Economic Galileo E5 Receiver

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Abstract. *The Galileo system introduces an extremely wideband civil E5 signal for high precision navigation. The structure of the receiver for the E5 signal is complicated due to the signal complexity and the large bandwidth. It is possible to process the whole E5 signal or process separately E5a and E5b parts combining obtained results afterwards (we call here such method as piece-wise processing). The second procedure has three times worse standard deviation of the pseudorange then first one. The main goal of the paper is to present a design of an E5 receiver which we will call the economic E5 receiver (ecoE5). It is built from jointly controlled correlators for the processing of the E5a and E5b signals which are parts of the E5 signal. Control of these partial E5a and E5b correlators is realized by only one delay and one phase lock loops. The performance, i.e. the pseudorange noise and multipath errors, of the receiver equipped with the ecoE5, is only slightly worse (the standard deviation of the pseudorange noise is 10 - 20% larger) than the performance of the optimal E5 receiver and it is much better than the performance of the receiver combining the piecewise (E5a and E5b) measurements. The ecoE5 receiver hardware demands are about one quarter of the hardware demands of the classical E5 receiver.*

Keywords

Galileo E5 receiver, Galileo E5 signal processing.

1. Introduction

The Galileo E5 signal is the most precise civil Global Navigation Satellite System (GNSS) signal which will be available in the near future. It uses an Alternate Binary Offset Carrier (AltBOC) modulation, see [4]. The resulting signal is featured by a large bandwidth of approximately 70÷90 MHz, which makes it possible to measure a pseudorange with novel accuracy but which could cause complications in planning the navigation receiver design and signal processing. The AltBOC modulation schema was therefore designed to be able to apply variously complex but variously precise methods of signal processing. The most precise methods process the complete Galileo E5 signal. Less precise but less complicated and less hardware demanding methods process only those partial signal components which are modulated on E5a and E5b sub-carriers; there are one to four components which can be processed partially. The list of nine signal processing methods is in [8].

The aim of this paper is to analyze and compare three methods of Galileo E5 signal processing

- the optimal processing of the whole E5 signal (8PSK in [8]) in structure [6], which we call here as E5 receiver,
- piece-wise processing of E5a and E5b components,
- economic signal processing, our original method which is the main goal of this paper.

The first optimal method has adverse performance to complexity ratio. Implementation of the second method is very simple at the cost of its worse performance. The third method performance is nearly as performance of the optimal method but its implementation cost is as the cost of the second, piece-wise, method.

The organization of the paper is as follows: The Galileo E5 signal structure is described in the second section. In the third section performance parameters of optimal E5 processing are established and compared with the same ones of the piece-wise method. Section 4 describes classical approach in the design of the E5a, E5b and E5 receivers. The economic E5 receiver (ecoE5) for the processing of the complete E5 signal is derived in the next section. The comparison of the performance of the optimal E5, piece-wise (E5a combined with E5b) and ecoE5 methods including comparison of the multipath errors and hardware complexity is included in sections 6 and 7.

2. Galileo E5 Signal Structure

The Galileo E5 signal is defined in [4]. The complex envelope representation is given

$$\begin{aligned}\tilde{s}_{E5}(t) = \; & \frac{1}{2\sqrt{2}}\left(e_{E5a-I}(t) + j.e_{E5a-Q}(t)\right) \\ & \left[sc_{E5-S}(t) - jsc_{E5-S}\left(t - T_{s,E5}/4\right)\right] + \\ & \frac{1}{2\sqrt{2}}\left(e_{E5b-I}(t) + j.e_{E5b-Q}(t)\right) \\ & \left[sc_{E5-S}(t) + jsc_{E5-S}\left(t - T_{s,E5}/4\right)\right] + \\ & \frac{1}{2\sqrt{2}}\left(\overline{e}_{E5a-I}(t) + j.\overline{e}_{E5a-Q}(t)\right) \\ & \left[sc_{E5-P}(t) - jsc_{E5-P}\left(t - T_{s,E5}/4\right)\right] + \\ & \frac{1}{2\sqrt{2}}\left(\overline{e}_{E5b-I}(t) + j.\overline{e}_{E5b-Q}(t)\right) \\ & \left[sc_{E5-P}(t) + jsc_{E5-P}\left(t - T_{s,E5}/4\right)\right]\end{aligned} \quad . \qquad (1)$$

$$\begin{aligned}\overline{e}_{E5a-I} &= e_{E5a-Q}e_{E5b-I}e_{E5b-I} & \overline{e}_{E5b-I} &= e_{E5b-Q}e_{E5a-I}e_{E5a-I} \\ \overline{e}_{E5a-Q} &= e_{E5a-I}e_{E5b-I}e_{E5b-I} & \overline{e}_{E5b-Q} &= e_{E5b-I}e_{E5a-I}e_{E5a-I}\end{aligned} \; . \; (2)$$

The e_{E5a-I}, .., e_{E5b-Q} are Non Return to Zero (NRZ) signals which comprise the primary $C_{P,E5a-I}$, .., $C_{P,E5b-Q}$ and secondary $C_{S,E5a-I}$, .., $C_{S,E5b-Q}$ codes and navigation message data D_{E5a-I} and D_{E5b-I}. The chip rate of the primary codes is f_{chip}.

$$\begin{aligned}e_{E5a-I} &= C_{P,E5a-I}C_{S,E5a-I}D_{E5a-I} = C_{E5a-I}D_{E5a-I} \\ e_{E5a-Q} &= C_{P,E5a-Q}C_{S,E5a-Q} \\ e_{E5b-I} &= C_{P,E5b-I}C_{S,E5b-I}D_{E5b-I} = C_{E5b-I}D_{E5a-I} \\ e_{E5b-Q} &= C_{P,E5b-Q}C_{S,E5b-Q}\end{aligned} \quad . \qquad (3)$$

The sc_{E5-S} represents main and sc_{E5-P} auxiliary (for signal envelope compensation) sub-carrier waveforms, where $T_{s,E5} = 1/f_{s,E5}$ is the sub-carrier period and $f_{s,E5}$ is the sub-carrier frequency.

The Galileo E5 signal consists of E5a-I, E5a-Q, E5b-I and E5b-Q components and the auxiliary component for compensation of the signal envelope.

The E5a-I and E5a-Q components are modulated on the E5a sub-carrier by the Quadrature Phase Shift Keying (QPSK) modulation. The E5b sub-carrier is modulated similarly. The E5a-I and E5b-I components are also called data components or data signals because they are modulated by the codes and by navigation message bits. The E5a-Q and E5b-Q components are modulated by the codes only and they are known as pilot signals.

The receiver can process the whole E5 AltBOC modulated signal or single or multiple signal components.

3. E5 Processing Methods Performance

In this paragraph we compare attainable pseudorange measurement errors of the Galileo E5 signal (in optimal E5 receiver) with errors of the pseudorange estimated as combination of results of separate measurements on the E5a and E5b signal components (E5a&b or piece-wise receiver).

The Cramer-Rao Lower Bound (CRLB) of the signal delay error for multi frequency signals under assumption of perfect carrier phase synchronization was derived in [2]

$$CRLB = \frac{1}{\sum_{i=1}^{K} \gamma_i \dot{E}_i} \cdot \qquad (4)$$

where K is a number of processed frequencies (1 for E5 receiver and 2 for E5a&b piece-wise receiver in our case), $\gamma_i = |\alpha_i|^2 / \sigma_i^2$, $|\alpha_i|$ is an amplitude transfer of the *i*-th frequency and σ_i is the standard deviation of the noise in the *i*-th frequency. $\dot{E}_i$ is the energy of the derivative of the processed signal on the *i*-th frequency.

$$\dot{E}_i = \int_{T_1}^{T_2} \left|s_i'(t)\right|^2 dt \, . \qquad (5)$$

Below we will assume the unity amplitude transfer of signals on the E5, E5a and E5b frequencies $|\alpha_{E5}| = |\alpha_{E5A}| = |\alpha_{E5B}| = 1$ and unity energy of the E5 signal $\int_{T_1}^{T_2} \left|s_{E5}(t)\right|^2 dt = 1$.

The Cramer-Rao Lower Bound of the error of the delay measured by the E5 receiver under these assumptions is given

$$CRLB_{E5} = \frac{\sigma_{E5}^2}{\dot{E}_{E5norm}} \cdot \qquad (6)$$

where $\dot{E}_{E5norm}$ is the energy of the derivative of the unity energy E5 signal.

The Cramer-Rao Lower Bound of the delay error estimated by the E5a&b piece-wise receiver is given similarly

$$CRLB_{E5A\_E5B} = \frac{1}{\frac{1}{\sigma_{E5A}^2}\dot{E}_{E5Anorm} + \frac{1}{\sigma_{E5B}^2}\dot{E}_{E5Bnorm}} = \frac{\sigma_{E5A}^2}{2\dot{E}_{E5Anorm}} \cdot \qquad (7)$$

We point out that the E5a and E5b signals have the same energies and similarly the energies of their derivatives are identical, too. We will assume the same standard deviation of the noise on the E5a and E5b frequencies.

For further analysis we will assume the E5 receiver reference bandwidth B_{E5}= 51.150 MHz and the E5a and E5b receiver reference bandwidth $B_{E5A} = B_{E5B} =$ 20.460 MHz [4].

The signal energy and energy of the signal derivative in a time interval (T_1, T_2) can be calculated in the frequency domain with the utilization of the Parseval's theorem

$$\begin{aligned} E_{E5} &= \frac{1}{2\pi}\int_{-\pi B_{E5}}^{\pi B_{E5}} \tilde{C}_{E5}(\omega)\,d\omega \\ \dot{E}_{E5} &= \frac{1}{2\pi}\int_{-\pi B_{E5}}^{\pi B_{E5}} \omega^2 \tilde{C}_{E5}(\omega)\,d\omega . \\ \dot{E}_{E5norm} &= \frac{\dot{E}_{E5}}{E_{E5}} \end{aligned} \tag{8}$$

$\tilde{C}_{E5}(\omega)$ is the spectral energy density of the E5 complex envelope. Similarly, we can derive energy of the E5a (and E5b) signal. As we mentioned above, the E5 signal consists of the E5a-I, E5a-Q, E5b-I, E5b-Q components and the component for the compensation of the signal envelope. The energies of each E5a-I, E5a-Q, E5b-I and E5b-Q components are identical and are equal to 21% of the E5 signal energy – see [4].

$$\begin{aligned} E_{E5A} &= \frac{1}{2\pi}\int_{-\pi B_{E5A}}^{\pi B_{E5A}} \tilde{C}_{E5A}(\omega)\,d\omega \\ \dot{E}_{E5A} &= \frac{1}{2\pi}\int_{-\pi B_{E5A}}^{\pi B_{E5A}} \omega^2 \tilde{C}_{E5A}(\omega)\,d\omega . \\ \dot{E}_{E5Anorm} &= \frac{\dot{E}_{E5A}}{E_{E5}} = \frac{2\cdot 0.21\dot{E}_{E5A}}{E_{E5A}} \end{aligned} \tag{9}$$

$\tilde{C}_{E5A}(\omega)$ is the spectral energy density of the E5a complex envelope signal.

The variances of the noise on E5, E5a and E5b frequencies are given

$$\begin{aligned} \sigma_{E5}^2 &= 2\pi B_{E5} N_0 \\ \sigma_{E5A}^2 &= \sigma_{E5B}^2 = 2\pi B_{E5A} N_0 \end{aligned} . \tag{10}$$

Performance improvement of E5 receiver can be expressed as a ratio of the Cramer-Rao Lower Bounds of the pseudoranges errors of both receivers. When we substitute expressions (6) – (10) we gain

$$\begin{aligned} \frac{CRLB_{E5A\_E5B}}{CRLB_{E5}} &= \frac{B_{E5A}\dot{E}_{E5norm}}{2B_{E5}\dot{E}_{E5Anorm}} = \\ \frac{B_{E5A}}{4\times 0.21 B_{E5}} & \frac{\int_{-\pi B_{E5A}}^{\pi B_{E5A}} \omega^2 \tilde{C}_{E5}(\omega)\,d\omega \int_{-\pi B_{E5A}}^{\pi B_{E5A}} \tilde{C}_{E5A}(\omega)\,d\omega}{\int_{-\pi B_{E5A}}^{\pi B_{E5A}} \tilde{C}_{E5}(\omega)\,d\omega \int_{-\pi B_{E5A}}^{\pi B_{E5A}} \omega^2 \tilde{C}_{E5A}(\omega)\,d\omega} . \end{aligned} \tag{11}$$

The analytical solution of the formula (11) is very complicated; the result will be calculated numerically. For this purpose the spectral energy density of the E5 signal was estimated from the E5 signal segment generated according to (1). The spectral energy density of the E5a signal was estimated in the same way. The result of numerical calculation of (11) is

$$\frac{CRLB_{E5A\_E5B}}{CRLB_{E5}} \approx 9.7 . \tag{12}$$

The Cramer-Rao Lower Bound of the delay error of measurement on the E5 frequency is approximately 9.7 times lower than the Cramer-Rao Lower Bound of the delay error measured on the E5a and E5b frequencies. The standard deviation of the pseudorange measurement error on the E5 frequency is therefore up to three times lower than a standard deviation of the estimated pseudorange error of piece-wise measurements on the E5a and E5b frequencies.

The reader will see that the economical receiver described in section 5 has similar complexity as piece-wise receiver but performance nearly as optimal one.

4. Classical Approach in the Design of the E5a, E5b and E5 Receivers

The standard method for estimating the pseudorange and carrier phase in the GNSS receiver is the tracking of the signal delay and the carrier phase by the Delay Lock Loop (DLL) and Phase Lock Loop (PLL) – see [5] and [7]. The key parts of these blocks are correlator and phase and delay detectors.

In this section we describe classical receivers for E5, E5a and E5b signals – see [8]. The classical GNSS receiver architecture with Early-Late (E-L) correlator is in Fig. 1. The correlator calculates the cross correlation function between the received signal and the replica signal for two delays. In the Early branch the replica precedes the measured signal delay of Δ/2 (Δis correlator space) and in the Late branch the replica is delayed by the same time Δ/2.

This correlator structure is applicable for all GNSS signals with unambiguous signal replica. Some GNSS signals are modulated by the navigation message, too. In the case of the BPSK modulated signal the unknown navigation message modulation causes oscillation (a change of the sign) of the cross correlation function of the received signal and code replica according to the transmitted navigation message bits. We use this oscillation for the navigation message demodulation.

The cross correlation function oscillation is removed in the Phase and Delay detector by applying suitable methods, for example a Costas Loop detector in the PLL and an E-L power detector in DLL.

The Galileo E5a or E5b signals are QPSK signals modulated by the data (code and unknown navigation message) and pilot (code only) signals (see section 2).

The replica cannot be used directly because of uncertainty of data bit D in (3).

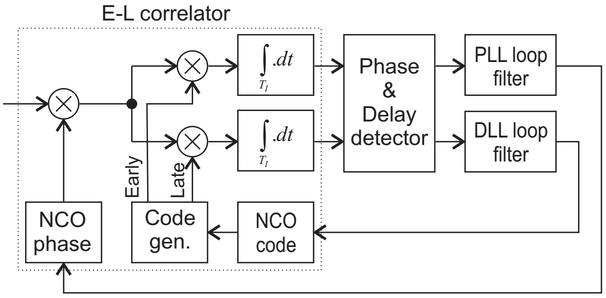

Fig. 1. Receiver with classical E-L correlator.

The solution of such problem can use the fact that the QPSK modulation may be considered as two orthogonal Binary Phase Shift Keying (BPSK) modulated signals. So we can process the data channel and the pilot channel independently in the BPSK correlators or we can design the QPSK E-L correlator Fig. 2, which consists de facto of two BPSK correlators which share some function blocks like the Numerically Controlled Oscillator (NCO) phase and NCO code blocks.

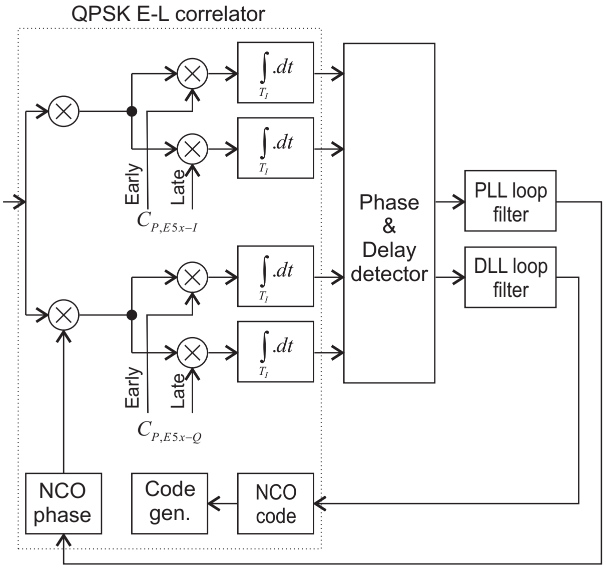

Fig. 2. E5a (or E5b) receiver with QPSK E-L correlator.

The other possibility is to generate two replicas for both possible navigation message bit values. The first cross correlation function is calculated for the hypothesis that the navigation message bit is equal to plus one while the second cross correlation function is calculated for the hypothesis that the navigation message bit is minus one. The correct hypothesis must be selected in the loop detector. The drawback of this method is the higher hardware complexity.

Similarly the E5 signal depends on two navigation message bits D_{E5a-I} and D_{E5b-I} , [6]. It complicates signal processing and makes the correlator more complicated. The E5 signal uses the AltBOC modulation which cannot be decomposed into parts, so in a general case, we must generate the replicas for all four possible navigation data bits and correlate the received signal with these four replicas. For the structure of such correlator see Fig. 3. The correlator is augmented with the fifth branch designed for processing the BPSK signals on the E5a or E5b sub-carriers. This fifth branch:

1. Supports signal acquisition,
2. Serves for the synchronization of the secondary codes,
3. Verifies whether the E5 correlator tracks the correct maximum of the E5 cross correlation function.

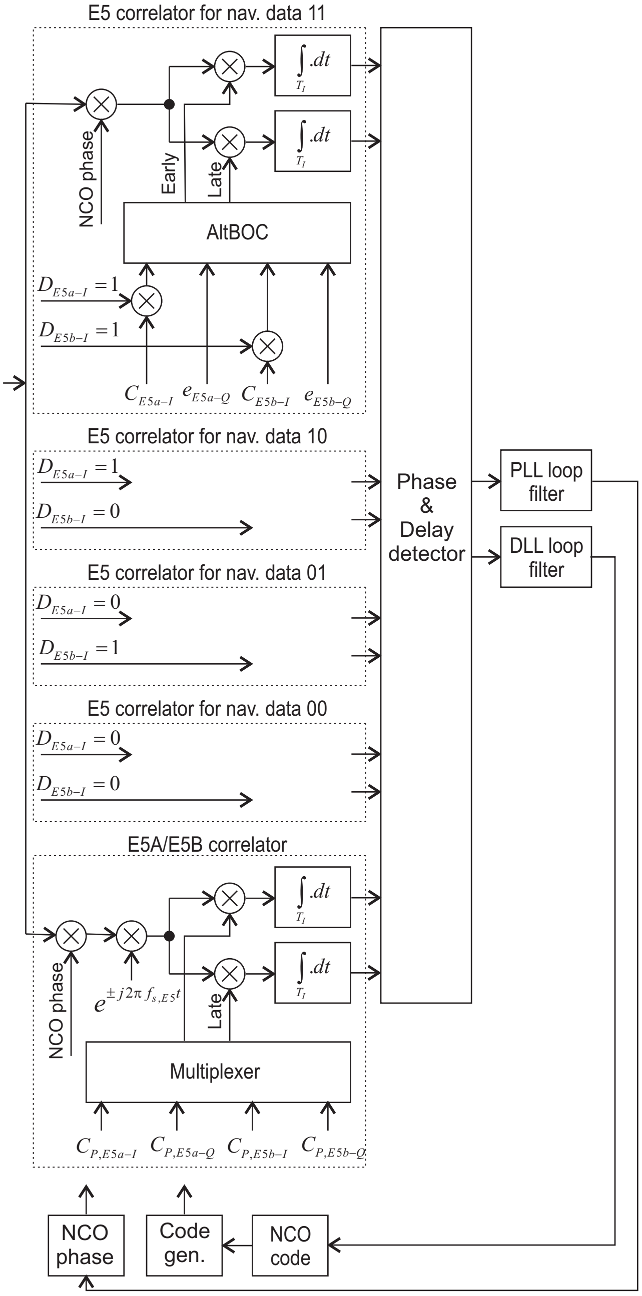

Fig. 3. E5 receiver consisting of five correlators, PLL and DLL for tracking.

The method for finding the correct hypothesis of the values of the navigation messages bits together with a correlator performance analysis is in [6]. The E5 receiver processes the whole E5 signal bandwidth. The receiver structure is then rather complicated. This E5 receiver will serve as a reference (or optimal) receiver for a performance analysis of the E5a&E5b piece-wise and economic E5 receiver.

5. Economic E5 Receiver

The idea of the economic E5 (ecoE5) receiver is based on the integration of two QPSK correlators designed for the processing of the Galileo signal on the E5a/E5b sub-carriers. This integration, described in this section, is based on joint control of both correlators by one common DLL and PLL.

As known to simplify the problem we replace the rectangular sub carrier sc_{E5-S} in (1) with a harmonic one and neglect signal components modulated on the auxiliary sub carrier sc_{E5-P}. The simplified signal is given

$$\tilde{s}_{mE5}(t)=\begin{bmatrix}\left(e_{E5a-I}(t)+j.e_{E5a-Q}(t)\right)e^{-j2\pi f_{s,E5}t}+\\ \left(e_{E5b-I}(t)+j.e_{E5b-Q}(t)\right)e^{j2\pi f_{s,E5}t}\end{bmatrix}. \quad (13)$$

This simplified signal opposed to the original AltBOC signal can be decomposed into parts. Without impact on the generality we consider the received signal has a null delay. The received signal is affected by the unknown phase shift φ only. The model of such received signal is given

$$\tilde{s}_r=\tilde{s}_{mE5}(t)e^{j\varphi}. \quad (14)$$

The cross correlation function of the simplified received signal (13) and the simplified replica signal is given

$$R_{mE5}(\tau)=\int_T \tilde{s}_{mE5}(t)\tilde{s}^*_{mE5}(t+\tau)e^{j\varphi}dt. \quad (15)$$

As the signal modulated on the E5a sub-carrier is not correlated with the signal on the E5b sub-carrier we can simplify the formula (15) into the following form

$$\begin{aligned}&R_{mE5}(\tau)=\\ &e^{j\varphi}\begin{bmatrix}e^{j2\pi f_{s,E5}\tau}\int_T \dfrac{\left(e_{E5a-I}(t)+j.e_{E5a-Q}(t)\right)}{\left(e_{E5a-I}(t+\tau)-j.e_{E5a-Q}(t+\tau)\right)}dt+\\ e^{-j2\pi f_{s,E5}\tau}\int_T \dfrac{\left(e_{E5b-I}(t)+j.e_{E5b-Q}(t)\right)}{\left(e_{E5b-I}(t+\tau)-j.e_{E5b-Q}(t+\tau)\right)}dt\end{bmatrix}=. \quad (16)\\ &=e^{j\varphi}e^{j2\pi f_{s,E5}\tau}R_{E5a}(\tau)+e^{j\varphi}e^{-j2\pi f_{s,E5}\tau}R_{E5b}(\tau)\end{aligned}$$

where R_{E5a} is the autocorrelation function of the E5a codes and R_{E5b} is the autocorrelation function of the E5b codes.

The first term $e^{j\varphi}e^{j2\pi f_{s,E5}\tau}R_{E5a}(\tau)=R_{E5A}(\tau)$ of the cross correlation function (16) can be obtained as an output of the E5a QPSK correlator and the second term $e^{j\varphi}e^{-j2\pi f_{s,E5}\tau}R_{E5b}(\tau)=R_{E5B}(\tau)$ can be obtained by the E5b one.

The phase and code NCOs of these correlators must be jointly controlled. The E5a phase NCO must generate signal $e^{j2\pi\left[\left(\hat{f}_{E5}+f_{s,E5}\right)t+f_{s,E5}\tau\right]}$ and the E5b NCO $e^{j2\pi\left[\left(\hat{f}_{E5}-f_{s,E5}\right)t-f_{s,E5}\tau\right]}$, where $\hat{f}_{E5}$ is the estimated E5 signal frequency uncertainty. The E5a and E5b code NCOs must guarantee synchronous generation of the codes.

The phase discriminator and delay discriminator must be designed for the signal tracking by the one PLL and DLL. The phase discriminator measures the phase shift φ of the processed signal carrier and the delay discriminator measures the delay shift between the received signal and the replica signal.

The phase shift of the received signal is mostly determined by the phase of the cross correlation function in the correlation maximum or in its vicinity. We can use various types of phase detectors, for example the four quadrants detector. The output of such detector is given

$$D_{\varphi 1}(\varphi)=\arg\left(R_{mE5}(0)\right)=\arg\left(R_{E5A}(0)+R_{E5B}(0)\right). \quad (17)$$

or the simpler detector

$$D_{\varphi 2}(\varphi)=\mathrm{Im}\left(R_{E5A}(0)+R_{E5B}(0)\right). \quad (18)$$

The design of the delay detector is a little bit more complicated. The delay detector must not depend on the carrier phase error φ. We apply the fact that each part of the cross correlation function (16) consists of the rapidly changing term $e^{j2\pi f_{s,E5}\tau}$ respectively $e^{-j2\pi f_{s,E5}\tau}$ and the slowly changing terms $R_{E5a}(\tau)$ and $R_{E5b}(\tau)$. If we consider that the slowly changing terms are constant in the vicinity of $\tau=0$, the output of the delay detector is given

$$\begin{aligned}D_{\tau 1}(\tau)&=\arg\left(\frac{e^{j\varphi}e^{j2\pi f_{s,E5}\tau}R_{E5a}(0)}{e^{j\varphi}e^{-j2\pi f_{s,E5}\tau}R_{E5b}(0)}\right)=\\ &=\arg\left(\frac{R_{E5A}}{R_{E5B}}\right)\approx 4\pi f_{s,E5}\tau\end{aligned}. \quad (19)$$

or a simpler detector

$$D_{\tau 1}(\tau)=\mathrm{Im}\left(\frac{e^{j\varphi}e^{j2\pi f_{s,E5}\tau}R_{E5a}(0)}{e^{j\varphi}e^{-j2\pi f_{s,E5}\tau}R_{E5b}(0)}\right)=\mathrm{Im}\left(\frac{R_{E5A}}{R_{E5B}}\right). \quad (20)$$

The derived delay detectors ((19) and (20)) are phase detectors which compare the phases of the E5a and E5b sub-carriers. The advantage of the derived detectors is that they require calculation of the cross correlation function for one delay only. Based on such simplification both of the detectors need only one correlator branch.

To evaluate the properties of the ecoE5 receiver we need a comparison of the characteristic of the detector (20) with the characteristic of the E5 E-L normalized power detector and the E5a E-L normalized power detector - Fig. 4. The E-L detectors are normalized by the power in the E and L correlator branches.

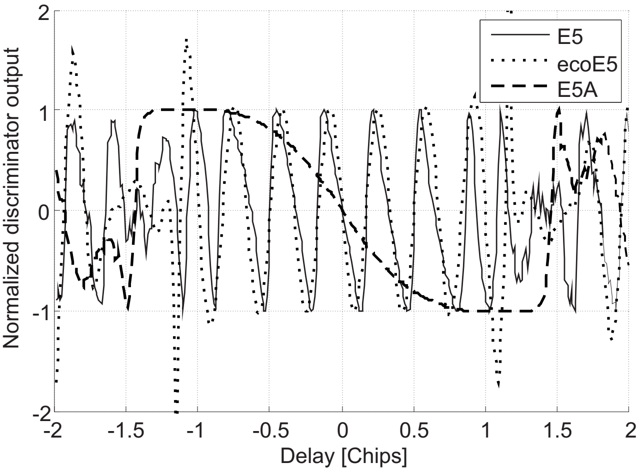

Fig. 4. E5, ecoE5 and E5a detector characteristics.

The detector characteristic has several stable and unstable nodes. The delay of the replica must be properly initiated in order for the DLL to track the correct stable node. The detector must indicate a transition to the incorrect stable node and must correct this delay slip. For the detection of the incorrect stable node tracking, the unutilized correlator branches of the E-L correlator can be applied.

6. Economic E5 Receiver Hardware Implementation

Main outlines of the hardware implementation of the ecoE5 receiver are discussed in this paragraph. Besides implementation of the own ecoE5 receiver the realization of some auxiliary functionality, for example verification of main correlation peak processing (tracking of the appropriate stable node), is outlined here.

The proposed delay detector (formula (19) or (20)) requires to measure $R_{E5A}(\tau)$ and $R_{E5B}(\tau)$ parts of cross correlation function separately. We can process received signals in separate (E5a and E5b) receiver front ends (Fig. 5a). The bandwidth of their outputs is much narrower then bandwidth of the classical E5 receiver (Fig. 5b) and therefore requirements on sampling frequency for digitalization of their outputs are much lower. The ecoE5 receiver itself is drawn in Fig. 6. One branch of E-L correlator is implemented as the hardware part of its correlator (Fig. 6).

The NCO's of the E-L correlators are controlled by single DLL and PLL loops and coupled together by proper software handling.

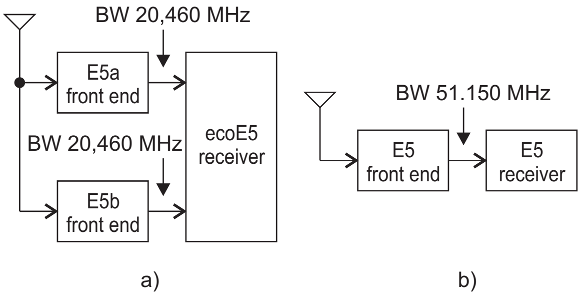

Fig. 5. EcoE5 a) and E5 b) front ends comparison.

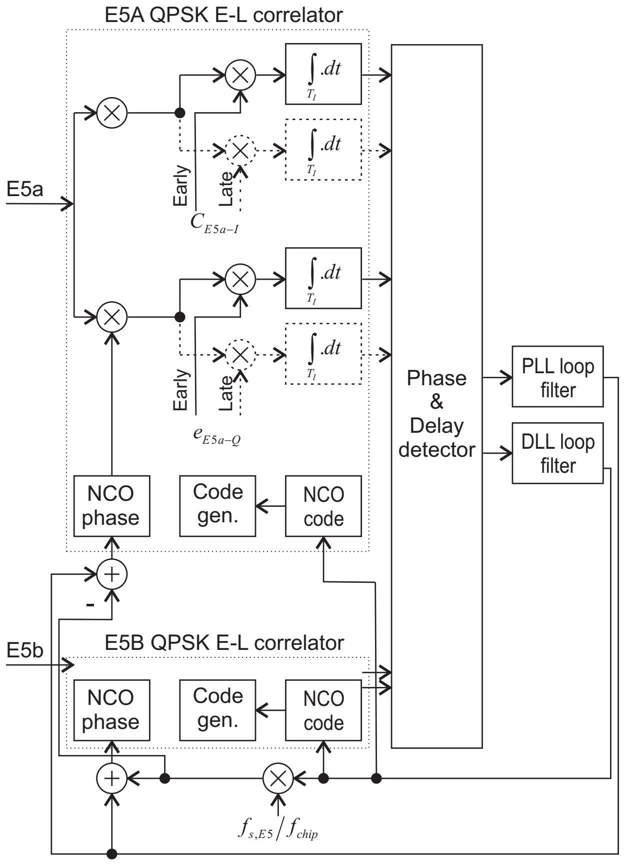

Fig. 6. EcoE5 receiver block diagram built from pair of jointly controlled QPSK E-L correlators (dash branches are used for auxiliary functionality, not for own ecoE5).

To provide correct (precise) functional values of the terms $R_{E5A}(\tau)$ and $R_{E5B}(\tau)$ the local oscillators of the E5a and E5b *front ends* should be properly initialized furthermore. The realization of this requirement is rather complicated. We can use specialized hardware for it or an alternative method. It consists in starting the local oscillators without phase initiation (random initial phases) and to calibrate the mutual phase shift of the signals on the output of E5a and E5b front ends. The calibration also compensates phase unbalance of the E5a and E5b front end channels. When we use calibration no specialized E5a and E5b front ends are required for ecoE5 receiver realization, so we can use standard front ends for piece-wise E5a and E5b reception.

There are several possibilities how to operate the ecoE5 receiver; we will describe one of them by the state diagram in Fig. 7. The acquisition is made by E5a or E5b signal processing by standard methods. The tracking (by piece-wise method) is started after signal detection. When the tracking loop is locked and the ambiguities are resolved the receiver can start the calibration process (if it is necessary) mentioned above.

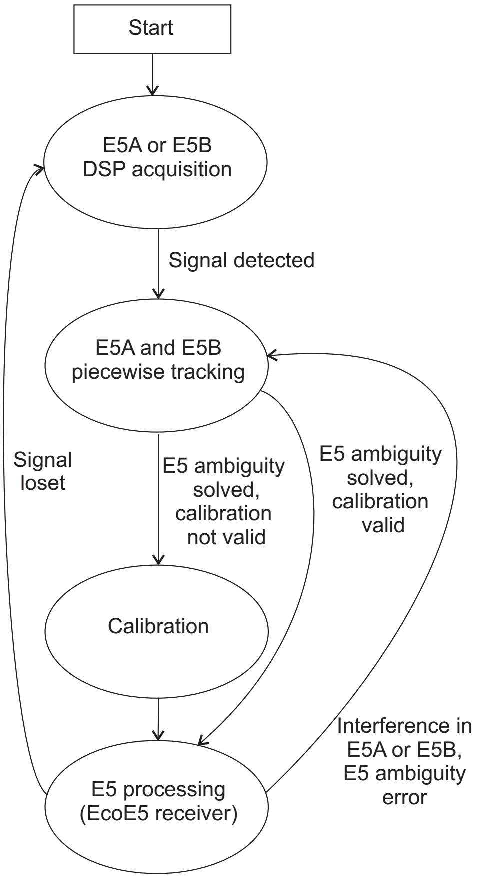

Fig. 7. EcoE5 a) and E5 b) front ends comparison.

The calibration is realized in piece-wise mode, too. When signal strength, or C/N$_0$, is good, we determine the mutual initial phase shift between E5a and E5b carriers and the mutual phase shift of the E5a and E5b local oscillators during calibration process. This is the simple method but sufficient enough because small phase uncertainty demonstrates itself as a systematic time shift of all processed satellite signals.

The calibration is followed by true processing in ecoE5 receiver or in ecoE5 mode. The correlators use only one E-L branch for it, whilst the second one can be used for verification of the correct correlation maximum tracking (Fig. 7). Presence of the E-L correlators is also useful for easy switching from ecoE5 mode to the piece-wise E5a and E5b tracking mode in case of interference or occurrence of ambiguity error.

If we use the early branch of the E-L detector for tracking the correlation peak on the E5a sub-carrier and the late branch for E5b, we can compare the correlation power measured on the E5a by the late branch with the correlation power in the early branch on the E5b for the detection of an incorrect stable node tracking (Fig. 8).

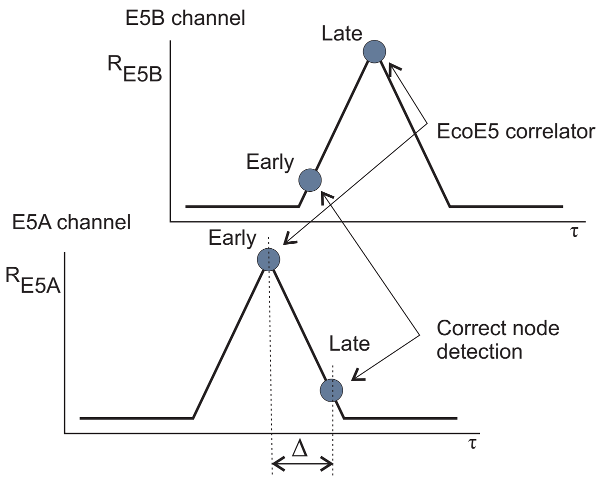

Fig. 8. EcoE5 correlator branches usage.

7. Performance Analysis

This paragraph analyses the performance of the ecoE5 receiver and compares it with the performance of E5, E5a, E5b and E5a&b receivers. We will investigate code tracking error and multipath sensitivity as quality parameters.

7.1 Code Tracking Error

The code tracking error (noise) was investigated by a computer simulation. We have generated the Galileo E5 signal with the AltBOC modulation and corrupted this signal by an Additive White Gaussian Noise (AWGN). The signal was then band-limited in the Finite Impulse Response (FIR) filters. The bandwidth of the E5 filter is B_{E5}= 51.150 MHz and the bandwidth of the E5a and E5b filters is B_{E5A}= B_{E5B}= 20.460 MHz. The signal was then processed in the receiver equipped with various correlators, i.e. the E5 correlator, the E5a&E5b correlator and the ecoE5 correlator. As the dynamic behavior of the tracking loop is not investigated, we have used merely the first order DLL of the noise bandwidth of 1, 3 and 10 Hz. The results are in Fig. 9-11.

The smallest pseudorange error was gained for the E5 receiver. The pseudorange error of the ecoE5 receiver is slightly higher but for a high signal to noise ratios C/N_0 the differences in performance of the E5 and ecoE5 receivers are nearly negligible. This performance degradation is caused by the simplification in the receiver design and ignoring of some of the auxiliary signal components of the AltBOC modulated signal.

The performance of the ecoE5 receiver is much better than the performance of the E5a&b receiver which combines independent measurements of the E5a and E5b receivers and which therefore requires the same correlator hardware. According to the expectations, the E5a and E5b receiver pseudorange errors were the greatest from the simulated receivers.

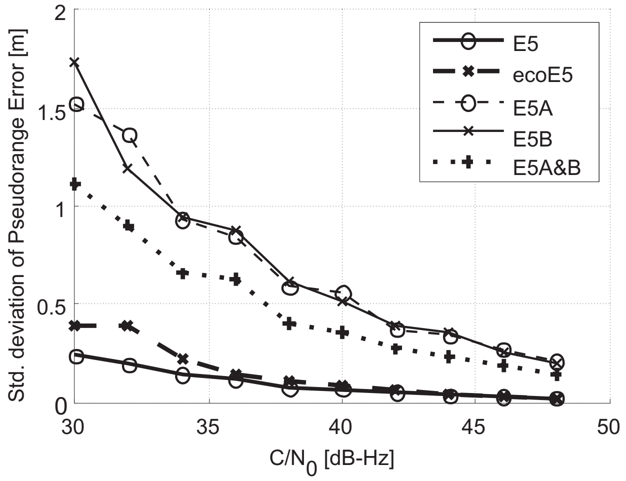

Fig. 9. Code tracking error of the E5, ecoE5, E5a, E5b and E5a&b receivers, Bn = 1 Hz, TI = 4 ms.

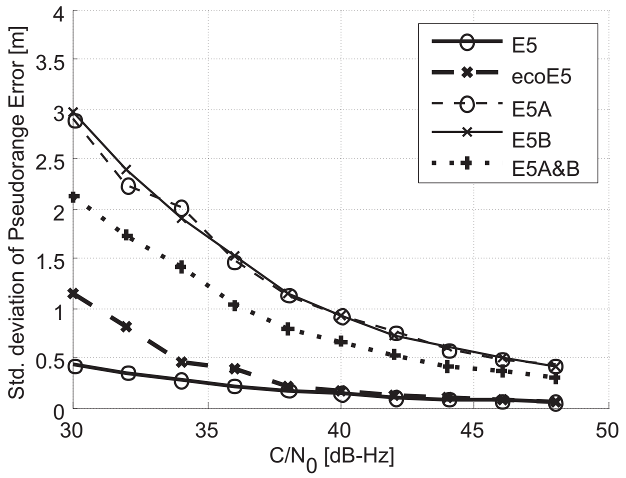

Fig. 10. Code tracking error of the E5, ecoE5, E5a, E5b and E5a&b receivers, B_n = 3 Hz, T_I = 4 ms.

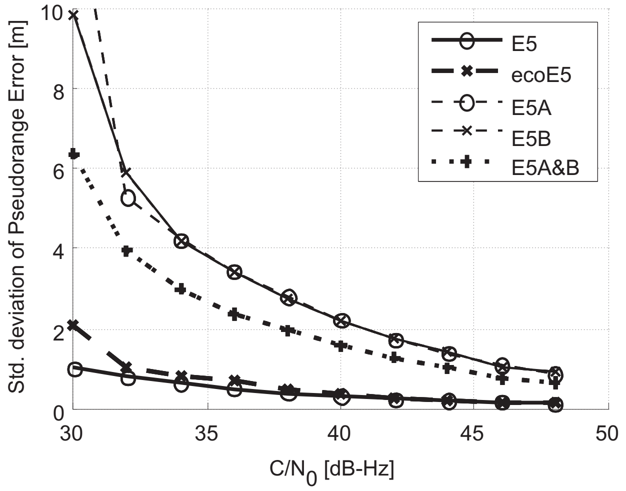

Fig. 11. Code tracking error of the E5, ecoE5, E5a, E5b and E5a&b receivers, B_n = 10 Hz, T_I = 4 ms.

7.2 Multipath Sensitivity

The goal of this paragraph is to compare multipath errors of the classical E5 correlator and the ecoE5 correlator. The standard method for the expression and comparison of the multipath errors of the GNSS signals is a multipath error envelope chart which displays the worst positive and the worst negative pseudorange errors for the multipath channel model with a line of sight (LOS) signal and one reflected signal. The impulse response of such channel is given

$$h_{ch}(t)=\delta(t)+SMR^{-0.5}\delta(t-\tau_m).e^{j\varphi_m}\,. \qquad (21)$$

where $\delta(t)$ is the Dirac pulse, SMR is the signal to multipath power ratio, τ_m is delay and φ_m is phase of the reflected signal.

The comparison of the multipath envelopes for SMR 6 dB of the ecoE5 correlator, the standard E5 correlator with normalized E-L power detector and the E5a correlator with the same type of delay detector is in Fig. 12. We can see the small differences between the E5 and ecoE5 correlators only. The simplification which was considered during the derivation of the ecoE5 correlator therefore has a minimal impact on the pseudorange errors caused by the multipath.

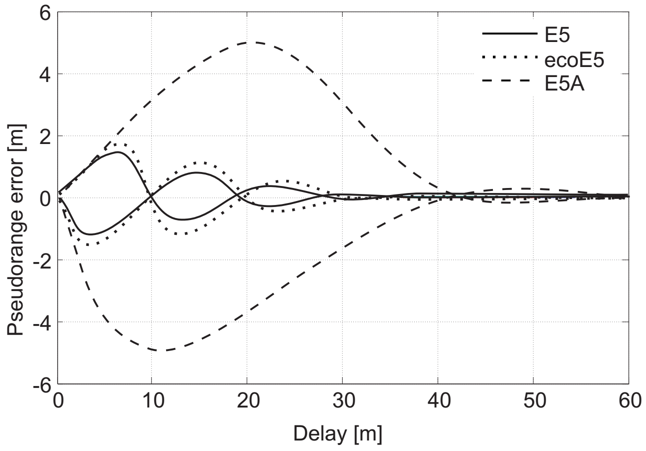

Fig. 12. Multipath envelope chart for the E5, ecoE5 and E5a correlators, SMR = 6 dB.

8. Hardware Complexity

The aim of this paragraph is to compare hardware complexity of the ecoE5 and E5 correlators. The hardware complexity is regularly expressed as a number of the MACs (multiply and accumulate operations) required for correlator realization. The drawback of this approach is that it does not consider all aspects like data manipulation. The practical realization of the receivers to the same hardware enables us to compare the real complexity of such algorithms. The comparison of the FPGA resources utilization for the implementation of the E5 and ecoE5 (ecoE5 = 4x E5a/E5b BPSK) correlators to the FPGA is in Tab. 1.

Resources	E5	ecoE5	ecoE5/E5 [%]
Slice Registers	2500	430	17
Slice LUTs (Look Up Tab.)	1182	200	17
RAM/FIFO [18 kb blocks]	7.8	6.6	85
DSP48E	24.5	6.6	27

Tab. 1. FPGA resources utilization for the E5 and ecoE5 (4 x BPSK) correlator.

It is evident that the resources utilization for the implementation of the ecoE5 correlator to the FPGA is much lower than that for the E5 correlator. The ecoE5 correlator utilizes 17 % of logic which is needed for the E5 correlator. The saving of the DSP48E blocks is also evident. The DSP48E block consists of one 18-bits embedded multiplier and of one 40-bits accumulator, i.e. it implements multiplication and summation operations. The relatively high RAM/FIFO memory blocks utilization in the ecoE5 correlator (85 % of E5 correlator) is due to the usage of the memory for the primary codes storage. All four $C_{P,E5a-I}, \ldots, C_{P,E5b-Q}$ primary codes are placed into this memory in both of the (E5 and ecoE5) correlators.

This large hardware savings of the ecoE5 correlator are partially achieved by the simpler structure of the ecoE5 correlator, but especially by the fact that all parts of the E5 correlator process the complete signal (bandwidth approximately 50 MHz), on the other hand, each of the E5a and E5b correlators of ecoE5 correlator process signals of a much lower bandwidth, approximately 20 MHz.

Both of the implemented correlators process 8 bits samples. Further hardware savings can be reached by the reduction of the bits for signal representation. An extreme is a one bit representation which is used in low cost GNSS receivers.

9. Conclusions

The paper deals with the architecture of the economical Galileo E5 correlator and receiver. The proposed ecoE5 receiver solution is based on the utilization of the standard Galileo E5a/E5b correlators designed for the processing of the E5a and E5b signals which are jointly controlled by common DLL and PLL. The performance of the ecoE5 receiver is coming near the performance of the reference E5 receiver and the performance is much better than the performance of the receiver which combines the E5a and E5b measurements. In addition, the hardware complexity of the ecoE5 correlator is much lower than the complexity of the E5 correlator. Moreover, the E5a and E5b correlators can be dynamically switched from the ecoE5 configuration (mode) to the E5a and E5b configuration by software only.

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