Galileo E1 and E5a Link-Level Performances in Single and Multipath Channels

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Abstract. The emerging global satellites system Galileo has gained much public interest regarding location and positioning services. Two new modulations, Composite Binary Offset Carrier (CBOC) and Alternate Binary Offset Carrier (AltBOC) will be used in the E1 and E5 band in the Galileo Open service (OS), respectively. The AltBOC modulation has the advantage that the E5a and E5b band can be processed independently as traditional BPSK signal or together, leading to a better tracking performance in terms of noise and multipath mitigation at the cost of a large front-end bandwidth and increased complexity. The theoretical study of the signal tracking in each band, separately, has been addressed before, but a comparison between the E1 and E5 signals and validation through the simulation with the realistic channel are still lacking in the current literature. In this paper, the tracking performance between the Galileo E5a signal and Galileo E1 signal with different noise level and multipath profiles are compared by using the Simulink-based simulators built within our department at Tampere University of Technology. The simulation results are shown in terms of Root Mean Square Error (RMSE). The probability distribution of code tracking error is also investigated.

Keywords: Galileo, E5a/E5 signal, E1 signal, Multiplexed Binary Offset Carrier (MBOC), AltBOC, error distribution, multipath channel, open source, Simulink Galileo simulator.

1 Introduction

During the second half of the last century, Global Navigation Satellite Systems (GNSS) have been widely used in personal devices, public transportation and industries. A GNSS device can point out the exact location of any user on the surface of the earth anytime and anywhere, provided that it is placed in a direct Line Of Sight (LOS) with at least four satellites. As one of the emerging GNSS, Galileo is going to provide more services, higher availability and higher accuracy than the only fully operational GNSS nowadays, Global Position System (GPS). Galileo will provide worldwide services depending on user needs. One of them is Open Service (OS), which is designed for mass-market and will be

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free of user charge. Two frequency bands, E5, consisting of two sub-bands E5a and E5b with carrier frequency at 1176.45 MHz and 1207.14 MHz and E1 with carrier frequency 1575.42 MHz, will be used for transmitting OS signals. Multiplexed Binary Offset Carrier or MBOC are defined to be the common modernized GPS and Galileo modulations for civilian use. MBOC introduces more power on higher frequencies compared with BOC(1,1) case, by multiplexing with a high frequency BOC(6,1) component, which improves the performance in tracking [1]. The MBOC implementation for Galileo is adding simultaneously a BOC(1,1) and BOC(6,1), defined as Composite-BOC (CBOC). The AltBOC modulation is designed to be used in Galileo OS E5 band. AltBOC(15,10) modulated E5 signal is by far the most sophisticated signal among all the signals used for GNSS. Four signal component are modulated into a wideband signal by AltBOC modulation [2]. Two of them will carry navigation messages and the remaining two are data-free pilot channels. The AltBOC modulation provides such advantage that E5a and E5b can be processed independently, as traditional BPSK(10) signal, or together, leading to a better tracking performance in terms of noise and multipath mitigation at the cost of a large front-end bandwidth and increased complexity [3]. In addition, E5 signal has chip rate of 10.23 MHz, which is ten times higher than the E1 signal's chip rate f_c=1.023 MHz. The higher chip rate may provide better tracking performance. Recently only E5a band has attracted attention in the context of dual/multi frequency Galileo receives. E5a can be acquired independently and the requested front-end bandwidth is less than half of the bandwidth for the whole E1 signal. It has also been proved that combining E1/E5a is the best choice for dual frequency receiver and has the additional property that it overlaps with GPS frequency L1/L5.[8] This property also provides the advantage of an easier integrability of a joint Galileo/GPS receiver. Many publications have addresses E5 acquisition strategies[7], [10], and code tracking noise based on mathematic formula [3], [11], [12]. However, very few studies have been published about the comparative performance of E1 with E5a in terms of signal tracking accuracy and the validation of potential performance of E5 signal in realistic channel at link level. In this paper, the authors evaluate and compare the signal tracking performance of E1 and E5a in link-level Simulink simulators.

This paper is organized as follows: first, the E1 and E5a signal simulators used in the paper are described. Then, the performance of code tracking with E1 and E5a is presented in terms of Root Mean Square Error (RMSE). Finally, the code tracking error distribution is analyzed.

2 Simulink Model Overview

2.1 Generic Structure

Simulation is a powerful method in the analysis and design of communication devices. The performance of new signals, new algorithms can be assessed before it is implemented on a real model. The E1 signal simulators and E5a signal simulators used in this paper for evaluating the tracking performance with E1 and E5a signal were created at Tampere University of Technology (TUT).

The generic structure of the simulators is shown in Fig. 1, which consists of five blocks: transmitter, propagation channel, front-end, acquisition and tracking block. More detail of E1 and E5a signal Simulink simulators will be described in the following sections.

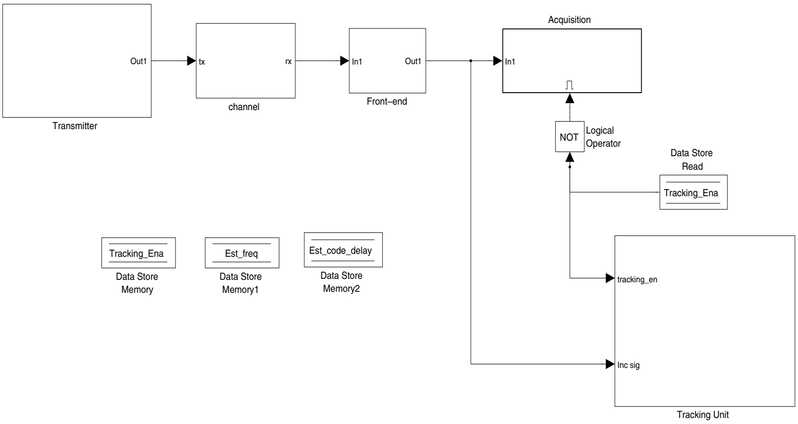


Fig. 1. Generic Simulink block of Galileo simulator at TUT

2.2 Galileo E1 Simulink Model

Transmitter. The E1 signal transmitter block is implemented based on CBOC modulation, including primary code and secondary code, in the accordance with the latest Galileo OS SIS ICD [2]. The snapshot of E1 signal transmitter block is shown in Fig. 2. In the transmitter block, E1B is CBOC(+) modulated signal with navigation data and E1C is CBOC(-) modulated signal with a pre-defined bit sequence of CS25 (i.e.,pilot channel). The E1 signal is formed as the difference between those two signals. The signal at the output of the transmitter is at Intermediate Frequency (IF).

Channel. The channel block generates the multipath signals and complex noise for a user-defined C/N_0. The interference from GPS or other sources, excepting noise and multipath are not considered here. Fig. 3 shows the snapshot of the channel block. The multipath delay and power are other two input parameters for channel block. Two channel configurations can be used: static and time variant. The input parameters for static channel are user defined, and for time variant channel, the path delay and power are defined through a Land and Mobile Multipath Channel Model from DLR [9].

Front-end The front-end block in E1 signal simulator is used for receiver front-end filtering. Several front-end bandwidths can be used, i.e., infinite bandwidth for the ideal case, 4 MHz which covers the main lobe of E1 signal.

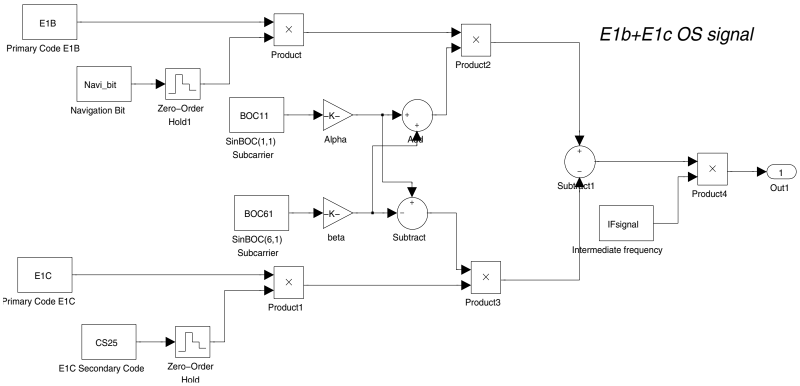


Fig. 2. The transmitter model in Galileo E1 signal simulator at TUT

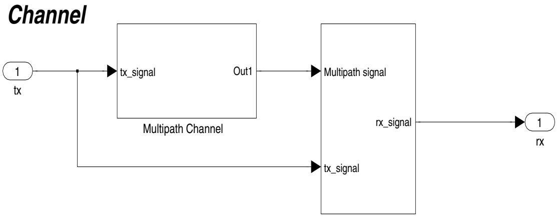


Fig. 3. The channel model in Galileo E1 simulator at TUT

Tracking. When a signal is detected in the 'Acquisition Block', a control signal 'Tracking Ena' will activate the 'Tracking Unit'. The tracking unit consists of three main blocks: carrier wipe-off block, code Numerically controlled Oscillator (NCO) block and dual channel correlation and discriminator block as in Fig. 5.

The task of the carrier wipe-off block is to down convert the incoming signal with the estimated frequency and phase from PLL and FLL in the tracking loop. After the carrier wipe-off, the real part and the imaginary part of the complex signal are separated as the in-phase (i.e., I channel in Fig. 5) and the quad-phase (i.e., Q channel in Fig. 5) channels in baseband. The 'code NCO' block is used to generate the local PRN reference code, which is shifted by the estimated code phase from DLL. According to the correlator offset and the status of phase holding shifter, the primary code and the sub-carrier offset can be determined. The reference code sequences are generated separately for E1B and E1C channel. Since the CBOC modulation combines two sub-carrier wave components, the tracking can be done either with CBOC modulated reference codes (i.e., CBOC(+) for E1-B data channel and CBOC(-) for E1-C pilot channel), or with SinBOC(1,1) modulated reference code for both E1-B and E1-C channels. The simulations in this paper are using SinBOC(1,1) modulated E1 reference code. In the dual channel correlation and discriminator block, the E1B

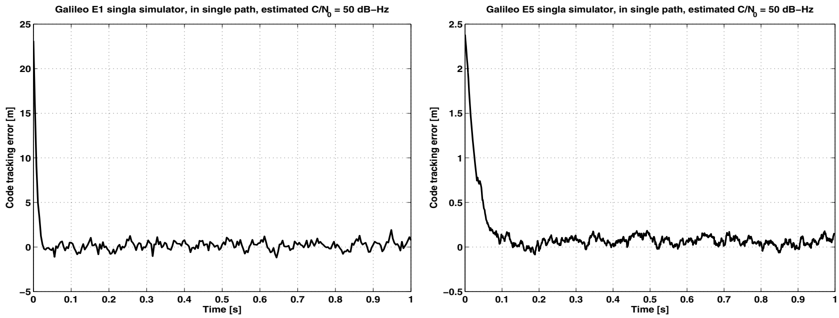


Fig. 4. Left: Code tracking error versus simulation time of E1 signal at estimated $C/N_0 = 50dB - Hz$ with non-coherent integration over 4 ms; Right: Code tracking error versus simulation time of E5a signal at estimated $C/N_0 = 50dB - Hz$ with non-coherent integration over 1 ms

and E1C channels are implemented separately. In both channels, FLL, PLL and DLL are included. In the DLL discriminator block, various conventional DLL discriminator functions are implemented, such as Narrow Correlator [5] and High Resolution Correlator (HRC) [6]. The C/N_0 estimator is also implemented. The C/N_0 estimation is performed based on the ratio of the signal's wideband power to its narrowband power as described in Fig. [14].

The code tracking error is calculated after the simulation is finished. An example of the code tracking error versus simulation time is shown as left figure in Fig. 4. The main parameters used in the E1 signal Simulink simulator are summarized in Table 1.

Table 1. E1 signal simulator parameters

Parameters	Typical value
Sampling frequency f_s in whole simulator	13 MHz, 26 MHz
Intermediate Frequency IF	3.42 MHz, 6.7 MHz
Early-Late correlator spacing	bandwidth dependent, 0.1 chips (infinite BW), 0.1 chips (13 MHz)
Reference code	E1 code with BOC(1,1) modulation

2.3 Galileo E5a Simulink Model

In the Galileo E5a Simulink simulator, the whole E5 signal is generated in the transmitter. At the receiver side, only the E5a band in processed.

Transmitter. The E5a signal transmitter generates E5 signal by using the AltBOC(15,10) 8-PSK modulation, as described in [2]. The snapshot of the E5 transmitter block is in Fig. 6. The transmitted signal at the output of transmitter block is shifted to Intermediate Frequency (IF), as shown in Fig. 7(a).

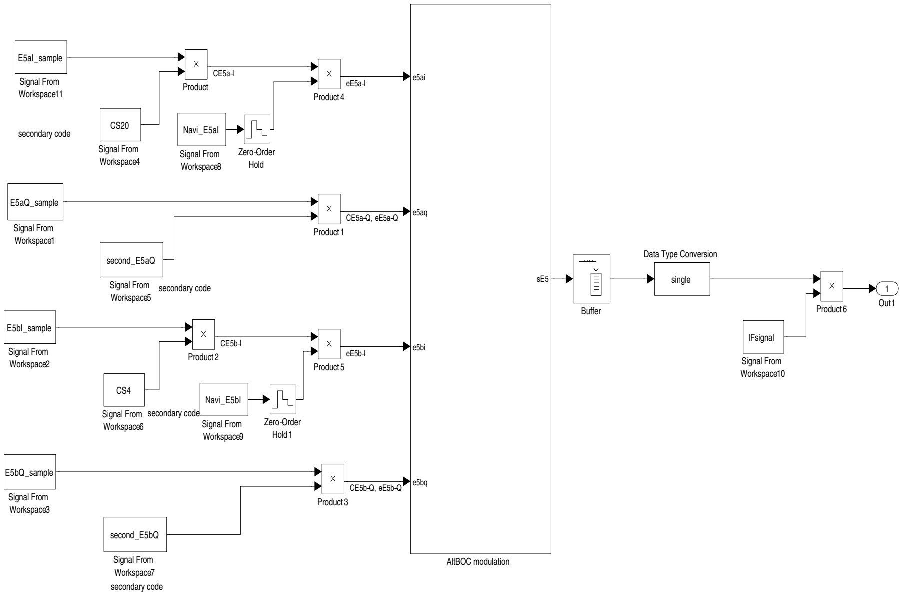


Fig. 5. The tracking block in Galileo E1 simulator at TUT

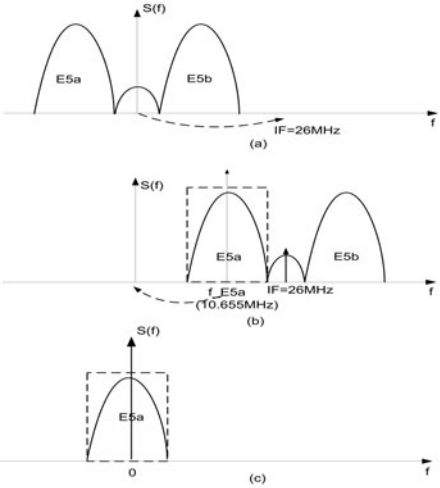


Fig. 6. The transmitter model in Galileo E5 simulator at TUT

Channel. The channel model used in E5a Simulink model has the same structure as that used in E1 simulator channel block. The complex noise and multipath are generated. The static and time variant channel can also be used.

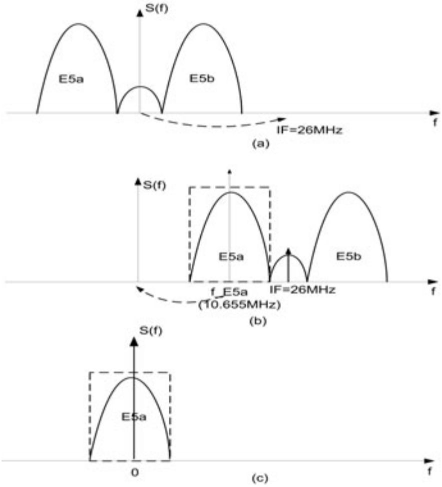


Fig. 7. (a)E5 signal spectra shifted to IF at transmitter; (b) Front-end filtering; (c) E5a signal down convert to baseband

Front-end. The front-end block in E5a simulator is used for filtering and down-sampling. The front-end filter has various bandwidth, i.e., 20.46 MHz bandwidth to cover the main lobe of E5a signal. The reason for using down-sample here is that the interested signal is only the main lobe of E5a signal, which has a much narrower band than the whole E5 band. Therefore, a lower sampling frequency used in the blocks after the filter without losing useful information can be realized.

Acquisition. The acquisition unit is also using FFT technique. Since the receiver only acquires the E5a signal, the E5aI without the sub-carrier is used as the reference code to estimate the frequency of E5a main lobe. The same as in E1 simulator, this estimated frequency will be used in the tracking unit to shift the filtered E5a signal.

Tracking. In the tracking unit, The structure and the functionality is the same as in E1 signal simulator. The carrier wipe-off down converts the E5a signal component to baseband, as shown in Fig. 7 (b) and (c). In the 'Code NCO' block, only the E5aI signals are generated in the code NCO. There is one channel in the 'Channel Correlation and discriminators' block to track E5a signal. PLL, FLL and DLL are implemented. Currently, Narrow Correlator [5] and HRC [6] are used in DLL as discriminator functions. The C/N_0 estimator is also implemented based on [14]. An example of code tracking error versus simulation time, which is calculated after the simulation is shown as right figure in Fig. 4 . The main parameter used in E5 signal simulator are summarized in Table 2.

Table 2. E5a simulator parameters

Parameters	Typical value
Sampling frequency f_s in transmitter and channel	126 MHz
Sampling frequency f_s in acquisition and tracking	42 MHz
Intermediate Frequency IF	26 MHz
E5a frequency f_{E5a}	10.655 MHz
Early-Late correlator spacing	bandwidth dependent, 0.1 chips (infinite BW), 0.8 chips (13 MHz)
Reference code	E5aI code

3 Simulation Results and Analysis

The tracking performances are evaluated with the E1 and E5a signal simulator, which have been described in the previous section. Due to the sensitivity of the receiver, the tracking units in both E1 and E5a signal simulators are enabled all the time in order to test the performance below the sensitivity. Different double-sided front-end bandwidths are considered in the simulations: 1. ideal infinite bandwidth; 2. 4 MHz for E1 band and 20.46 MHz for E5a band, which cover the main lobe the signals, respectively; 3. 13 MHz for both signals, which is a bandwidth chosen between 4 MHz and 20.46 MHz in order to have a fair comparison between two signals. The $E - L$ correlator spacing Δ are defined by the rule of $\Delta \geq f_c/BW$ [15], where f_c is the chip rate and BW is double-sided front-end bandwidth. RMSEs between the estimated delay and the true Line-Of-Sight (LOS) delay are calculated. The parameters used in the simulations are summarized in Table. 3.

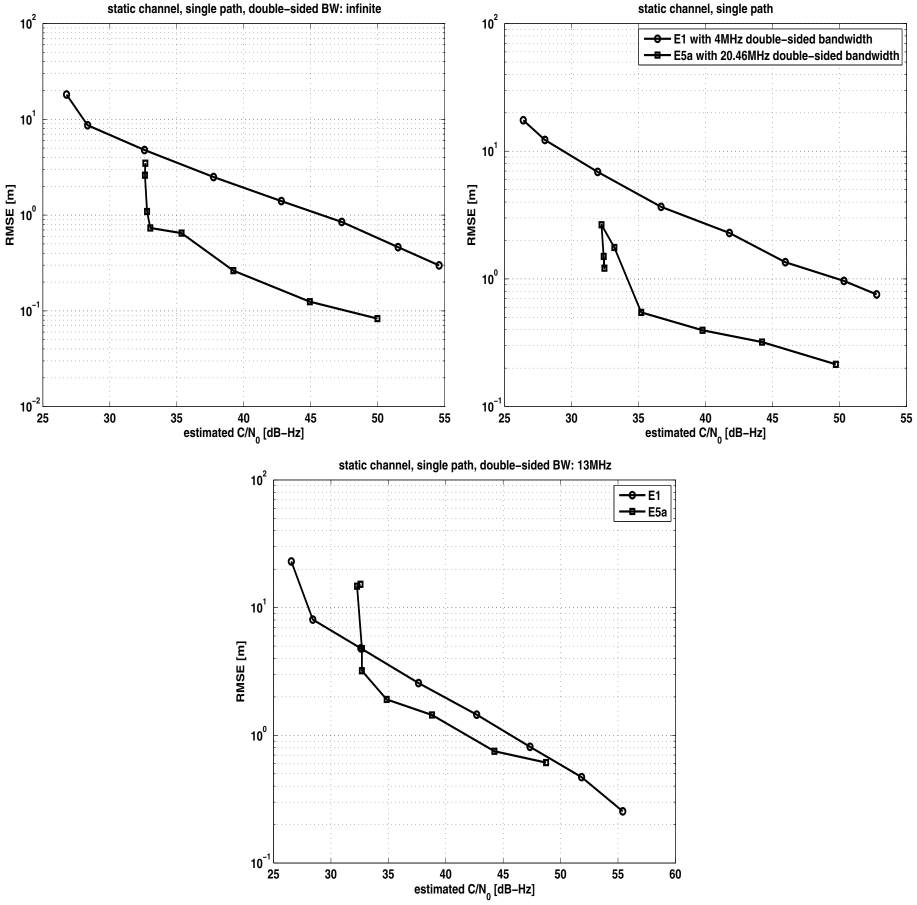
Table 3. Simulation parameters for multipath scenario

Signal	E1			E5a		
Channel	Static channel					
f_s (MHz)	13	13	26.3	126	126	126
Bandwidth (MHz)	inf	4	13	inf	13	20.46
E-L spacing (chips)	0.1	0.1	0.26	0.1	0.5	0.8
Multipath distance (chips)	0.1	0.1	0.1	0.1	0.1	0.1

3.1 Delay Tracking in Single Path-Simulation Results

The tracking performances with E1 and E5a signal are first evaluated in a single path static channel profile. The simulation parameters used in the simulation can be found in the Table 3.

The tracking errors in meter versus estimated C/N_0 in a single path scenario are shown in Fig. 8. As can be seen from the figures, tracking E5a signal has better performance than tracking E1 signal with infinite bandwidth and the 20.46 MHz bandwidth, which covers the main lobe of the E5a band. With 13 MHz, the performance of tracking E5a signal outperforms than that of E1 signal most of the times. When the estimated C/N_0 drops to around 33 dB-Hz, the tracking performance with E5a signal degrades and is worse than the performance of E1 signal due to the signal energy loss on E5a band.


static channel, single path, double-sided BW: infinite

static channel, single path

static channel, single path, double-sided BW: 13MHz

Fig. 8. RMSE simulation results with single path in static channel; Left: infinite bandwidth for both E1 and E5a signals; Right: 4 MHz double-sided bandwidth for E1 signal, 20.46 MHz double-sided bandwidth for E5a signal; Lower: 13 MHz double-sided bandwidth for both E1 and E5a signal

3.2 Delay Tracking in Multipath-Simulation Results

The performance of tracking E1 and E5a signal in a multipath scenario is shown in Fig. 9. The parameters used in the simulation are shown in Table. 3. As expected, E5a signal has better tracking performance than E1 signal if the front-end bandwidth is wide enough to cover the E5a band. With narrower band 13 MHz, E5a signal losses the benefit at the lower C/N_0.

A special case is also considered here, which is assumed that E1 signal is transmitted through a good channel (the LOS signal has much higher power than NLOS signal) and E5 signal is transmitted through a bad channel (the LOS signal has very weak power and LOS and NLOS has similar power). The channel profiles are generated with DLR channel model. The result is as given in the lower right figure in the Fig. 9. It can be observed that the tracking performance of E5a signal is much worse than E1 signal most of the time. Although the transmitted signal in both simulator have the same nominal C/N_0, the performance becomes worse because of the channel condition.

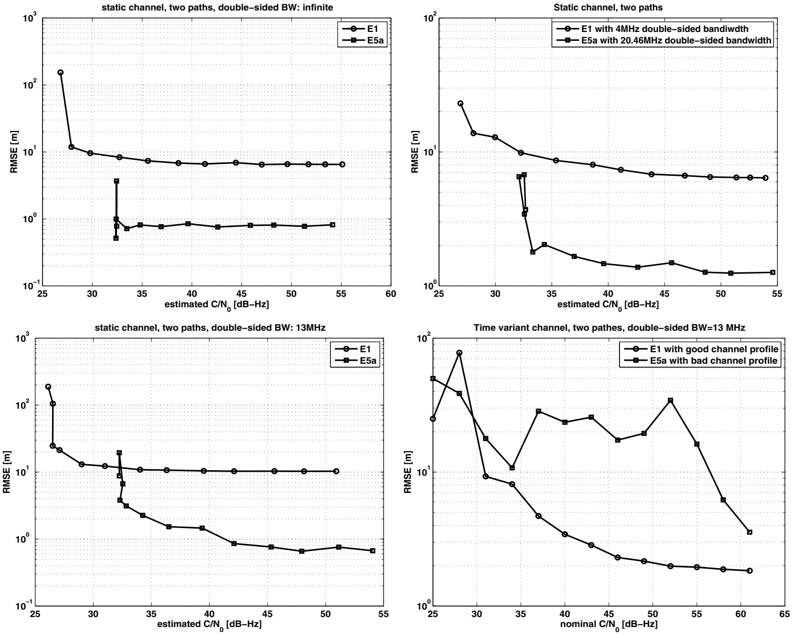


Fig. 9. RMSE simulation results with two paths in static channel; Upper left: infinite bandwidth for both E1 and E5a signals; Upper right: 4 MHz double-sided bandwidth for E1 signal, 20.46 MHz double-sided bandwidth for E5a signal; Lower left: 13 MHz double-sided bandwidth for both E1 and E5a signals; Lower right: 13 MHz double-sided bandwidth for E1 and E5a with DLR channel model

3.3 Delay Errors Distribution

The histograms of tracking error obtained from above simulations are presented in this section. Since the noise added in the channel block is Gaussian white noise, the histograms are compared with the Gaussian distribution, of which the mean and variance are calculated from the corresponding code tracking error. In order to ignore the effect from filtering, the histogram of the tracking error under the infinite bandwidth are considered here, as in Fig.10 and Fig.11. As it can be seen from the figures, the Gaussian distribution is more fit to E1 signal no matter if the signal is transmitted in a single path or multipath scenario. The tracking error of E5a signal in single path scenario has Gaussian-like distribution, however, it is not like Gaussian distribution any more in multipath scenario, which could be the effect from down-sampling.

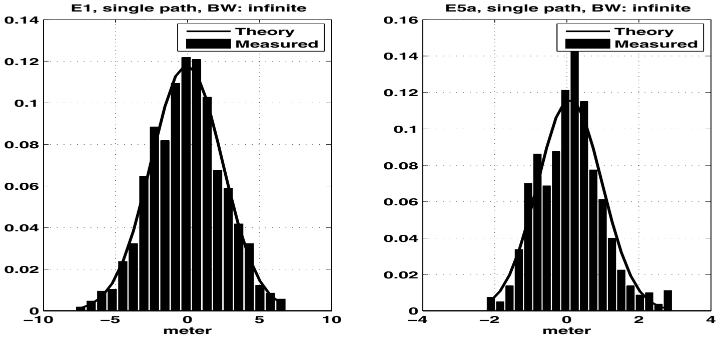


Fig. 10. Histogram of code tracking error of E1 and E5a signal at nominal $C/N_0 = 40$ dB-Hz

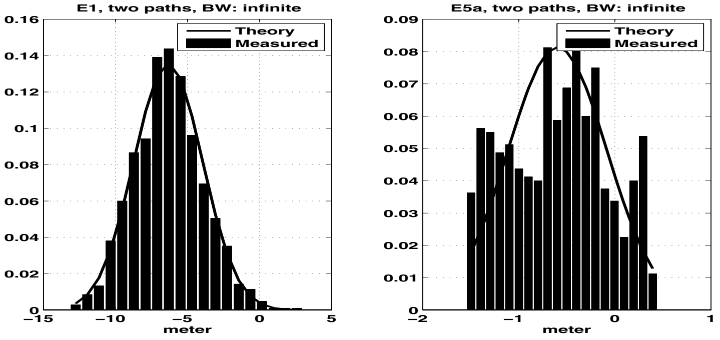


Fig. 11. Histogram of code tracking error of E1 and E5 signal at nominal $C/N_0 = 40$ dB-Hz

4 Conclusions

In this paper, the tracking performance with E1 and E5a signals has been evaluated in Simulink-based simulator built at TUT. The E1 and E5a signal simulators are described in the context of the paper. The tracking performances were evaluated in different channel profiles and receiver front-end configurations. They were shown that the tracking performances with E5a signal are better than those with E1 signal most of the time, especially at high C/N_0. In certain cases, when the E5a signal was transmitted through a much worse channel than that for E1 signal, tracking E5a lost its benefit .

The histogram of the code tracking error showed that the Gaussian distribution is more fit to E1 signal than E5 signal. It also indicated that in the E5a chain, there was not only the noise and multipath as error source, but also other aspects in the chain, such as the down-sampling.

For future work, it remains to be investigated how to combine E1 and E5a results for better accuracy results in a dual-frequency receiver mode . In addition, the E1 signal simulator is an open source, which is available at $www.cs.tut.fi/tlt/pos$.

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