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Variable vs. Fixed Window Width Code Correlation Reference Waveform Receivers for Multipath Mitigation in Global Navigation Satellite Systems with Binary Offset Carrier and Multiplexed Binary Offset Carrier Signals

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Abstract—This paper compares the multipath mitigation performance of code correlation reference waveform receivers with variable and fixed window width, for binary offset carrier and multiplexed binary offset carrier signals typically used in global navigation satellite systems. In the variable window width method, such width is iteratively reduced until the distortion on the discriminator with multipath is eliminated. This distortion is measured as the Euclidean distance between the actual discriminator (obtained with the incoming signal), and the local discriminator (generated with a local copy of the signal). The variable window width have shown better performance compared to the fixed window width. In particular, the former yields zero error for all delays for the BOC and MBOC signals considered, while the latter gives rather large nonzero errors for small delays in all cases. Due to its computational simplicity, the variable window width method is perfectly suitable for implementation in low-cost receivers.

Keywords—Correlation reference waveform receivers, binary offset carrier, multiplexed binary offset carrier, global navigation satellite systems

I. INTRODUCTION

MULTIPATH is the main source of error in satellite communications [1]–[3], and it is due to the interference from delayed versions of the signal that are received in addition to the same signal arriving in a direct-path from the transmitter. The techniques for multipath mitigation can be one of three types: (i) techniques that use the radiation pattern of the antennas [4], (ii) techniques in the navigation stage without estimating the channel [5], and (iii) techniques in the navigation stage that use channel estimation [5]. The main challenge is to mitigate its effect using low-cost receivers.

As part of the evolution of Global Navigation Satellite Systems (GNSS) during the last two decades, the Early-Late (E-L) receivers that use Binary Phase Shift Keying (BPSK) CDMA modulation with multiplexing [1]–[3], have been replaced by Code Correlation Reference Waveform (CCRW) receivers employing Binary Offset Carrier (BOC) modulations. CCRW receivers are capable of overcoming limitations of E-L, such as the occurrence of false locks in the presence of multipath, which result in errors in the calculation of the signal travel time [6], [7].

The CCRW receiver was proposed by Young et al. [6], and uses one of six correlation techniques: narrow correlator, W_1, W_2, W_3, W_4 or Gated E-L CCRW [6]. On the other hand, $\mathrm{BOC}(m, n)$ modulation was developed by Betz et al. [3], [10]–[12] and incorporates a square subcarrier to the satellite original Binary Phase Shift Keying (BPSK) signal; this square subcarrier is obtained as the sign function of a sinusoidal signal. In addition to being effective in multipath mitigation, BOC modulation has been used to correct errors in the received information, taking advantage of its redundancy around the central frequency of the channel, and has shown to be robust in the presence of noise [1], [3], [10]–[12].

$\mathrm{BOC}(kn, n)$ modulations are utilized for military (fewer users, high precision required) purposes in the L1 and L2 bands of the GPS system, and in the E1 and E6 bands of the GALILEO system [1], [7], [8]. Later, multiplexed BOC (MBOC) modulations were developed in 2006 to increase the amount of information that can be transmitted, thus facing the massive civilian (many users, lower precision) use of GNSS systems. MBOC modulations include Time multiplexed BOC $(\mathrm{TMBOC}(6, 1, 4/33))$ in the carrier of the L1C band of the GPS system, and Composite BOC $(\mathrm{CBOC}(6, 1, 1/11))$ in the carrier of the E1 OS band of the GALILEO system. MBOC signals were also designed to guarantee high interoperability between both systems [1].

In CCRW receivers, the use of windows W_1, W_2, W_3 and W_4 (and combinations) to mitigate the effect of multipath has been evaluated for BOC [13]–[19] and MBOC [19]–[22] modulations. These works mainly search for the appropriate shape and width of the pulses, considering that a shorter pulse will be better for multipath mitigation, but will tend to reduce the number of satellites “seen” by the receiver [23]. Specifically, this has been formulated as an inverse problem [13]–[22]: given a desired discriminator, find the correlation functions that generate it, and further find the windows that will result in those correlation functions. Algorithms for solving such inverse problems may be time consuming and computationally demanding, and thus not appropriate for implementation in low-cost receivers [23]. A more rigorous

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mathematical analysis of such inverse problems is presented in [24]–[27].

As a more effective alternative, AlHussein et al. [23] proposed a method of variable window width in a CCRW receiver, which will mitigate the effect of multipath of any delay. Such width was iteratively reduced, until finding the first value for which the distortion produced by multipath was eliminated. The proposed approach was tested for $\mathrm{BOC}(kn, n)$ modulation, with $k = 1$ and $k = 2$, using the windows and the receiver proposed by L. Zhe [17], and resulted in zero error for multipath of any delay, thus outperforming those which, in general, exhibit a nonzero error for small delays.

This work compares the multipath mitigation performance of CCRW receivers with variable window width proposed in [23] and fixed window width proposed by Zhe [17], [19], [21], for different BOC and the multiplexed BOC (MBOC) modulations $\mathrm{CBOC}(6, 1, 1/11)$ and $\mathrm{TMBOC}(6, 1, 4/33)$.

The rest of the paper is structured as follows. Section II describes the BOC and MBOC signals in GNSS. Section III presents the CCRW receiver with fixed window width, while section IV describes the receiver with variable window width. Finally, Section V presents the results and Section VI concludes the paper.

II. BOC, CBOC AND TMBOC SIGNALS IN GNSS

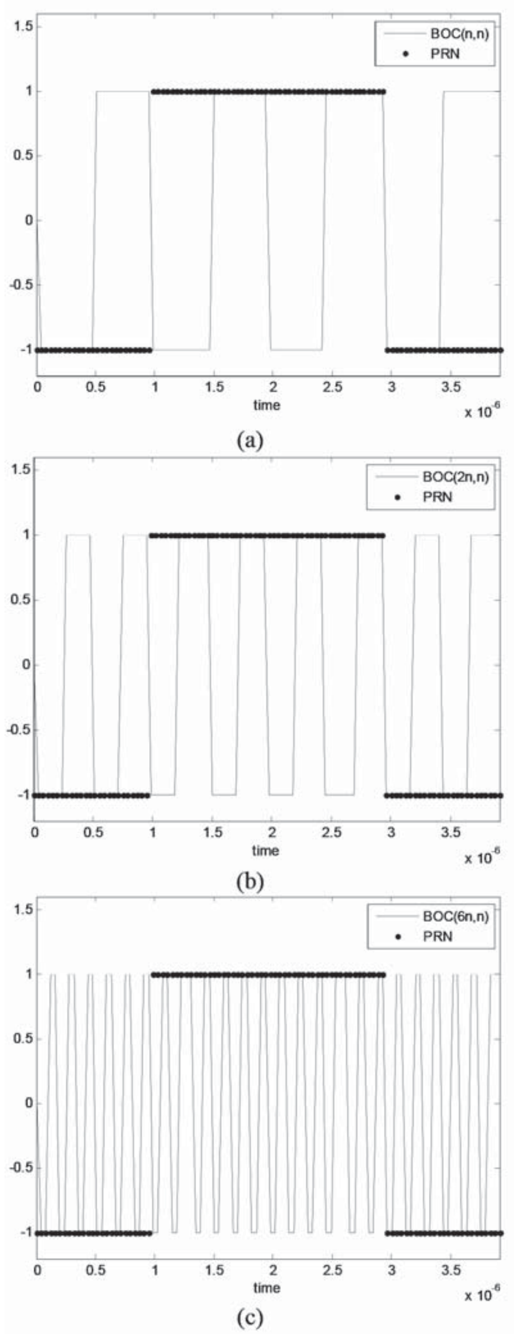
The $\mathrm{BOC}(kn, n)$ signal is generated modulating a BPSK signal with a square wave sub-carrier of frequency nkf_0 ($f_0 =$ 1.023 MHz). The BPSK signal is obtained modulating the PRN code with a 50 Hz binary signal containing the satellite data. On the other hand, the subcarrier is obtained as the sign of a sine (sine-phased BOC) or a cosine (cosine-phased BOC) waveform [1]. In other words, the sine-phased BOC signal is given by

$$\mathrm{BOC}(kn, n) = c_i(t).\,\mathrm{sign}\left(\sin(2\pi nkf_0 t)\right) \tag{1}$$

where $c_i(t)$ is the BPSK signal [23]. Figs. 1 (a)-(c) show GNSS $\mathrm{BOC}(kn, n)$ signals with a length of four chips, for $k = 1, 2$ and 6. $\mathrm{BOC}(2n, n)$ is used as a military signal, while $\mathrm{BOC}(n, n)$ and $\mathrm{BOC}(6n, n)$ are used as civilian signals in the MBOC modulation of the GPS system. These signals are summarized in Table I. The signals $\mathrm{CBOC}(6, 1, 1/11)$ and $\mathrm{TMBOC}(6, 1, 4/33)$ are now described.

TABLE I
SUMMARY OF BOC AND MBOC SIGNALS USED IN GNSS

Modulation	**Service**	**Band**	**System**
$\mathrm{BOC_{sin}}(10, 5)$	L1M-code	L1	GPS
$\mathrm{TMBOC}(6, 1, 4/33)$	L1C	L1	GPS
$\mathrm{CBOC}(6, 1, 1/11)$	E1 OS	E1	GALILEO
$\mathrm{BOC_{cos}}(15, 2.5)$	PRS	E1	GALILEO
$\mathrm{BOC_{cos}}(10, 5)$	E6 PRS	E6	GALILEO



(a)

(b)

(c)

Fig. 1 BOC signals with a length of 4 chips: (a) $\mathrm{BOC}(n, n)$ (b) $\mathrm{BOC}(2n, n)$ (c) $\mathrm{BOC}(6n, n)$

A. $\mathrm{CBOC}(6, 1, 1/11)$ *Modulation*

The CBOC modulation was developed by the CNES research group at the University FAF Munich. The $\mathrm{CBOC}(6, 1, 1/11)$ signal is used in GALILEO, and is given as the sum of signals $\mathrm{BOC}(1, 1)$ and $\mathrm{BOC}(6, 1)$ with different amplitudes, such that their interference generates an appropriate Power Spectral Density (PSD). Specifically, the $\mathrm{CBOC}(6, 1, 1/11)$ signal is given by [1]:

$$\begin{aligned} z(t) = \Big[& C_D(t) d(t) \big(P \cdot x(t) + Q \cdot y(t)\big) + \\ & C_P(t) \big(P \cdot x(t) - Q \cdot y(t)\big) \Big] \end{aligned} \tag{2}$$

where $z(t)$, $x(t)$ and $y(t)$ are the $\mathrm{CBOC}(6, 1, 1/11)$, $\mathrm{BOC}(6, 1)$ and $\mathrm{BOC}(1, 1)$ signals, respectively, C_D is the data-spreading code sequence, C_P is the pilot-spreading code sequence, d is the navigation message, and $P = \sqrt{1/11}$ and $Q = \sqrt{10/11}$ are the weight factors of $\mathrm{BOC}(6,1)$ and $\mathrm{BOC}(1,1)$, respectively. The sign inversion of the $\mathrm{BOC}(6,1)$ sub-carrier between the data and pilot channels in (2), cancels the $\mathrm{BOC}(1,1)/\,\mathrm{BOC}(6,1)$ crossterms which appear on each channel [1].

In this work, the simplified version

$$z(t) = P \cdot x(t) + Q \cdot y(t) \tag{3}$$

of the $\mathrm{CBOC}(6,1,1/11)$ is used, which considers the high- and low-frequency signals in one chip, without including the data signal. Fig. 2 displays a $\mathrm{CBOC}(6,1,1/11)$ signal with a length of four chips.

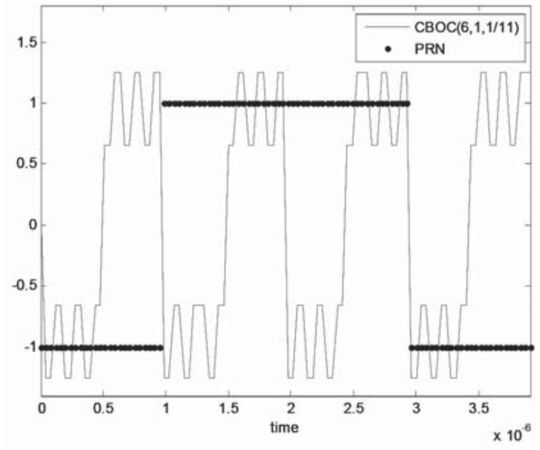


Fig. 2 $\mathrm{CBOC}(6,1,1/11)$ signal with length of 4 chips

B. $\mathrm{TMBOC}(6,1,4/33)$ *Modulation*

The GPS system adopted the MBOC modulation $\mathrm{TMBOC}(6,1,4/33)$, which is obtained by multiplexing in time the high frequency signal $\mathrm{BOC}(6,1)$ in the first 4 chips and the low-frequency signal $\mathrm{BOC}(1,1)$ in the last 29 chips of a frame of 33 chips, i.e.

$$z(t) = \begin{cases} c(t) \cdot x(t) & t \in \dfrac{4}{33}\text{chips} \\ c(t) \cdot y(t) & t \in \dfrac{29}{33}\text{chips} \end{cases} \tag{4}$$

where $z(t)$ is $\mathrm{TMBOC}(6,1,4/33)$ signal, $c(t)$ is the data, and $x(t)$ and $y(t)$ are the $\mathrm{BOC}(6,1)$ and the $\mathrm{BOC}(1,1)$ signals, respectively. Fig. 3 shows chip 3 to chip 6 of a signal $\mathrm{TMBOC}(6,1,4/33)$ i.e., two before and two after the change in the multiplexed signal.

III. CCRW RECEIVERS WITH FIXED WINDOW WIDTH

Code Correlation Reference Waveform (CCRW) refers to different code correlation techniques used by some major GPS receiver manufacturers. These techniques were specially designed to mitigate multipath, and use a reference waveform instead of a replica of the navigation signal [23].

CCRW are simple low-cost receivers designed to construct a discriminator that eliminates the ambiguity generated by the use of BOC modulation and by the presence of multipath. They contain filters and correlation blocks that result in an adequate interaction between the BOC signals and the stroboscopic windows to mitigate the effect of multipath.

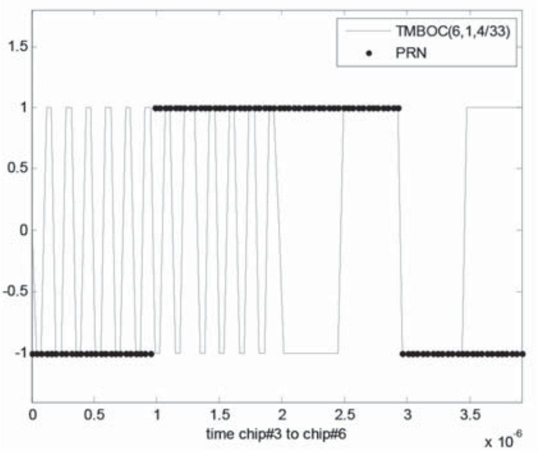


Fig. 3 $\mathrm{TMBOC}(6,1,4/33)$ signal with length of 4 chips

Zhe [19] proposed a CCRW receiver for $\mathrm{MBOC}(kn,n,p)$ signals. This receiver is a modified version of the one described in [23]. Specifically, the incoming MBOC signal is not correlated with its local version, but with an additional stroboscopic window called $\mathrm{BRW}(t)$. As a consequence, the ambiguities generated by the MBOC signal are located at the extremes of the pull-in region. Therefore, the algorithm for generating the discriminator for MBOC signals comprises the following steps:

Step 1. Generate a BPSK signal $y(t)$ using the Double Side Band (DSB) method [4], [28], according to which two pass-band filters of aperture $2 \cdot n \cdot f_0$ are employed. This BPSK signal corresponds to the PRN code modulated in the BOC signal, and has an in-phase component $y_i(t)$ and a quadrature component $y_q(t)$.

Step 2. Construct window W as

$$W(t) = \sum_{i=0}^{\infty} g(t - iT_C)c_i(t) \tag{5}$$

where

$$g(t) = \begin{cases} 1, & -\dfrac{T_C}{2k} \leq t < -\dfrac{T_C}{4k} \\ -1, & -\dfrac{T_C}{4k} \leq t < 0 \\ 1, & 0 \leq t < \dfrac{T_C}{4k} \\ -1, & \dfrac{T_C}{4k} \leq t < \dfrac{T_C}{2k} \\ 0, & \text{else} \end{cases} \tag{6}$$

and $c_i(t)$ is a local version of the PRN code.

Step 3. Correlate the in-phase component $s_i(t)$ and quadrature components $s_q(t)$ of the incoming BOC signal with

$W(t)$ to obtain

$$I_{\widehat{XW}} = \operatorname{corr}\Big(s_i(t), W_2(t-\varepsilon)\Big), \tag{7a}$$

$$Q_{\widehat{XW}} = \operatorname{corr}\Big(s_q(t), W_2(t-\varepsilon)\Big). \tag{7b}$$

Step 4. Construct the BRW window as

$$\mathrm{BRW}(t) = \sum_{i=0}^{\infty} g_{\mathrm{BRW}}\left(t - iT_C + \frac{Tc}{2}\right) c_i(t) \tag{8}$$

where

$$g_{\mathrm{BRW}}(t) = \begin{cases} -1, & -\dfrac{G_{BW}}{2} \leq t < 0 \\ 1, & 0 \leq t < \dfrac{G_{BW}}{2} \\ 0, & \text{else} \end{cases} \tag{9}$$

where G_{BW} is the width of the stroboscopic pulse.

Step 5. Correlate $y_i(t)$ and $y_q(t)$ with the local version $\mathrm{BRW}(t-\varepsilon)$ of the BOC signal to obtain

$$I_{\widehat{XB}} = \operatorname{corr}\Big(y_i(t), BRW(t-\varepsilon)\Big), \tag{10a}$$

$$Q_{\widehat{XB}} = \operatorname{corr}\Big(y_q(t), \mathrm{BRW}(t-\varepsilon)\Big). \tag{10b}$$

Step 5. Determine the discriminator by means of the equation

$$d(\varepsilon) = I_{\widehat{XW}}(\varepsilon) I_{\widehat{XB}}(\varepsilon) + Q_{\widehat{XW}}(\varepsilon) Q_{\widehat{XB}}(\varepsilon) \tag{11}$$

Note that: (i) the discriminator is a function of the delay (given in chips) and (ii) the signal mainly corresponds to the in-phase component (the quadrature component is neglected since the angle of the error is approximately zero). Fig. 4 is a plot of the discriminator corresponding to a signal without multipath.

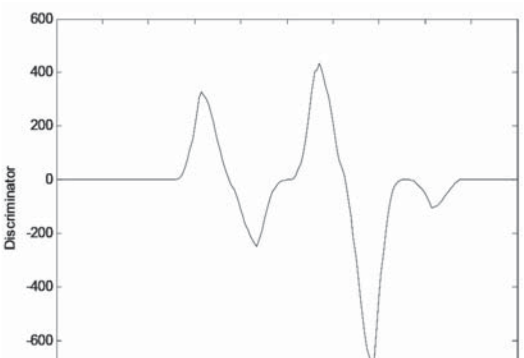


Fig. 4 Discriminator for a $\mathrm{BOC}(10,5)$ signal on a CCRW receiver with W_2

IV. CCRW RECEIVER WITH VARIABLE WINDOW WIDTH

The improvement to the previous algorithm consists of incorporating an iterative procedure to find the maximum width of the W window that will result in the mitigation of the effect of multipath [23]. It is important to remark that the width of the BRW window is kept constant at the value specified in [17], because it does not impact the effect of multipath, it is only used to eliminate the ambiguity generated by the multiple modulation of the TMBOC and CBOC signals.

Specifically, an initial window width ε equivalent to a half chip is iteratively reduced until the distortion on the actual discriminator (generated using the incoming signal) is eliminated. Such distortion is measured as the Euclidean distance between the actual discriminator da and the local discriminator dl (generated using a local copy of the signal), i.e.

$$ED = \sqrt{\sum_i \Big(da_i(\varepsilon) - dl_i(\varepsilon)\Big)^2}; \quad i = 1, \cdots, N \tag{12}$$

where N is the number of samples is smaller than a certain threshold [23]. The algorithm including the improvement is depicted in Fig. 5. On the other hand, the architecture of the receiver is illustrated in Fig. 6.

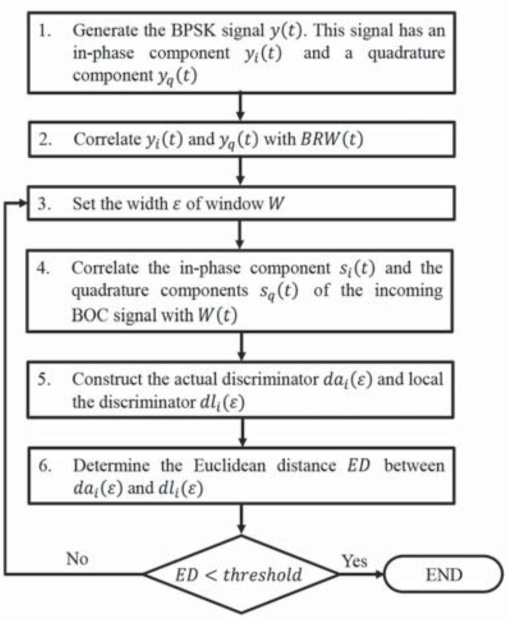

1. Generate the BPSK signal $y(t)$. This signal has an in-phase component $y_i(t)$ and a quadrature component $y_q(t)$
2. Correlate $y_i(t)$ and $y_q(t)$ with $BRW(t)$
3. Set the width ε of window W
4. Correlate the in-phase component $s_i(t)$ and the quadrature components $s_q(t)$ of the incoming BOC signal with $W(t)$
5. Construct the actual discriminator $da_i(\varepsilon)$ and local the discriminator $dl_i(\varepsilon)$
6. Determine the Euclidean distance ED between $da_i(\varepsilon)$ and $dl_i(\varepsilon)$

Fig. 5 Proposed algorithm for multipath mitigation using MBOC signals

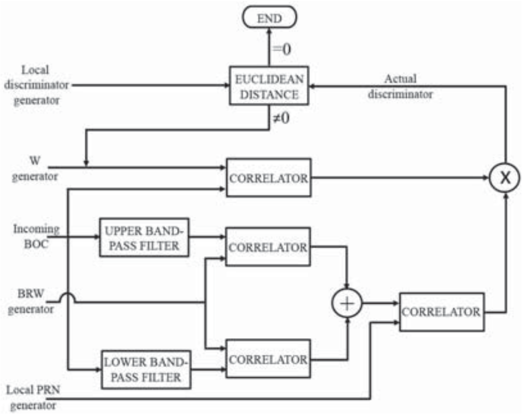


Fig. 6 Architecture of the proposed receiver

V. RESULTS

As stated before, this work compares the multipath mitigation performance of the CCRW receivers with variable window width [23] and fixed window width [17], [19], [21], for the BOC and MBOC used in GPS y GALILEO that are summarized in Table I [1].

Both types of receivers were implemented in MATLAB, and the performance criterion is the distortion or error in the actual discriminator, measured as the Euclidean distance between the actual discriminator and the local (undistorted) discriminator (generated using a local copy of the signal) as a function of the multipath delay.

First, the multipath mitigation performance on signals $\mathrm{BOC}(kn, n)$ is evaluated. Then, the performance for multiplexed BOC signals $\mathrm{CBOC}(6, 1, 1/11)$ and $\mathrm{TMBOC}(6, 1, 4/33)$ were evaluated.

A. $\mathrm{BOC}_{\sin}(10, 5)$, $\mathrm{BOC}_{\cos}(10, 5)$

For these cases, which correspond to $k = 2$ and $n = 1$, Zhe [17] and AlHussein [23] use the W_2 window. W_2 was also used here. Fig. 4 displays the undistorted discriminator for this signal, while Fig. 7 shows the error for both the variable and fixed window width CCRW receivers. Note that the former yields a zero error for all delays, as compared to the latter which exhibits nonzero errors for delays smaller than 0.1 chips, with an error even greater than 1.000 for delays smaller than 0.08 chips.

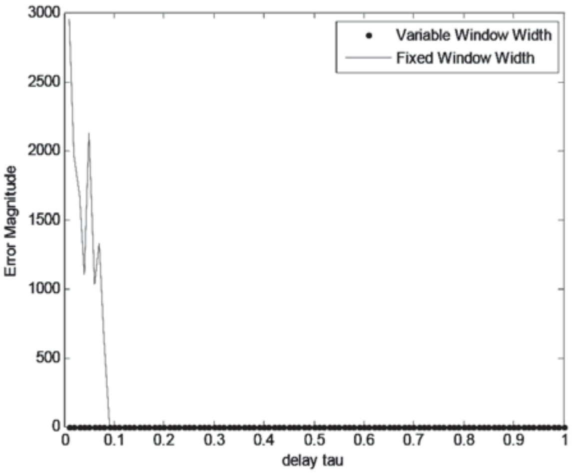


Fig. 7 Error of both receivers for $\mathrm{BOC}(10, 5)$

B. $\mathrm{BOC}_{\cos}(15, 2.5)$

This modulation corresponds to $\mathrm{BOC}(kn, n)$ with $k = 6$, $n = 1$. For this signal, a window W_2 with fixed width does not yield a good performance, and Zhe [17] indicates that window W_1 is applicable for multipath mitigation. Therefore, the latter is used here.

Fig. 8 shows the corresponding undistorted discriminator, while Fig. 9 plots the error for both approaches. Similar to the previous case, the variable window width yields zero error for all delays, while the fixed width gives nonzero errors for delays smaller than 0.1 chips, with errors greater than 100 for delays smaller than 0.09 chips.

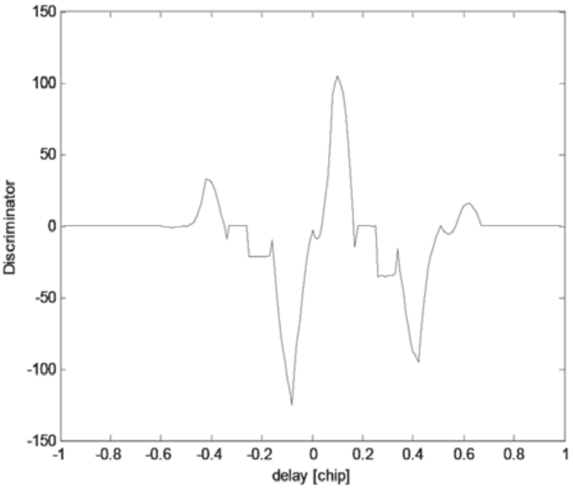


Fig. 8 Discriminator for $\mathrm{BOC}(15, 2.5)$ with W_1

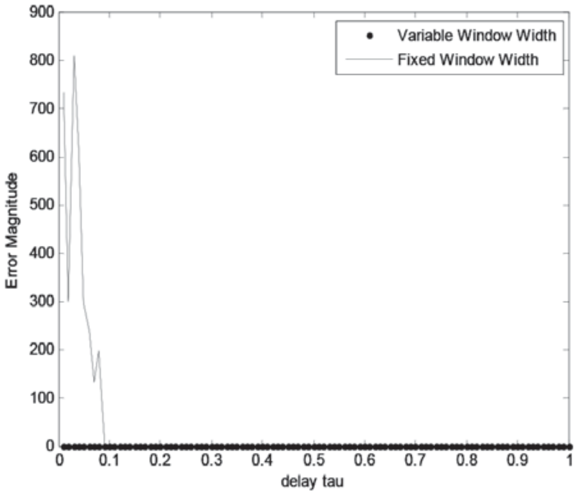


Fig. 9 Error of both receivers for $\mathrm{BOC}(15, 2.5)$

C. $\mathrm{CBOC}(6, 1, 1/11)$

This signal was implemented using ((7)). The undistorted discriminator for this case is shown in Fig. 10, while Fig. 11 plots the error for both schemes. Once again, the receiver with variable window width yields zero error for all delays, while the one with fixed window width results in nonzero errors for delays smaller than 0.1 chips and these errors are greater than 2000 for delays below 0.08 chips.

D. $\mathrm{TMBOC}(6, 1, 4/33)$

In this case, the signal was implemented by means of ((6)). Fig. 12 shows the undistorted discriminators for the $\mathrm{BOC}(1, 1)$ and $\mathrm{BOC}(6, 1)$ signals, and Fig. 13 shows the errors of both schemes for the same signals. As before, the variable window width scheme gives zero error for all delays and both signals, while the fixed width scheme yields nonzero errors for delays smaller than 0.08 chips.

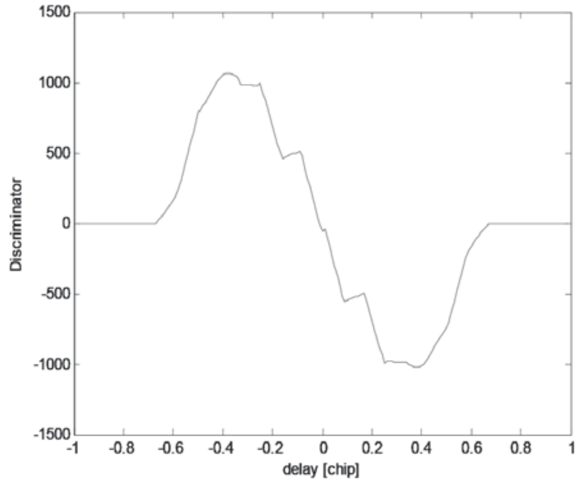


Fig. 10 Discriminator for $\mathrm{CBOC}(6, 1, 1/11)$ with W_2 and $\mathrm{BRW} = W_1$

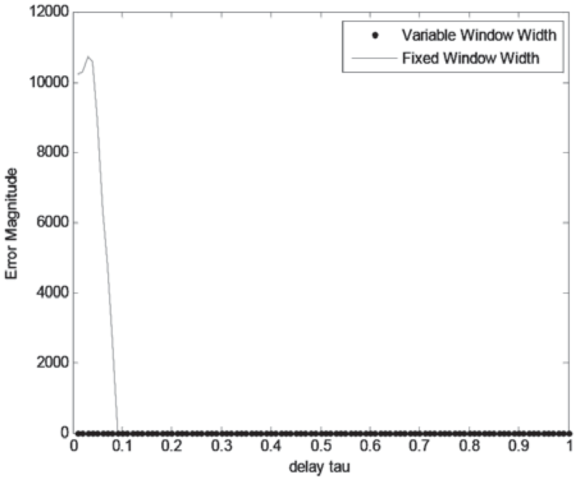


Fig. 11 Error of both receivers for $\mathrm{CBOC}(6, 1, 1/11)$

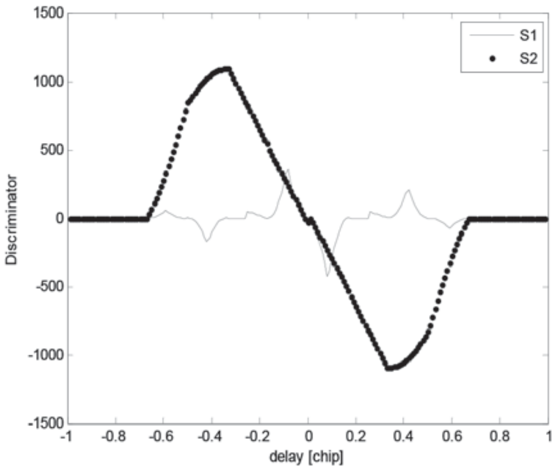


Fig. 12 Discriminators for $\mathrm{TMBOC}(6, 1, 4/33)$ with W_2 and $\mathrm{BRW} = W_1$

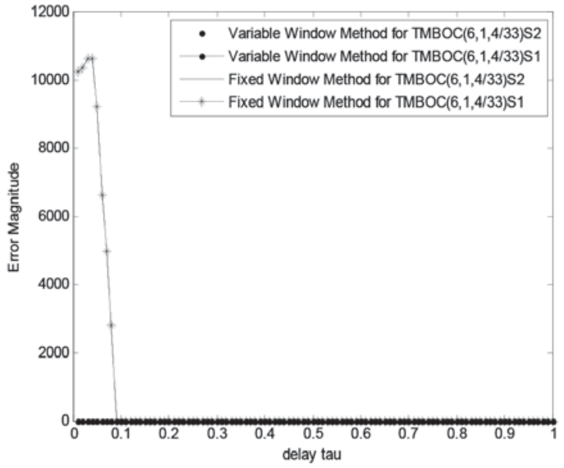


Fig. 13 Errors of both receivers for $\mathrm{TMBOC}(6, 1, 4/33)$

VI. CONCLUSIONS

This paper compared the multipath mitigation performance of CCRW receivers with variable and fixed window width, for signals $\mathrm{BOC}(kn, n)$, and multiplexed BOC signals $\mathrm{CBOC}(6, 1, 1/11)$ and $\mathrm{TMBOC}(6, 1, 4/33)$, which are typically used in GNSS.

The variable window width method incorporates a procedure in which the width of the window is iteratively reduced until the distortion on the discriminator with multipath is eliminated.

Results show that the method with variable window width outperforms the traditional fixed window width method. Specifically, the former yielded zero error for all delays for all signals under consideration, as opposed to the latter which gave rather large nonzero errors for small delays in all cases.

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