A Novel Cosine-Phased Binary Offset Carrier Signal Tracking

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Abstract—This paper addresses a novel cosine-phased binary offset carrier (BOC) signal tracking, enabling an unambiguous signal tracking. Two novel locally-generated signals are first obtained by dividing the cosine-phased BOC sub-carrier into multiple parts, and then, cross-correlations between each of the locally-generated signals and the received signal are generated. Finally, the cross-correlations are efficiently combined, yielding a correlation function with no side-peaks, thus consequently, removing ambiguity in signal tracking. The tracking error performance comparison between the proposed and conventional correlation functions shows us that the proposed correlation function can offer a significant improvement in performance compared with the conventional correlation functions.

Keywords: global navigation satellite systems (GNSSs), global positioning system (GPS), binary offset carrier (BOC), tracking

1. Introduction

Due to the sharp main-peak of the binary offset carrier (BOC) signal correlation function providing an improved location accuracy, next generation global navigation satellite systems (GNSSs) such as the modernized global positioning system (GPS) and Galileo have adopted the BOC as a modulation scheme, instead of the conventional phase shift keying (PSK) signal [1]. Despite the advantage in main-peak of the BOC, the BOC-modulated signal has multiple side-peaks in its autocorrelation, and the side-peaks could bring on an ambiguity in signal tracking, eventually could lead to a serious location error [2], [3].

Although several correlation functions [3]-[6] have been proposed to remove the side-peaks so far, most of the correlation functions can be used for sine-phased BOC signals only, i.e., they are inapplicable to cosine-phased BOC signals used in many GNSS bands including Galileo E1 and E6 bands. [4] is applicable to cosine-phased BOC signals to some degree; however, it cannot remove the side-peaks completely, thus leaving the ambiguity problem unsolved. So, in this paper, we propose a novel unambiguous correlation function for cosine-phased BOC signals. Removing the cosine-wave pattern in the BOC sub-carrier causing the side-peaks, first, we design two novel locally-generated signals and generate the corresponding cross-correlations. Combining the cross-correlations in a specialized way based on the absolute-value arithmetic, then, we create a novel correlation function with no side-peaks. The proposed correlation function has two significant advantages over the conventional correlation functions: First, the side-peaks causing an ambiguity in signal tracking are removed completely. Second, the sharpness of the proposed correlation function can be adjusted according to system design requirements, allowing us more flexibility in designing a system.

The rest of this paper is organized as follows: In Section 2, we describe the signal model of the cosine-phased BOC signal. In Section 3, we propose a novel correlation function for cosine-phased BOC signal tracking. In Section 4, we compare the tracking performances of the proposed and conventional correlations. Finally, we conclude this paper in Section 5.

2. Cosine-phased BOC signal model

The cosine-phased BOC signal is denoted by $BOC_{\cos}(kn, n)$, where $k$ is the ratio of the PRN code chip duration and the sub-carrier period, and $n$ is the ratio of the PRN code chip rate and 1.023 MHz.

The $BOC_{\cos}(kn, n)$ signal $C(t)$ can be expressed as

$$C(t) = \sqrt{P} \sum_{i=-\infty}^{\infty} h_i p_{T_c}(t - iT_c) s_{cs}^{i}(t),$$  \hspace{1cm} (1)

where $P$ is the signal power, $h_i \in \{-1, 1\}$ is the $i$th chip of a PRN code with a period $T_c$, $p_{T_c}(t)$ denotes the unit rectangular pulse over $[0, \alpha]$, $T_c$ denotes the PRN code chip duration, and $s_{cs}^{i}(t)$ denotes the cosine-phased sub-carrier.

Since the cosine-phased sub-carrier over one PRN code chip duration consists of $4k$ sub-carrier pulses, the sub-carrier $s_{cs}^{i}(t)$ can be expressed as

$$s_{cs}^{i}(t) = \sum_{l=0}^{4k-1} m_l p_{T_s}(t - iT_s - lT_s),$$ \hspace{1cm} (2)

where $m_l = (-1)^{2k+l+[l/2]}$ is the sign of the $l$th sub-carrier pulse in the $i$th PRN code chip, $T_s = T_c/(4k)$ is the sub-carrier pulse duration, $s_{l}(t)$ is the $l$th sub-carrier pulse in the $i$th PRN code chip, and $[x]$ denotes the smallest integer not less than $x$ [7].
3. Proposed correlation function

First, we design locally-generated signals to be used instead of the BOC sub-carriers, and obtain cross-correlations by correlating each of the locally-generated signals and received signal, respectively. To design the locally-generated signals, we use the following absolute-value arithmetic property

$$|A| + |B| - |A - B| = \begin{cases} > 0, & \text{for } AB > 0 \\ 0, & \text{otherwise}. \end{cases}$$

From (3), we can see that the side-peaks would be removed under the following three conditions: (i) The multiplication of the cross-correlation main-peaks is positive, (ii) the multiplication of the cross-correlation side-peaks is negative,
and (iii) the two cross-correlations must be symmetric to each other to generate a symmetric unambiguous correlation function, due to the side-peaks being caused by the cosine-wave pattern of the sub-carrier. Based on these observations, in this paper, we design two locally-generated signals as

\[
\begin{align*}
\ell_1(t; a) &= \sum_{m=-\infty}^{\infty} \sqrt{\frac{4k}{1 + a^2}} (s_0^m(t) - a s_{2k}^{m-1}(t)), \\
\ell_2(t; a) &= \sum_{m=-\infty}^{\infty} \sqrt{\frac{4k}{1 + a^2}} (-a s_0^m(t) + s_{2k}^{m-1}(t)),
\end{align*}
\]

where \(\ell_1(t; a)\) and \(\ell_2(t; a)\) are the locally-generated signals, \(0 \leq a < 1\) is a parameter for adjusting the sharpness of the proposed correlation function. Then, we correlate the locally-generated signals and received signal, yielding cross-correlations

\[
R_j(\tau; a) = \frac{1}{PT} \int_0^T C(t) \ell_j(t + \tau; a) dt, \quad j = 1, 2.
\]

In Fig. 1, we can see that the locally-generated signals are symmetric to each other and have no cosine-wave pattern, and also that the multiplication of the cross-correlations

\[
R(\tau; a) = \frac{1}{PT} \int_0^T C(t) \ell_1(t) \ell_2(t + \tau; a) dt,
\]

Fig. 3: The proposed correlation and autocorrelation functions for BOC_{cos}(n, n) and BOC_{cos}(2n, n).

satisfy

\[
\begin{align*}
R_1(\tau; a)R_2(\tau; a) &> 0, \\
&\text{for } -\frac{(1 - a)T_c}{4k(2 - a)} < \tau < \frac{(1 - a)T_c}{4k(2 - a)}, \\
R_1(\tau; a)R_2(\tau; a) &= 0, \text{ otherwise.}
\end{align*}
\]

Thus, from (3) and (6), we can generate an unambiguous correlation function

\[
R(\tau; a) = |R_1(\tau; a)| + |R_2(\tau; a)| - |R_1(\tau; a) - R_2(\tau; a)|,
\]

and the process of (7) is depicted in Fig. 2, where we can see that the side-peaks are removed, and the main-peak height and width of \(R(\tau; a)\) are adjusted by the parameter \(a\).

Fig. 3 depicts that the proposed correlation and autocorrelation functions for BOC_{cos}(n, n) and BOC_{cos}(2n, n). From the figure, we can see that the side-peaks on the autocorrelation are removed completely through the process (7). In addition, we can see that the height and width of the proposed correlation are adjustable by fixing the parameter \(a\).

4. Numerical results

In this section, we compare tracking error standard deviation (TESD) performances of the proposed and conventional
correlation functions. The TESD is defined as

$$\sigma_G \sqrt{2B_L T_I},$$  \hspace{1cm} (8)

where \( \sigma \) is the standard deviation of the discriminator output at \( \tau = 0 \), \( B_L \) is the loop filter bandwidth, \( T_I \) is the integration time, and \( G \) is the discriminator gain at \( \tau = 0 \) [8]. For simulations, we consider the following parameters: \( B_L = 1 \) Hz, \( T = T_I = 4 \) ms, \( T_c^{-1} = 1.023 \) MHz, and the early-late spacing \( \Delta = T_c/16 \).

Fig. 4 shows the TESD performances of the proposed and conventional correlation functions for BOC cos \((n, n)\) and BOCcos \((2n, n)\) as a function of the carrier to noise ratio (CNR) defined as \( P/W_0 \) with \( W_0 \) the noise power spectral density. From the figure, it is observed that the proposed correlation function provides a better TESD performance than the conventional correlation functions including the auto-correlation function in the CNR range of \( 20 \sim 40 \) dB-Hz of practical interest. In addition, it is seen that the proposed correlation function performs better as the value of \( a \) increases. This is because the correlation main-peak becomes sharper, as the value of \( a \) increases. However, it should be noted that the tracking range would be smaller for a larger value of \( a \), and thus, the value of \( a \) should be determined according to system design requirements.

5. Conclusion

A novel correlation function has been proposed for unambiguous cosine-phased BOC signal tracking. We have first designed locally-generated signals to be used instead of the cosine-phased BOC sub-carrier and then have obtained the corresponding cross-correlation functions. Subsequently, by combining the cross-correlation functions in a specialized way, we have created an unambiguous correlation function. The numerical results has confirmed that the proposed correlation function has a much better tracking performance than the conventional correlation functions.

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