mapped into them [3,9].

The second type of modulation of interest is the orthogonal modulation based on Hadamard codes. So far, lots of different types of Hadamard codes are well-known: Walsh-type, cyclic-type in general, and cyclic-type using an m-sequence [10], etc.

Consider a given $N \times N$ Hadamard matrix and its N rows as N orthogonal codes all of length N. Now, the orthogonal modulation based on these Hadamard codes is a mapping of N distinct symbols into N orthogonal codes. The authors of [5] have reported some results on the orthogonal modulations using various types of Hadamard codes, Walsh-type and cyclic-type using m-sequences, and of sizes 256, 512 and 1,024. The concluding recommendation of [5] is a use of those based on cyclic-type using m-sequences with an appropriate parameters in QZSS-LEX as an alternative to CSK modulation with Kasami codes, and a claim that the computational complexity at the receiver can be reduced.

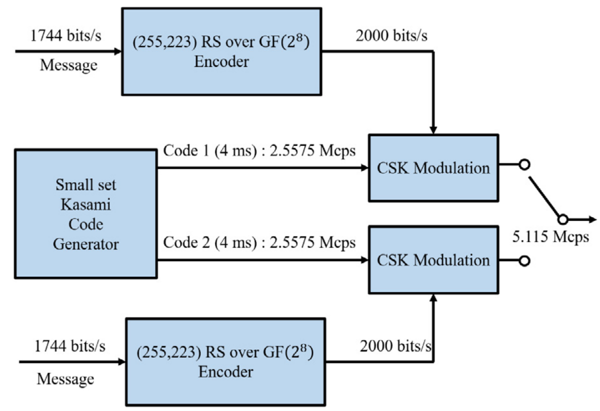


Fig. 1. QZSS-LEX L62 signal structure.

2.4. QZSS-LEX message structure

The QZSS-LEX signal is specifically designed to enable high accuracy real-time positioning [4,11]. The major characteristics are larger message frame and higher code rate than other GNSS signals. For example, its data rate is 4,000 coded bits per sec, which is much higher than 100 coded bits per sec in GPS L1C or Beidou B1C signals [12].

The overall scheme of QZSS-LEX L62 signal structures is shown in Fig. 1. It consists of two identical streams whose outputs are multiplexed at the end. We will describe only one of them here briefly.

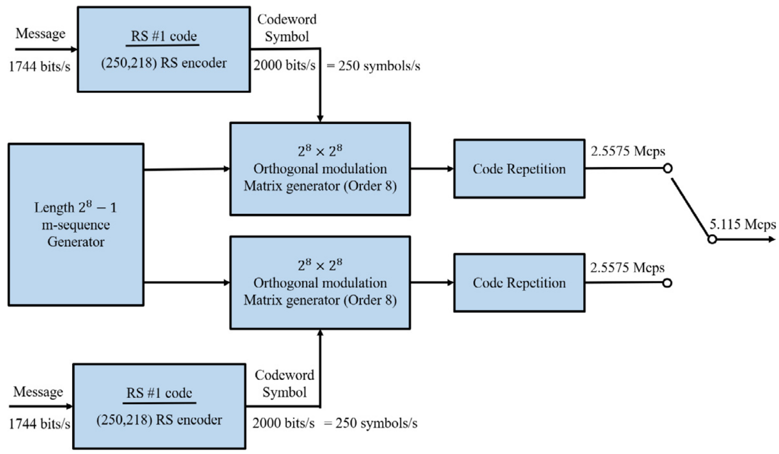
The shortened RS code of length 246 over $GF(2^8)$ is used for the initial FEC. The 1,744 bits per sec at the input is a concatenation of 32 bits for synchronization (that will be not be coded) and 1,712 navigation data bits (that will be coded). The uncoded 32 bits are then attached to the codeword of 1,968 bits, and the result is of length 2,000 bits or 250 symbols per sec. Therefore, the symbol time is 4 msec per symbol.

The small set Kasami codes of length $2^{20} - 1$ is truncated to the length 10,230 and then the result is used for the CSK modulation. The orthogonality between different satellites is achieved by using different members of the Kasami codes, and a specific single code is assigned to each satellite and repeatedly used 250 times per sec for the 250 symbols from the RS encoder. Each symbol from the encoder consists of 8 bits, and it is converted into a decimal in the range from 0 to 255. The Kasami code is then shifted by the amount corresponding to this decimal number. Therefore, the overall chip rate is given as 250×10230 chips per sec ($= 2.5575$ Mcps).

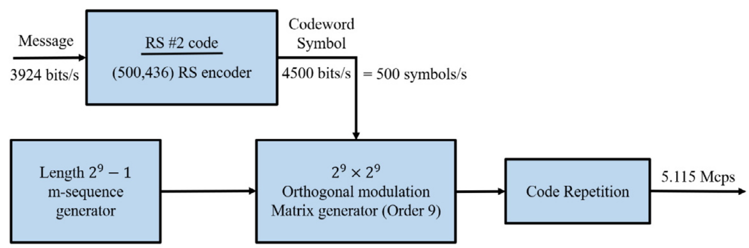
3. The RS-coded orthogonal modulation schemes

3.1. Parameters of the proposed schemes

Assuming that the data rate for the future GNSS will increase, we propose two different RS codes as shown in



(a) RS #1 code and dual stream orthogonal modulations of order 8



(b) RS #2 code and single stream orthogonal modulation of order 9

Fig. 2. The proposed RS-coded orthogonal modulation schemes.

Table 1
The proposed Reed-Solomon codes.

	RS #1	RS #2
Field	GF(2^8)	GF(2^9)
N	250	500
K	218	436
$N - K$	32	64
e.c.capability	16	32
Code rate	0.872	
Coded data rate	4000 bps	4500 bps

Table 2
The orthogonal modulation with rate 2.5575 Mcps.

	RS #1	RS #2
Order	8	9
Length of PN codes	2^8	2^9
Number of repetitions	$\approx$ 39.96	$\approx$ 19.98

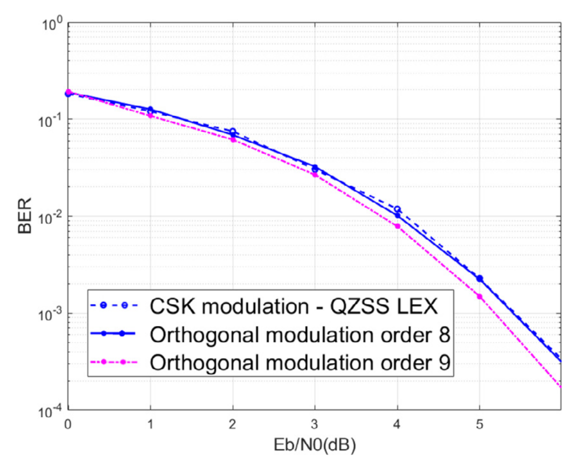


Fig. 3. Performance of three modulation types.

Table 1. Each RS code is used with the orthogonal modulation described in Table 2. We set the code rates of the proposed codes the same. Also, we set the number of bits per symbol and the orthogonal modulation order equally. The overall block diagrams of the proposed schemes are shown in Fig. 2.

The proposed structure depicted in Fig. 2(a) is similar to those of QZSS-LEX L62 in that both have dual stream of input data which are multiplexed at the output and the final chip rate is the same as 5.115 Mcps.

There are two major differences between the proposed structure and QZSS-LEX L62: First is that 32 synch bits in QZSS-LEX is now unnecessary since orthogonal modulation does not require any synchronization signal. Therefore, unlike QZSS-LEX, all the 1,744 input bits in the proposed system can be used as a navigation message. Second is the length of PN codes for modulation. In the proposed structure, only a code of length 256 (order 8) is used to modulate every 8-bit symbol from the RS encoder in Fig. 2(a). Therefore, at the output of the orthogonal modulator, we have a speed of 250×256 chips per sec. To achieve the same overall chip rate,

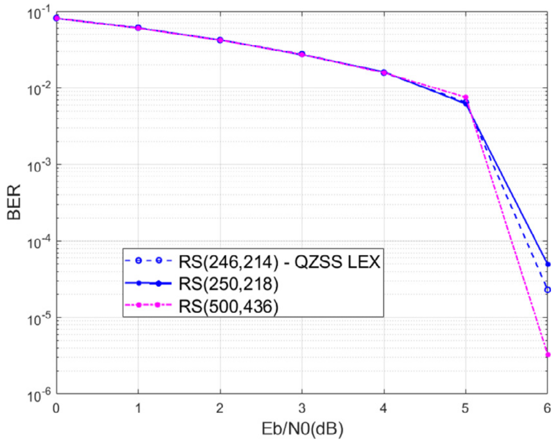


Fig. 4. Performance of three RS codes.

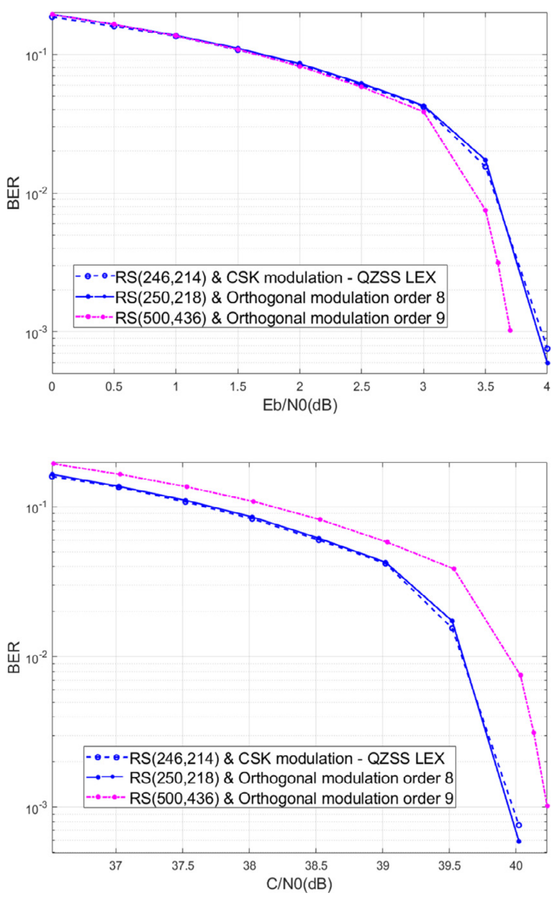


Fig. 5. Performance comparison of the proposed schemes.

every 256 chips corresponding to an 8-bit symbol is repeated about 39.96 times.

The proposed structure in Fig. 2(b) is a generalized version of those in Fig. 2(a). First, the dual stream of inputs is now combined into a single stream of inputs which accepts 3,924 bits which is 436 bits more than the previous structure. Second, the RS code is designed over GF(2^9) with the parameters $N = 500$, $K = 436$ and the error-correction capability equal to 32 in hoping that it could provide better reliability than the previous structure. Thus, each symbol consists of 9 bits and the orthogonal modulation requires a PN code of length 512 (order 9) and a 512 × 512 Hadamard matrix. Third, by code repetition about 19.98 times, the overall chip rate is the same as 5.115 Mcps.

3.2. Performance of the proposed schemes

The bit energy to noise power density ratio E_b/N_0 is in fact the SNR per bit. Therefore, the BER performance of modulation schemes or FEC schemes with respect to E_b/N_0 provides the performance depending only on SNR per bits, and can be regarded as an important metric of the scheme for the designers. The practical performance of a system on the other hand depends not only on SNR per bit but also on data rate and/or bandwidth etc. To provide the performance depending on all these, one uses a similar parameter, the carrier power to noise spectral density ratio C/N_0. The relationship between E_b/N_0 and C/N_0 is given as

$$C/N_0[\text{dB-Hz}] = 10\log_{10}(E_b/N_0) + 10\log_{10} R,$$

where R is the (coded) data rate [13].

We have done some extensive computer simulations to compare various performance of each individual part and the overall systems. Basically, we compare the performance of modulations in Fig. 3, the performance of RS codes in Fig. 4, and finally, the performance of RS-coded modulations in terms of E_b/N_0 and also in terms of C/N_0 in Fig. 5. We would like to observe the following:

The performances of CSK modulation in QZSS-LEX and the orthogonal modulations in Table 2 are shown in Fig. 3. It shows that the higher order orthogonal modulation has a better performance as already given in [13]. The gain is about 0.3 dB at the BER of 10^{-3}, which is predicted also in [13].

The performance of QZSS-LEX RS code and both RS codes in Table 1 is shown in Fig. 4. It shows that RS #2 code has better performance (about 0.2 dB and more) than the others. We guess that it is because RS #2 has better error-correction capability, and that it is well-expected result.

The QZSS-LEX and the proposed RS-coded orthogonal modulation schemes are simulated and their performances are shown in Fig. 5, one vs E_b/N_0 and the other vs C/N_0. The performance of RS #1 scheme is comparable to those of QZSS-LEX. The RS #2 scheme is slightly better, even though it has enlarged frame size than the others. It is also expected since the performances of the stronger RS code and the orthogonal modulation of order 9 are better than their counterparts.

4. Conclusions

In this paper, we propose some RS-coded orthogonal modulations as alternatives to those in the QZSS-LEX. The simulation results show that, though the frame size (hence, the data rate) is increased, the performance is slightly better than or comparable to that of the QZSS-LEX with reduced complexity in the receiver.

Some immediate future works would be the followings. (1) The orthogonality between different satellites must be achieved by adopting some scrambling codes on top of orthogonal Hadamard codes of the proposed schemes. (2) We may investigate some possibility of compromising the number of repetitions in Code Repetition of Fig. 2 so that either the date rate can further be increased and/or much stronger FEC can be utilized maintaining the overall chip rate of 5.115 Mcps.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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