An Improved Unambiguous CBOC Signal Tracking Scheme in the Galileo System

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***Abstract*—Based on the cancellation and reinforcement of the autocorrelation side-peaks and main-peak, respectively, this paper proposes an improved unambiguous tracking scheme for composite binary offset carrier (CBOC) signals used in the Galileo system. Dividing the CBOC autocorrelation into multiple partial correlations, first, we obtain individual correlation components making up the autocorrelation side-peaks and main-peak. Then, we re-combine the components to cancel out the side-peaks, and at the same time, to reinforce the main-peak, thus yielding a correlation function with no side-peaks and a sharp main-peak. Numerical results demonstrate that the proposed scheme provides a significant improvement in tracking performance over the conventional schemes.**

Keywords–Global navigation satellite system (GNSS); Composite binary offset carrier (CBOC); Signal tracking; Ambiguity

I. INTRODUCTION

Galileo is a European alternative global navigation satellite system (GNSS) to the United States' global positioning system (GPS) [1]-[3], where the composite binary offset carrier (CBOC) modulation has been adopted instead of the conventional phase shift keying (PSK) modulation, since the CBOC provides a higher signal tracking accuracy and an efficient bandwidth sharing capability [2]. The CBOC signal is generated as a weighted sum of two kinds of sine-phased BOC signals, and in this paper, we consider the CBOC(6,1,1/11) signal used most widely, where '(6,1,1/11)' means that the CBOC signal is generated as a weighted sum of the sine-phased BOC(6,1) and BOC(1,1) signals with a power split ratio of 1/11 (i.e., the power of the sine-phased BOC(6,1) accounts for 1/11 of the whole CBOC signal power) [4][5].

The major problem in the CBOC signal is ambiguity in signal tracking caused by the multiple side-peaks of the CBOC autocorrelation function, i.e., the tracking loop may lock on one of the side-peaks. Thus, various schemes [6]-[12] have been proposed to alleviate this problem. [6]-[8] proposed unambiguous tracking schemes for the BOC signal, and so, they are not appropriate for the CBOC signal. In [9], a side-peak cancellation scheme applicable for the CBOC signal was proposed; however, its tracking performance is worse than that of the CBOC autocorrelation. [10] and [11] proposed autocorrelation side-peaks cancellation schemes for the CBOC signal using various auxiliary signals; however, the improvement in tracking performance over the conventional autocorrelation is not significant, and also, the auxiliary signals increase the system complexity. Although [12] proposed a tracking structure for the CBOC signal that does not use the autocorrelation, and thus, is free from the side-peaks, it has a much worse tracking performance than that of the autocorrelation-based tracking.

In this paper, we propose a novel unambiguous CBOC signal tracking scheme providing a significant improvement in tracking performance without any auxiliary signal. We first divide the autocorrelation function into multiple partial correlations, and then, we perform a re-combining process with the partial correlations to yield a correlation function with no side-peaks (unambiguous) and a sharp main-peak (good performance). In numerical results, the proposed scheme is found to offer a much better tracking performance than those of the conventional schemes.

The rest of this paper is organized as follows: In Section II, we describe the CBOC(6,1,1/11) signal model. In Section III, we present the proposed scheme. In Section IV, the tracking error performances of the proposed and conventional schemes are compared, and in Section V, conclusion and future work are presented.

II. SYSTEM MODEL

Assuming that there is no data modulation, the CBOC(6,1,1/11) signal can be expressed as [13]

$$r(t) = \sqrt{S} \sum_{i=-\infty}^{\infty} a_i r_{T_c}(t - iT_c) c_{sc}^i(t), \qquad (1)$$

where S is the signal power, $a_i \in \{-1, 1\}$ is the ith chip of a pseudo random noise (PRN) code with a period T, $r_\alpha(t)$ denotes the unit rectangular pulse over $[0, \alpha)$, T_c is the chip period of the PRN code, and

$$c_{sc}^i(t) = \sqrt{\frac{10}{11}} c_{\mathrm{BOC}(1,1)}^i(t) - \sqrt{\frac{1}{11}} c_{\mathrm{BOC}(6,1)}^i(t) \qquad (2)$$

is the square wave sub-carrier for the ith PRN code chip, where $c_{\mathrm{BOC}(1,1)}^i(t)$ is the sub-carrier of the sine-phased BOC(1,1) signal for the ith PRN code chip, and $c_{\mathrm{BOC}(6,1)}^i(t)$ is the sub-carrier of the sine-phased BOC(6,1) signal for the ith PRN code chip. Therefore, the CBOC sub-carrier $c_{sc}^i(t)$ can be re-written as

$$c_{sc}^i(t) = \sum_{j=0}^{11} [\sqrt{\frac{10}{11}} (-1)^{\lfloor \frac{j}{6} \rfloor} r_{T_s}(t - iT_c - jT_s) - \sqrt{\frac{1}{11}} (-1)^j r_{T_s}(t - iT_c - jT_s)], \qquad (3)$$

where $\lfloor x \rfloor$ denotes the largest integer not larger than x, and $T_s = T_c/12$ denotes the sub-carrier pulse duration of the sine-phased BOC(6,1) signal.

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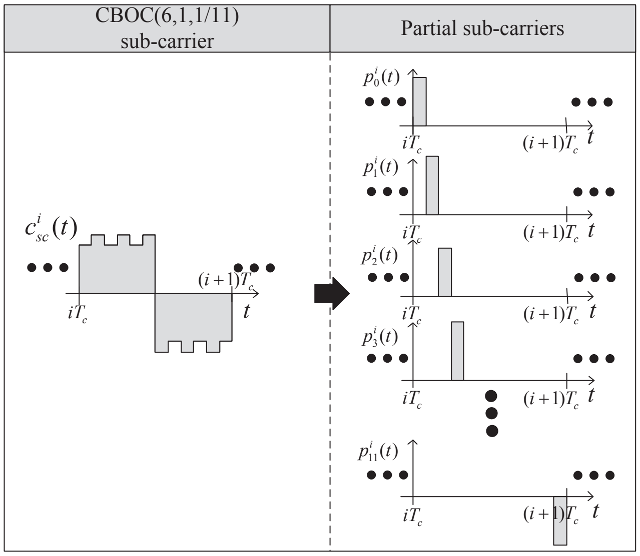

Figure 1. A sub-carrier and partial sub-carriers for CBOC(6,1,1/11).

The aim of this paper is to propose a novel correlation generator yielding an unambiguous correlation function with a sharp main-peak. We first observe that the autocorrelation side-peaks arise due to changes in the CBOC sub-carrier value, and then, to remove the value changes, we divide the CBOC sub-carrier into 12 pulses, each of which has a duration of $\frac{T_c}{12} = T_s$, which are called partial sub-carriers and are used as locally generated sub-carriers instead of the CBOC sub-carrier. Thus, the CBOC sub-carrier can be expressed as the sum of the partial sub-carriers, i.e.,

$$c_{sc}^i(t) = \sum_{m=0}^{11} p_m^i(t), \tag{4}$$

where $p_m^i(t)$ is the mth partial sub-carrier for the ith PRN code chip. Figure 1 depicts the sub-carrier and partial sub-carriers for CBOC(6,1,1/11). Then, the normalized CBOC(6,1,1/11) autocorrelation function can be expressed as

$$\begin{aligned} R(\tau) &= \frac{1}{ST}\int_0^T r(t)r(t+\tau)dt, \\ &= \sum_{m=0}^{11} \frac{1}{ST}\int_0^T r(t)r_m(t+\tau)dt, \\ &= \sum_{m=0}^{11} C_m(\tau), \end{aligned} \tag{5}$$

where

$$r_m(t) = \sqrt{S}\sum_{i=-\infty}^{\infty} a_i r_{T_c}(t - iT_c)p_m^i(t) \tag{6}$$

and $C_m(\tau)$ is called the mth partial correlation corresponding to the mth partial sub-carrier, and is depicted in Figure 2 for $m = 0, 1, 2, \cdots, 11$.

III. PROPOSED CORRELATION FUNCTION

To obtain an unambiguous and sharp correlation function, we re-combine the partial correlations, and the re-combining process consists of (i) removing ambiguity, (ii) narrowing the correlation function width, and (iii) elevating the correlation function height.

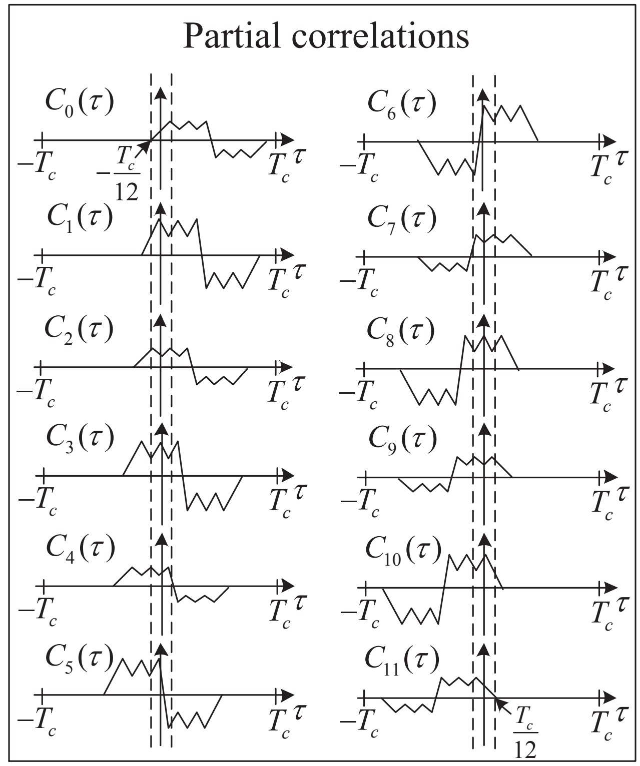

Figure 2. Partial correlations for CBOC(6,1,1/11).

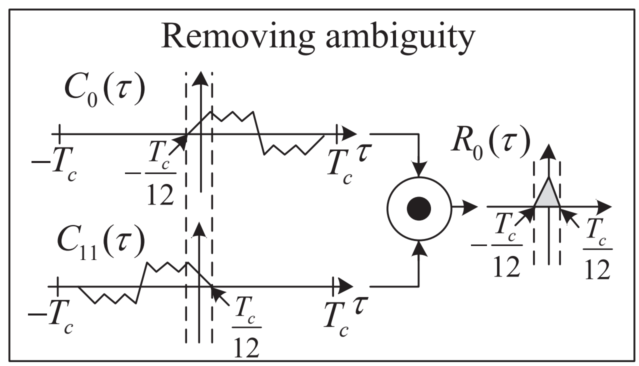

Figure 3. Ambiguity removal process.

A. Removing ambiguity

First, we focus on $C_0(\tau)$ and $C_{11}(\tau)$ to remove the ambiguity. From Figure 3, we can observe that $C_0(\tau)C_{11}(\tau) > 0$ for $|\tau| \leq T_c/12$ and $C_0(\tau)C_{11}(\tau) = 0$ otherwise.

Thus, we can obtain an unambiguous correlation function by the arithmetic property $|x| + |y| - |x - y| = 0$ for $xy \leq 0$ and $|x| + |y| - |x - y| > 0$ otherwise, i.e., an unambiguous correlation $R_0(\tau)$ can be obtained as

$$\begin{aligned} R_0(\tau) &= C_0(\tau) \odot C_{11}(\tau), \\ &= |C_0(\tau)| + |C_{11}(\tau)| - |C_0(\tau) - C_{11}(\tau)|, \end{aligned} \tag{7}$$

where $A \odot B$ denotes $|A| + |B| - |A - B|$.

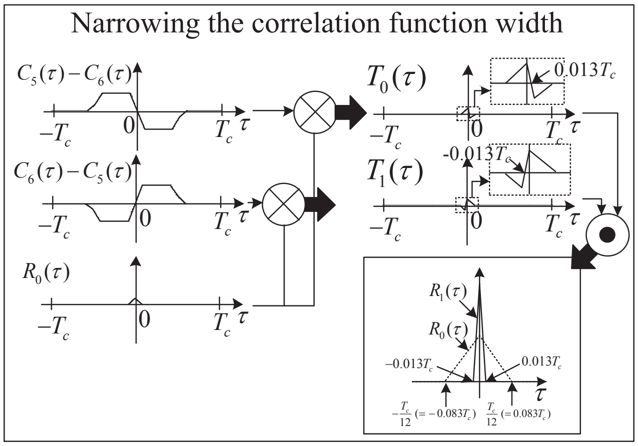

Figure 4. The generation process of a narrow correlation function.

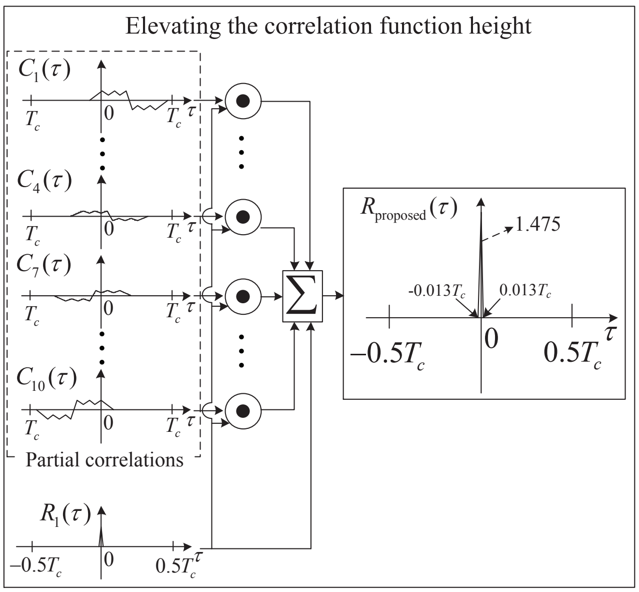

Figure 5. The generation process of the proposed correlation function.

B. Narrowing the correlation function width

Even though the side-peaks are removed completely by (7), we can make $R_0(\tau)$ narrower by using the remaining partial correlations. From Figure 3, we can observe that the half-width of $R_0(\tau)$ depends on the zero-crossings of $C_0(\tau)$ and $C_{11}(\tau)$. Thus, to reduce the width of $R_0(\tau)$, we generate the following two correlations

$$\begin{aligned} T_0(\tau) &= (C_5(\tau) - C_6(\tau)) \otimes R_0(\tau), \\ T_1(\tau) &= (C_6(\tau) - C_5(\tau)) \otimes R_0(\tau), \end{aligned} \tag{8}$$

where $A \otimes B$ denotes $|A+B| - |A|$, which have smaller zero-crossings than those of $C_0(\tau)$ and $C_{11}(\tau)$, and we obtain a narrower correlation

$$R_1(\tau) = T_0(\tau) \odot T_1(\tau), \tag{9}$$

which is narrower than $R_0(\tau)$ as shown in Figure 4.

C. Elevating the correlation function height

To make the correlation function sharper, and consequently, to improve the tracking performance, we combine the partial correlations $\{C_i(\tau)\}_{i=1,i\neq 5,6}^{10}$ with $R_1(\tau)$, respectively, via the operator '$\odot$', and then, add the results to $R_1(\tau)$, i.e., the proposed unambiguous correlation function is obtained as

$$R_{\text{proposed}}(\tau) = R_1(\tau) + \sum_{m=1,m\neq 5,6}^{10} C_m(\tau) \odot R_1(\tau), \tag{10}$$

and its generation process is described in Figure 5. The proposed and conventional correlation functions are depicted in Figure 6 (note that [12] is not a correlation-based scheme and so does not have a correlation function), where we can see that the proposed correlation function is the sharpest with the height and half width of 1.475 and $0.013T_c$, respectively, and thus, we anticipate that the proposed scheme provides an improvement in tracking performance over the conventional schemes.

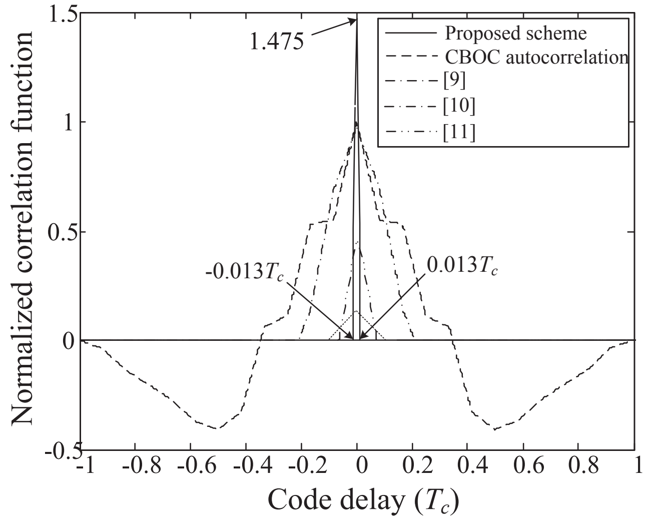

Figure 6. The proposed and conventional correlation functions for CBOC(6,1,1/11) signal tracking.

IV. Numerical results

In this section, we compare the tracking performances of the proposed and conventional schemes in terms of the tracking error standard deviation (TESD) defined as [14]

$$\frac{\sigma}{G}\sqrt{2B_L T_I}, \tag{11}$$

where σ is the standard deviation of the discriminator output $D(\tau)$ at $\tau = 0$, G is the discriminator gain at $\tau = 0$, i.e., $G = \frac{dD(\tau)}{d\tau}\big|_{\tau=0}$, B_L is the loop filter bandwidth, and T_I is the integration time. For simulations, we consider the following parameters of practical interest [3]: $T = T_I$ = 4 ms, B_L = 1 Hz, T_c^{-1} = 1.023 MHz, the early-late spacing of $\frac{T_c}{48}$ and $\frac{T_c}{96}$ for a delay lock loop (DLL) structure shown in Appendix, and MATLAB Monte-Carlo simulations with 10^4 runs for performance evaluation.

Figure 7 and Figure 8 show the TESD performances of the proposed and conventional schemes as a function of the carrier to noise ratio (CNR) defined as S/W_0 with W_0 the noise power spectral density when $\Delta = T_c/48$ and $T_c/96$, respectively. From the figures, we can clearly see that the proposed scheme offers a significant improvement in performance over the

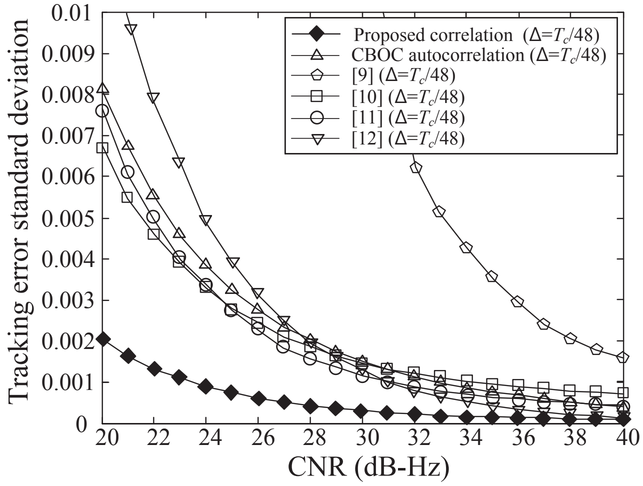

Figure 7. TESD performances of the proposed and conventional schemes when $\Delta = T_c/48$.

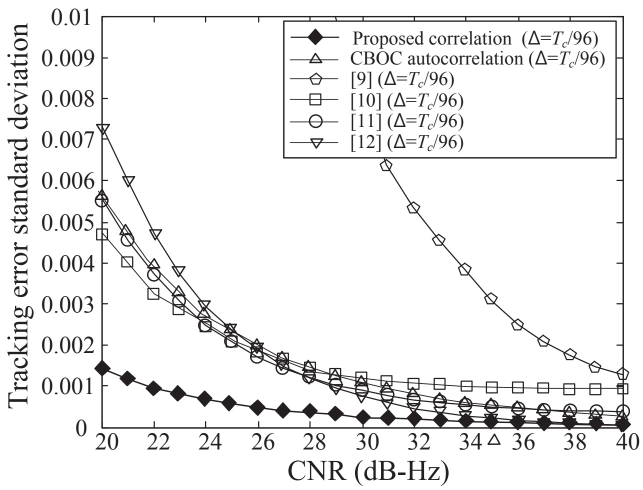

Figure 8. TESD performances of the proposed and conventional schemes when $\Delta = T_c/96$.

conventional schemes in the CNR range of $20 \sim 40$ dB-Hz of practical interest. This stems from the fact that the proposed correlation function is not only unambiguous (no side-peaks), but also the sharpest.

V. Conclusion and Future Work

In this paper, we have proposed a novel unambiguous CBOC signal tracking scheme providing a significant improvement in tracking performance. Dividing the CBOC autocorrelation into multiple partial correlations, first, we have obtained individual components making up the autocorrelation side-peaks and main-peak, and then, re-combining the individual components, we have canceled out and reinforced the side-peaks and main-peak, respectively, and have generated a correlation function with no side-peaks and a sharp main-peak. In numerical results, it has been confirmed that the proposed scheme has a much better tracking performance than those of the conventional schemes. In future work, we will investigate design parameters affecting the width and height of the correlation function, thus allowing us to adjust the sharpness of the proposed correlation function according to system design requirements. In addition, we will discuss the performance of the proposed scheme in multipath environments in terms of the multipath error envelop.

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Appendix: A DLL structure

Figure 9 depicts the DLL structure used in evaluating the TESD performances of the proposed and conventional correlation functions, where τ represents the phase difference between the received and locally generated CBOC signals and

$$D(\tau) = R^2(\tau + \frac{\Delta}{2}) - R^2(\tau - \frac{\Delta}{2}) \qquad (12)$$

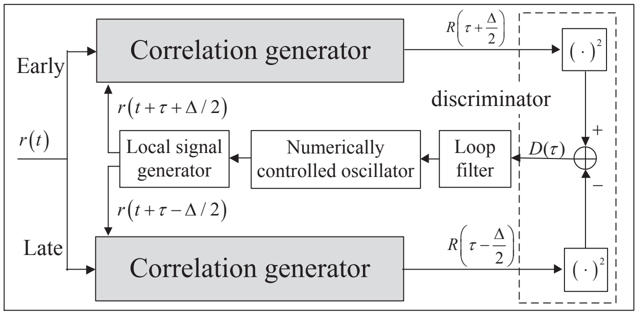

Figure 9. The DLL structure for CBOC(6,1,1/11) signal tracking.

is the discriminator output with Δ the early-late spacing and $R(\cdot)$ the correlation generator output. The operation of the DLL is as follows: The clock of the local signal generator is advanced or delayed by the numerically controlled oscillator, and finally, is locked when τ is zero.