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Time domain raised cosine-binary coded symbol modulation for satellite navigation

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ABSTRACT

The number of satellite navigation signals in space grows dramatically as the number of global and regional navigation satellites constant increases. This phenomenon further aggravates an already crowded radio spectrum in-band and increases out-of-band (OOB) emissions. One feasible solution to the issue of signal compatibility is to design a spectrum-efficient modulation signal that has better navigation performance and backward compatibility with adjacent signals and services in operation. In this study, a time domain raised cosine (TDRC) pulse is introduced as an alternative waveform. A binary coded symbol (BCS) modulation family based on TDRC pulse called TDRC-BCS is also proposed as a candidate for future global navigation satellite system (GNSS). An extensive study on the multipath model analysis approach is also provided. The proposed modulation and existing modulations are then comprehensively evaluated. Theoretical analysis and simulation results show that TDRC-BCS signals offer superior navigation performance compared with existing modulations in terms of code tracking accuracy, multipath mitigation capacity, while maintaining comparable or better anti-jamming performance. These signals can also attain higher spectral efficiency and better backward compatibility with the existing GNSS signals. The proposed modulation scheme provides additional degrees of freedom for GNSS signal design.

1. Introduction

The modulation scheme, completely determining the upper bound of the performance of the global navigation satellite system (GNSS), is the core part of the signal structure, and the power spectrum envelopes determined by the modulation waveforms have a very significant effect on the performance of a navigation system, such as code tracking accuracy, multipath mitigation, anti-jamming, and compatibility [1,2]. From the perspective of the modulation development process, binary phase shift keying (BPSK) with rectangular pulse shape has been successfully applied to the first-generation Global Positioning System (GPS). However, BPSK modulation has a limited ranging capability when the available bandwidth of the receiver is not sufficiently large [3]. Also, BPSK is very vulnerable to the noise and multipath propagations. The transmitted power of BPSK signals on satellites must be augmented, and a wider bandwidth receiver is also required to improve the tracking accuracy. These requirements undoubtedly increase the cost and implementation complexity at both the transmitter and receiver sides.

Since its introduction, the binary offset carrier (BOC) modulation with a square wave subcarrier [4] has received particular attentions. This scheme has been successfully applied to global and regional navigation satellite systems because of its more desired compatibility with legacy navigation signals, potentially better time-resolution capabilities, and higher robustness against the multipath effect and noise compared to BPSK [3,4]. Subsequent modulations developed from the BOC concept are also currently utilized to modernize GPS, Galileo, and BeiDou system (BDS). For examples, multiplexed BOC (MBOC) modulations using composite BOC and time-multiplexed BOC are recommended for Galileo E1 OS signals and GPS L1C signals [5–8] respectively; Galileo E5 signals and BDS B2 signals have adopted alternative BOC modulation [8]. Moreover, several innovative BOC modulation schemes are emerging, such as BOC with adjustable width modulation [9], double-BOC modulation [10], generalized BOC modulation [11], etc. These modulations are specific subclasses of binary coded symbol (BCS) modulation [12] and are generated by a judicious configuration of BCS sequences. Unfortunately, the above-mentioned modulations, including BOC, have relatively high spectral side lobes and low spectral efficiency. These disadvantages consume large amounts of spectrum resources and are prone to introduce larger

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mutual interference with the existing signals and services of other coexisting navigation systems.

At present, GNSS is growing from previous US GPS and Russian GLONASS to additional European Galileo and Chinese BDS, as well as space-based augmentation systems and various regional navigation satellite systems, such as the Japanese QZSS and Indian IRNSS. Moreover, the new satellites are capable of transmitting multiple signals in multiple frequency bands [13–17]. A total of 150 satellites and over 400 GNSS signals are predicted to be present in space by 2030 [18,19]. Such large amounts of signals will further aggravate the situation of signal congestion in space and indirectly degrade the performance of all satellite navigation systems sharing same radio frequency resources. To allow the peaceful coexistence with minimal mutual interference among spaced signals and services in operation, a modulation with high spectral efficiency and improved navigation performance must be designed for future GNSS.

In views of this, the spectrum profiles of future desired GNSS signals should have the following properties: (1) The signal power near the region of the carrier frequency must be weakened for better compatibility with narrow band signals. (2) The amplitudes of the side lobes closer to the main lobe must be increased to improve the tracking accuracy and robustness against multipath. (3) The larger power fluctuation of high frequency components far from the main lobes must be cut down to minimize mutual interference with wide band signals and ensure lower out-of-band (OOB) emissions within adjacent services. A radical method achieving spectrally efficient signals is to substitute the chip shape with some continuous and smooth waveforms, given that smooth changes in the complex amplitude of signals tends to result in a quite compact spectrum. In this paper, a novel pulse waveform called time domain raised cosine (TDRC) is designed, which satisfies the above-mentioned requirements well. Based on the BCS technique, a particularly promising modulation family called TDRC-BCS is proposed. A comprehensive evaluation for GNSS signals is employed to assess the proposed modulation in terms of tracking accuracy, multipath mitigation, anti-jamming, and compatibility, compared with legacy modulations such as BPSK and BOC.

The rest of this paper is organized as follows: Section 2 establishes the mathematical model of TDRC-BCS modulation and provides a general derivation of the theoretical power spectrum density (PSD) for TDRC-BCS modulation, along with its particular cases of TDRC-BOC modulation. Section 3 presents a comprehensive evaluation criterion for GNSS signal design and introduces an extensive study on the multipath model analysis approach. A comparison of the performance of the proposed TDRC-BCS modulation with that of current GNSS modulations are also conducted comprehensively in this section. Finally, Section 4 draws the conclusions.

2. TDRC-BCS modulation

2.1. Mathematical model

BCS modulation is considered to be a generalization of BPSK and BOC. Each code chip can be divided into rectangular pulses, each with an equal length k. The particular generation scheme makes BCS modulation a promising modulation given that the well-selected configuration of the BCS sequence offers clear performance advantages and the possibility of organizing spectrum properties in a more efficient way than the current BPSK and BOC modulations. The chip waveform is defined as

$$q(t) = \sum_{i=0}^{k-1} s_l rec_{T_c/k}\left(t - l\frac{T_c}{k}\right) \tag{1}$$

where s_l is the lth coded symbol of the BCS sequence and takes value ± 1, T_c is the spreading code period and $rec_\tau(t)$ denotes the rectangular pulses of duration τ, given by

$$rec_\tau(t) = \begin{cases} 1, & 0 \le t \le \tau \\ 0, & \text{others} \end{cases} \tag{2}$$

Here, a notation of BCS($[s_0, s_1, \ldots, s_{k-1}], m$) is used to describe the BCS modulation with the BCS sequence $[s_0, s_1, \ldots, s_{k-1}]$ for each chip and a spreading code rate of $f_c = m \times 1.023$ MHz.

The PSD characteristics entirely depend on the signal pulse waveform. As for above-mentioned specific requirements for PSD, we introduce a novel pulse waveform called TDRC:

$$p_\tau(t) = \begin{cases} \sqrt{\frac{2}{3}}[1 - \cos(\frac{2\pi t}{\tau})], & 0 \le t \le \tau \\ 0, & \text{others} \end{cases} \tag{3}$$

The normalized PSD (i.e., unit power over infinite bandwidth) of TDRC is derived as

$$\begin{aligned} P_{TDRC}(f) &= \frac{1}{\tau}\left\| \int_{-\infty}^{\infty} p_\tau(t)e^{-j2\pi f t}dt \right\|^2 \\ &= \frac{2}{3\tau}\left\| rec_\tau(f) - \frac{1}{2}rec_\tau\left(f - \frac{1}{\tau}\right) - \frac{1}{2}rec_\tau\left(f + \frac{1}{\tau}\right) \right\|^2 \\ &= \frac{2\sin^2(\pi f t)}{3\pi^2\tau f^2(f^2\tau^2 - 1)^2} \end{aligned} \tag{4}$$

with $rec_\tau(f) = \int_{-\infty}^{\infty} rec_\tau(t)e^{-j2\pi f t}dt = e^{-j\pi f \tau}\sin(\pi f \tau)/\pi f$. Fig. 1 compares the TDRC with a conventional rectangular chip in the time and frequency domains. As shown in this figure, TDRC can provide a high spectral efficiency compared to that of the rectangular because of its waveform smoothness and continuity in the time domain. The TDRC also obtains a smaller peak value near the center frequency that is more prone to be compatible with narrow band signals using same carrier frequency. TDRC also imposes stronger spectrum roll-off and less OOB emission in the side lobes, beneficial to minimize mutual interference with wide band signals. Besides, TDRC has a main lobe twice wider than that of the rectangular, offering an opportunity to maximize the ranging potentials and multipath mitigation capability due to the large amounts of high frequency components concentrated at the edge of available receiver bandwidth of great interests. The proposed pulse waveform perfectly fulfills the previously mentioned design requirements of new signals for the future GNSS.

Based on the good spectrum property of TDRC, an interesting modulation family with spreading code rate $f_c = m \times 1.023$ MHz, denoted as TDRC-BCS($[s_0, s_1, \ldots, s_{k-1}], m$), can be obtained by substituting the rectangular shape of BCS modulation with TDRC. The equivalent baseband signal is expressed as

$$\begin{aligned} s_{TDRC\text{-}BCS}(t) = &\sum_i m_i \sum_j a_{i,j} rec_{T_c}(t - jT_c - iT_m) \\ &\times \sum_{l=0}^{k-1} s_l p_{T_c/k}\left(t - l\frac{T_c}{k} - jT_c - iT_m\right), \quad t > 0 \end{aligned} \tag{5}$$

where m_i is the ith message data symbol (i.e., the value is always 1 for the pilot channel), $a_{i,j}$ is the jth spreading code chip of the ith message data symbol, $T_c = 1/f_c$ denotes the spreading code period, and T_m is the symbol period.

An example of the time-domain waveforms for BOC and TDRC-BCS is shown in Fig. 2. In particular, if the BCS sequence takes k sign representation of a sine waveform with $k = 2f_s/f_c = 2n/m$ or