QUANTIZATION EFFECTS ON CORRELATION LOSSES FOR GALILEO E1 SIGNAL ACQUISITION AND TRACKING

Mohammad Zahidul H. BHUIYAN, Kazi Wali ULLAH and Elena Simona LOHAN

Department of Communications Engineering
Tampere University of Technology, Tampere, Finland
{mohammad.bhuiyan, kazi.ullah, elena-simona.lohan}@tut.fi

ABSTRACT

The Global Navigation Satellite System (GNSS) receivers typically use a low resolution quantizer, generally 1 or 2 bits, which eventually leads to signal quality degradation and consequently degrades the performance of the receiver. In this paper, the authors present the effect of quantization on signal processing performance at the acquisition and tracking stages for Galileo E1 Open Service signal. Simulations have been carried out in an open access Galileo E1 signal simulator in a single path channel for two different receiver configurations. The goals of the paper are two-folds: first to validate the open-link Galileo Simulink model, created at TUT as open-access model and secondly to offer some measures of quantization losses with a practical Galileo receiver architecture.

Keywords: *GNSS, quantization, acquisition, tracking.*

1. INTRODUCTION

Galileo E1 Open Service (OS) signal employs Composite Binary Offset Carrier (CBOC) modulation according to the more recent Galileo Signal In Space - Interface Control Document (SIS-ICD) [1]. The E1 OS signal consists of two different components: a data channel (or E1B channel) and a pilot channel (or E1C channel). The data channel is modulated by the so-called CBOC(+) modulation (where the sine BOC waveforms are weighted and added together), whereas the pilot channel is modulated by the CBOC(-) modulation (where the sine BOC waveforms are weighted and subtracted) [1]. More details about CBOC modulations can be found in [2], [3].

The effect of quantization on signal processing performance has been a subject of interest for many years. Theoretical and analytical experiments have been developed for decades, where results are most readily available for 1 or 2 bits quantization. Also, in the context of Global Navigation Satellite System (GNSS) receiver processing, results are well-known for legacy signals with conventional Binary Phase Shift Keying (BPSK) modulation in the presence of white noise. Recently, an analytical model for the quantization losses in GNSS receivers was presented in [4], which evaluated the quantization losses for sine BOC(1,1) and Multiplexed BOC (MBOC) signals for different set of sampling and bandlimiting combinations. However, those analytical studies were strictly based on the power spectral densities of signals and noises, and they did not include some realistic tracking loops. In this paper, the authors analyze the effect of quantization on signal processing performance at the acquisition and tracking stages for Galileo E1 OS signal with a sine BOC(1,1) reference receiver. A sine BOC(1,1) reference receiver only employs sine BOC(1,1) component while demodulating the received signal, and therefore, offers a simple low-cost implementation at a reasonable performance loss, which makes it a good choice for mass-market receivers [5]. Section II describes the quantization process used in the Simulink receiver, followed by a description about the Simulink model in Section III. Then, the simulation results at the acquisition and tracking stages are presented in Section IV and V, respectively. Finally, Section VI draws some general conclusions.

2. QUANTIZATION PROCESS

The quantization is the process of approximating a continuous range of values by a range of finite set of discrete values or symbols. In this paper, a uniform quantization method is used, based on the reasoning that this is the most common model employed in GNSS mass-market receivers. This type of quantization is applicable when the input data range is within a finite range ($f_{\max}$, $f_{\min}$) and it assumes equal spacing between successive quantized values. In this process, the entire data range is divided into L equal intervals of length Q (known as quantization interval or quantization step-size), with $Q = \frac{f_{\max} - f_{\min}}{L}$, and the number of quantization bits is defined as: $R = \log_2 Q$.

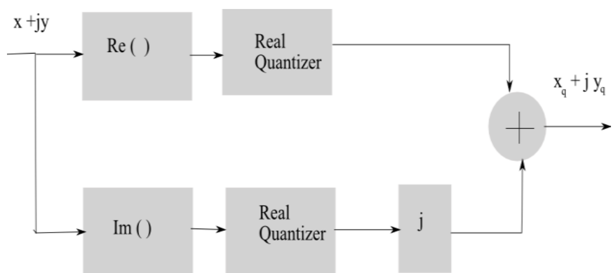


Figure 1: *A complex uniform quantizer*

Since the data is complex, we apply in fact two real uniform quantizers on real and imaginary parts of the signal, as illustrated in Figure 1, and as explained in [6]. In order to convert the analogue value to its corresponding discrete digital value, the index of the interval is generated and mapped to a corresponding digital value from a lookup table. The quantizer threshold (for quantizer employing more than 1 bit) was also generated according to [6].

3. SIMULATION MODEL

All the simulations have been carried out in an open-source TUT Galileo E1 signal simulator, which is developed in Simulink-based platform at Tampere University of Technology (TUT), Finland [12]. The simulator was divided into two separate models in order to run the simulations in acquisition and tracking stages separately, as shown in Figs. 2 and 3, respectively. This makes sense since we are interested to analyze the effect of quantization at the acquisition stage in terms of signal detection probability and at the tracking stage in terms of Root-Mean-Square Error (RMSE). However, both the acquisition and tracking models have in common a transmitter block, an AWGN channel block, a front-end filter block and a quantization block, as shown in Figs. 2 and 3, respectively. The quantization block is removed from the transmitter-receiver chain in both the models when no quantization is used. The detail description about each individual block can be found in [5], [7]. The Simulink blocks, which are of interest in the context of this paper (for example, front-end filter block, quantization block, etc.), are described briefly in the following.

3.1 Digital Filter Design Block

Simulations have been carried out for two different receiver bandwidths: (i) Narrow front-end filter with 3 MHz double-sided bandwidth (suitable for mass-market receivers), and (ii) Wide front-end filter with 24.552 MHz double-sided bandwidth (suitable for high-end receivers). In the first occasion, a Chebyshev type I filter is implemented with a 3-dB 6^{th} order double-sided bandwidth of 3 MHz; while in the later occasion, a Chebyshev type I filter is implemented with a 3-dB 4^{th} order double-sided bandwidth of 24.552 MHz.

3.2 R bits Quantization Block

The R bits quantization block follows the quantization process mentioned in Section II. The detail block diagram is shown in Fig. 4, where the quantization bit R takes any of the values from the set [1, 2, 3, 4, 8]. In the 'No Quantization' scenario, the R bits quantization block is simply removed from the transmitter-receiver chain.

3.3 Acquisition Block

The acquisition block utilizes an FFT-based acquisition technique, where the FFT transform of the down-converted input signal is multiplied with the FFT transform of the conjugate of the reference code. The result of the multiplication is then transformed into time domain by taking inverse FFT transform. The absolute of the output of the inverse FFT transform represents the correlation between the input signal and the reference code. A 'Joint Data-Pilot' acquisition scheme is implemented in Matlab-based S-function as mentioned in [5]. In the simulations, the acquisition block is continuously running and generates output after each 4 ms, which are then stored in memory for later use to compute the final statistics. The acquisition detection is implemented according to the Constant False Alarm Rate (CFAR) algorithm as described in [8]. The decision variable for signal detection is computed according to the ratio of peaks [8]. The detection threshold is currently set to 1.25, which offers a good trade-off between the detection and false alarm probability. The coherent integration used to run the simulations is 4 ms (or one code epoch). The frequency uncertainty range is from -4.98 kHz to +4.98 kHz with a step of 166 Hz [9]. The time uncertainty range is equal to the code epoch length (i.e., 4092 chips) with a time-bin step equals to 0.1137 chips in case of 3 MHz double-sided bandwidth, and 0.1180 chips in case of 24.552 MHz double-sided bandwidth.

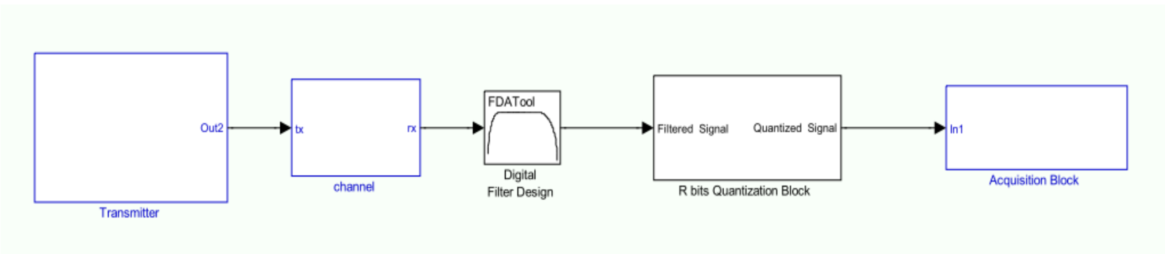


Figure 2: *TUT Galileo E1 signal simulator with acquisition only receiver (upper level block diagram)*

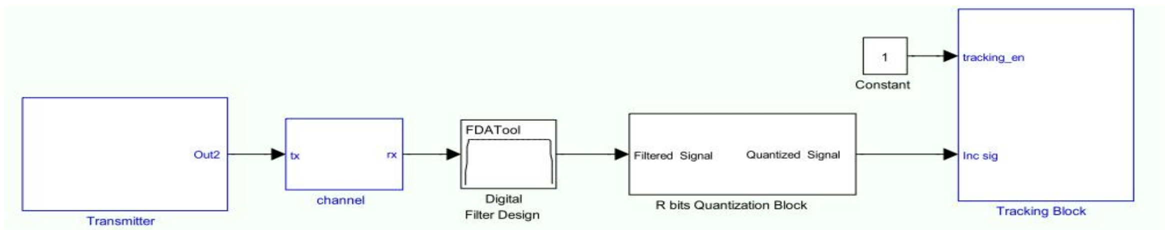


Figure 3: *TUT Galileo E1 signal simulator with tracking only receiver (upper level block diagram)*

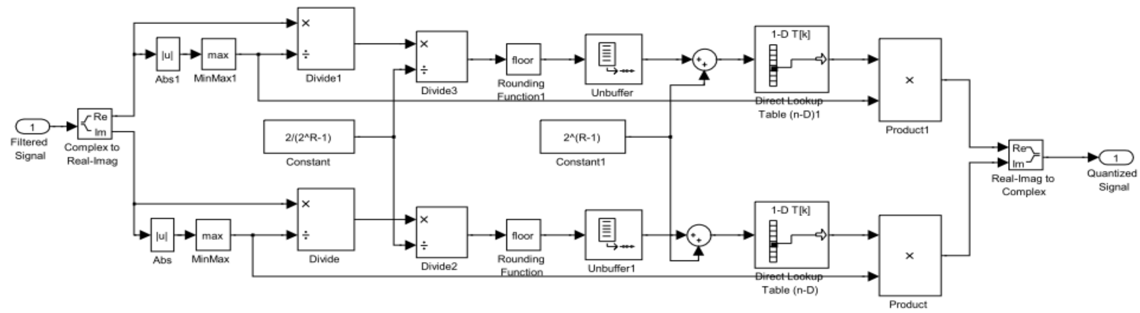


Figure 4: *The detail Simulink block diagram for 'R bits Quantization Block'*

3.3 Tracking Block

The tracking block consists of three major blocks: 'Carrier Wipe-Off' block, 'Code NCO' block, and 'Dual Channel Correlation and Discriminators' block, as detailed in [5, 7]. The incoming signal is down converted to the baseband in the 'Carrier Wipe-Off' block. 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) channel and the quad-phase (i.e., Q channel) channel in baseband. The 'Code NCO' block considers the estimated code phase error from the Delay Lock Loop (DLL) filter in order to shift the code phase accordingly. This block generates four signals as output: the adjusted E1B and E1C replicas, the trigger enabling signal and the shifted NCO phase. Both the code and carrier NCOs are implemented using C-language based S-function, the details of which are not addressed here for the sake of compactness. The tracking loop discriminator is based on normalized Narrow Early-Minus-Late (NEML) power, which has the following discriminator function [10]:

$$D = \frac{I_E^{\,2} + Q_E^{\,2} - (I_L^{\,2} + Q_L^{\,2})}{I_P^{\,2} + Q_P^{\,2}} \tag{1}$$

The discriminator is implemented using an m-language based S-function. The code tracking loop filter bandwidth is currently set to 2 Hz, and the early-late spacing for NEML is set according to [10] $\Delta_{EL} \geq \frac{f_c}{BW}$, where f_c is the chip rate and BW is the available double-sided front-end bandwidth. In case of 3 MHz bandwidth, the early-late spacing is set to 0.35 chips, whereas for 24.552 MHz bandwidth, the early-late spacing is set to 0.1 chips. The initially estimated frequency and the initially estimated code delay, which are to be used by the tracking block, are set such that the initial frequency error is less than ±88 Hz, and the initial code delay error is less than ±0.1 chips. The reason for such a scheme is to run the tracking block independently in order to be able to calculate the tracking error in terms of RMSE.

4. SIMULATION RESULTS IN ACQUISITION STAGE

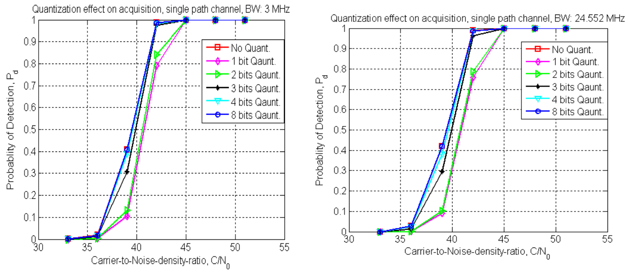
Simulations have been carried out in Galileo E1 acquisition only receiver (as shown in Fig. 2) in a single path channel for different quantization bits in order to quantify the losses coming from Analog-to-Digital Conversation (ADC) with various quantization bits. We also consider the 'No Quantization' case just by removing the quantization block from the transmitter-receiver chain. All the simulation results are obtained for two different receiver configurations as mentioned in Section 3.3. The statistics are computed for 5 seconds in each C/N_0 (varying from 33 dB-Hz to 51 dB-Hz with a step of 3 dB), giving a total of 1250 statistical points. The probability of detection (P_d) vs. C/N_0 plots is shown in Fig. 5 for two different front-end configurations. As shown in Fig. 5, the C/N_0 losses are relatively small (<0.5 dB on an average) for quantization bits equal to 3 or higher, and are significant (around 1.5 to 2 dB on an average) for 1 to 2 bits quantization. A better conclusion can be drawn from Fig. 6, which shows the C/N_0 losses for different quantization bits at probability of detection, P_d=0.9. As seen from Fig. 6, for such a moderate probability of detection (i.e., P_d=0.9), the C/N_0 losses are negligible for quantization bits equal to 3 or higher, and are around 1.6 to 2.2 dB for 1 to 2 bits quantization. It is important to note here that the C/N_0 losses are in fact the losses due to quantization only, since all the parameters are same for no quantization and with quantization scenarios except the quantization bits used in ADC for a certain bandwidth configuration. However, it will not be fair to compare the results obtained for two different bandwidth configurations, since the C/N_0 losses are correlated with the front-end bandwidth and the associated sampling frequency [11].

5. SIMULATION RESULTS IN TRACKING STAGE

Simulations have also been carried out in Galileo E1 tracking only receiver (as shown in Fig. 3) in a single-path channel for different quantization bits in order to analyze the impact of quantization on the tracking performance in terms of RMSE. We also consider the 'No Quantization' case by removing the quantization block from the transmitter-receiver chain. In the final statistics, the RMSE error is computed only after 0.5 seconds, which allows the tracking loop to discard the initial error bias that may come from the initial coarse estimate.

The RMSE vs. C/N_0 plots for two different receiver configurations are shown in Fig. 7. The quantization losses for 3 bits or higher are relatively small as compared to 1 or 2 bits quantization case. Fig. 8 shows the quantization losses for different quantization bits at RMSE=2.5 meters.

It can be seen from Fig. 8 that the quantization losses are around 1.6 to 2 dB for 1 to 2 bits, and are ≤0.5 dB for 3 bits or more for both the front-end configurations at RMSE=2.5 meters. The results shown here are matching well with other results reported in the literature (e.g., [11]).



(a) 3 MHz BW (b) 24.552 MHz BW

Figure 5: *P_d vs. C/N_0 in single path channel (a) BW=3 MHz, (b) BW=24.552 MHz; (No quantization and 8 bits quantization plots are overlapping with each other in the above plots)*

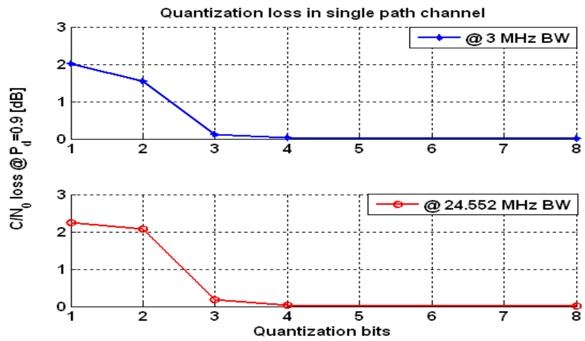


Figure 6*: C/N_0 loss in dB at P_d=0.9.*

6. CONCLUSIONS

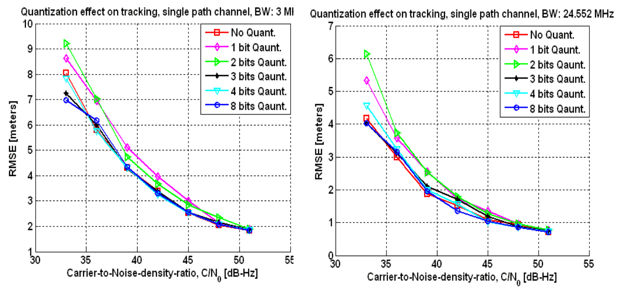
The effect of quantization on signal processing performance at acquisition and tracking stages was analyzed for Galileo E1 OS signal with sine BOC(1,1) reference receiver in two different receiver configurations. The quantization losses for different quantization bits were quantified for a certain accuracy level, for example, P_d=0.9 at the acquisition stage, and RMSE=2.5 meters at the tracking stage. It was shown that 1 to 2 bits quantization incur a loss of around 1.6 to 2.2 dB, whereas 3 or higher bits quantization incurs a loss less than 0.5 dB in both the receiver configurations for the specified accuracy level. The future research direction will be to analyze the impact of bandlimitation, sampling and quantization on the signal processing performance and to try to come up with a set of optimum parameters for different receiver configurations.

ACKNOWLEDGEMENT

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement number 227890, from Academy of Finland, and from TISE graduate school. The authors would also like to thank Nokia Foundation and Tampere Doctoral Programme in Information Science and Engineering (TISE) for their financial support.

REFERENCES

[1] "Galileo Joint Undertaking - GPS-Galileo Working Group A (WGA) Recommendations on L1 OS/L1C optimization," *http://www.galileoju.com/page3.cfm* (active Oct 2006), Mar 2006.



(a) 3 MHz BW (b) 24.552 MHz BW

Figure 7: *RMSE vs. C/N_0 in single path channel (a) BW=3 MHz; (b) BW=24.552 MHz*

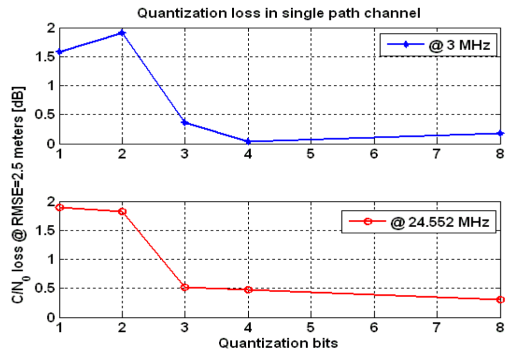


Figure 8: *C/N_0 loss in dB at RMSE=2.5 meters.*

[2] Hein, G. W., Avila-Rodriguez, J. A., Wallner, S., Pratt, A. R. Owen, J., Issler, J. L., Betz, J. W., Hegarty, C. J., Lenahan, L. S. , Rushanan, J. J., Kraay, A. L. , and Stansell, T. A., "MBOC: The new optimized spreading modulation recommended for Galileo L1 OS and GPS L1C," in *Position, Location, And Navigation Symposium*, IEEE/ION'2006, pp. 883– 892, April 2006.

[3] Lohan, E. S. and Renfors, M., "Correlation Properties of Multiplexed-BOC (MBOC) Modulation for Future GNSS Signals," in *European Wireless Conference*, Paris, France, April 2007.

[4] Betz, J. W., "Bandlimiting, Sampling, and Quantization for Modernized Spreading Modulations in White Noise," in *ION NTM'2008*, CA, USA, January 2008.

[5] Siddiqui, B. A., Zhang J., Bhuiyan, M. Z. H., and Lohan, E. S., "Joint Data-Pilot Acquisition and Tracking of Galileo E1 Open Service Signal," in *Ubiquitous Positioning, Indoor Navigation and Location-Based Service, UPINLBS'2010*, Helsinki, Finland, October 2010.

[6] Hegarty, C. J., "Analytical Model for GNSS Receiver Implementation Losses," in *ION GNSS'2009*, pp. 3165 – 3178, GA, USA, September 2009.

[7] Bhuiyan, M. Z. H., Zhang J., and Lohan, E. S., "Enhanced Delay Tracking Performance of a C/N_0-based Two-Stage Tracker for GNSS Receivers," in *ENC GNSS'2010*, Braunschweig, Germany, October 2010

[8] Pajala, E., Lohan, E. S., and Renfors, M., "CFAR detectors for hybrid-search acquisition of Galileo signals", in *ENC-GNSS'2005*, Munich, Germany, July 2005.

[9] Kaplan, E. D., and Hegarty, C. J., "Understanding GPS: Principles and applications", *Artech House*, 2006.

[10] Dierendonck, A. V., Fenton, P., and Ford, T. "Theory and performance of narrow correlator spacing in a GPS receiver*,"* in *Journal of the Institute of navigation*, vol. 39, pp. 265–283, Fall 1992.

[11] Parkinson, B. W., Spilker, J. J. Jr., "Global Positioning System: Theory and Applications," vols. 1 and 2, *American Institute of Aeronautics*, Washington, DC, 1996.

[12] TUT, Open-source Simulink Galileo E1 simulator, http://www.cs.tut.fi/tlt/pos/Software.htm