Analysis of Galileo E1 Receiver Performance with a Power-controlled Front-end

Article · May 2015

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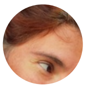

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European Journal of Navigation

Vol. 13 · No. 1

The leading journal for systems, services and applications

April 2015

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Assessment of tug assistance parameters as result of FMBS studies

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Analysis of Galileo E1 Receiver Performance with a Power-controlled Front-end

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Abstract

Power consumption is an important figure of merit for Global Navigation Satellite Systems (GNSS) receiver design. Low power consumption is essential in mass-market GNSS receivers which depend upon a battery for a power source. To achieve the reduction in the power consumption, the front-end of the receiver can be powered down for a fraction of time, but in a continuous manner so that the baseband can still keep track of the signals. This method can reduce the average power while still continuously tracking. However, its effects on the receiver performance have not been studied much in the literature. In this article, the authors analyze the receiver performance in terms of detection probability, code tracking error and bit error rate with different power switching time intervals. The analysis is performed both from the theoretical point of view and via signal simulations. Our results show that the performance of a power-controlled GNSS receiver is meaningfully degraded when power-blanking is applied. According to the obtained results, there is a loss of around 3 dB in terms of Carrier-to-Noise-density ratio (C/N0) of the received signal in both acquisition and tracking while compared with the traditional receiver without having any power reduction.

1. Introduction

Over the past two decades, Global Navigation Satellite Systems (GNSS) receivers have changed dramatically. The receivers have evolved from large analog equipment in the 1970s' to today's sophisticated and miniaturized platforms. A portable GNSS receiver usually utilizes a battery as a power source. However, the limited amounts of energy that can be stored and delivered from a battery severely constrain the power life of a GNSS receiver. Typical devices can now operate continuously for only a few hours 1. Some applications using GNSS technology, such as animal tracking applications request much longer power life of the GNSS receiver for long-duration animal studies 2. Therefore, reducing power consumption of a receiver for long-time running becomes a great topic for re-search. To achieve low power consumption, some receivers have an on/off modulator to control the operating power in Radio Frequency (RF) section 3. The on/off modulator switches power on and off alternatively, but in a continuous manner, so the base-band can keep track of the signal. The off time duration is less than the correlation period of the signal in order to ensure that there is some useful information within each correlation period. This technique, which was patented in 3 may reduce the power in RF section while the receiver continues to correlate GPS satellite signals and to provide a location fix to the user.

However, to the best of the authors' knowledge, how the power reduction and the switching time duration will affect the receiver baseband performance is yet to be studied in detail. Only recently, researchers from Politecnico di Torino and European Space Agency analyzed the performance of different power saving techniques for GNSS mass-market receivers 4. The analysis of different power saving techniques in 4 was carried out from power management point-of-view, and at the end a duty cycle based power saving technique was proposed and implemented in a software receiver based on open loop processing. In 5, the authors analyzed the effect of a flexible power-controlled front-end structure on the code tracking performance in a multi-frequency receiver. The work mentioned in 5, did not analyze the receiver performance with a power-controlled switching architecture for a single frequency receiver. In addition to that, the analysis was carried out only via theoretical modeling and the performance evaluation was performed only at the tracking stage based on a single parameter, i.e., tracking error standard deviation of the received GNSS signal.

In this research work, we investigate the feasibility of implementing a power-controlled switching architecture for a single frequency receiver by analyzing the baseband receiver performance at different signal processing stages of a GNSS receiver (i.e., at acquisition stage via probability of detection, at tracking stage via tracking error standard deviation, and at navigation stage via bit error rate). Therefore, the goal of this article is to present the Galileo E1 receiver baseband performance analysis for different power switching time intervals in terms of theory and signal simulations. The reminder of this article is organized as follows: Section 2 presents the theoretical analysis of the signal with power reduction. Section 3 shows the simulation con-figuration as well as the simulation results in terms of signal acquisition, signal tracking and navigation da-ta-bit detection. Section 4 discusses the challenges and opportunities brought by the power on/off modulated RF unit. Finally, conclusions are drawn in Section 5.

2. Theoretical background

Let's assume that the signal at the input of a GNSS receiver can be represented as:

$$r(t)=Ax(t)+n(t) \tag{1}$$

where x(t) is a GNSS signal with infinite bandwidth and with power $|x(t)|^2$ =1, A is its amplitude and n(t) is the thermal noise with the power spectral density N_0 that lumps in all sources of interference. Here we assume the signal is in a single path model in order to derive the performance bound. In the baseband, the correlation Y between the local replica x(t) and the received signal $r(t)$ over correlation period T can then be expressed by the following equation:

$$Y=\int_{t=0}^{T}x(t)\left[Ax(t)+n(t)\right]dt \tag{2}$$

The Signal-to-Noise Ratio (SNR) after the correlation period T can be calculated by:

$$SNR=\frac{E\left[Y\right]^2}{\operatorname{var}\left[Y\right]} \tag{3}$$

$$\begin{aligned}E[Y]&=E\left[\int_{t=0}^{T}x(t)Ax(t)dt\right]+E\left[\int_{t=0}^{T}x(t)n(t)dt\right]\\&=A\int_{t=0}^{T}|x(t)|^2dt+0=AT\end{aligned} \tag{4}$$

$$\operatorname{var}\left[Y\right]=N_0\int_{t=0}^{T}|x(t)|^2\,dt=TN_0 \tag{5}$$

Therefore, SNR in the ideal case can be written as:

$$SNR=\frac{E[Y]^2}{\operatorname{var}[Y]}=\frac{A^2T^2}{TN_0}=\frac{A^2T}{N_0}=\frac{E_b}{N_0} \tag{6}$$

where E_b denotes the bit energy.

When a power on/off modulator is implemented in the RF section, the baseband receiver only receives part of the original signal during one correlation period. Let's assume that the switching has the function m(t) which switches between 0 and 1, then the signal at the baseband receiver input can be expressed as:

$$r_1(t)=\left[Ax(t)+n(t)\right]m(t) \tag{7}$$

The correlation between the local replica x(t) and the signal after power on/off modulation can now be written as:

$$Y_1=\int_{t=0}^{T}x(t)\left[Ax(t)+n(t)\right]m(t)dt \tag{8}$$

The SNR can now be calculated in the following manner:

$$\begin{aligned}SNR=\frac{E\left[Y_1\right]^2}{\operatorname{var}\left[Y_1\right]}&=\frac{\left(A\int_{t=0}^{T}|x(t)|^2m(t)dt\right)^2}{N_0\int_{t=0}^{T}|x(t)m(t)|^2dt}\\&=\frac{A^2T\mu^2}{N_0\mu}=\frac{E_b}{N_0}\mu\end{aligned} \tag{9}$$

where μ is the ratio of the duration when the modulator is active (i.e., m(t)=1) during the correlation period. This means that in case of $\mu=0.3$, the signal exists for 0.3T and is powered off for the remaining of T (1-0.3 =0.7T). Therefore, SNR is degraded by 5.2 dB during a single correlation period.

With 50% duty cycle, the switching time for on and off duration is the same during the whole running time. However, the SNR of each correlation output will depend on the overlap between the on/off duration and the correlation period. For example, assume that the correlation period is 1 ms and the power on/off is switched after each 0.3 ms. Now, if we align the signal with 0.3 ms on/0.3 ms off, we will have 60% of the ideal energy, but if the alignment has started with 0.3 ms off /0.3 ms on, then we will only have 40% of the ideal signal energy. The SNR at each correlation output will individually show higher or lower value depending on how much signal is present during the whole correlation period.

3. Simulation configuration and result analysis

The code tracking error variance with a narrow correlator discriminator for different is first evaluated in theory with the equations given in[6]. Fig. 1 shows the code tracking error standard deviation in meters for different Carrier-to-Noise-density ratios (C/N_0) with a range from 35 to 50 dB-Hz. The correlation is performed between the Composite Binary Offset Carrier CBOC(+)-modulated Galileo E1 signal and a locally generated SinBOC(1,1)-modulated E1 signal. It can be seen from Fig. 1 that within a single correlation period, the code tracking error increases dramatically with the decreasing amount of signal presence during that correlation interval. At C/N_0=35, the code tracking error can be increased by about 6 meters as compared to the one without power reduction, if (the receiver is switched ON only one tenth of the time) is chosen. It can also be observed from Fig. 1 that the lower the presence of the signal during the correlation period, the more the tracking error we can expect from the receiver.

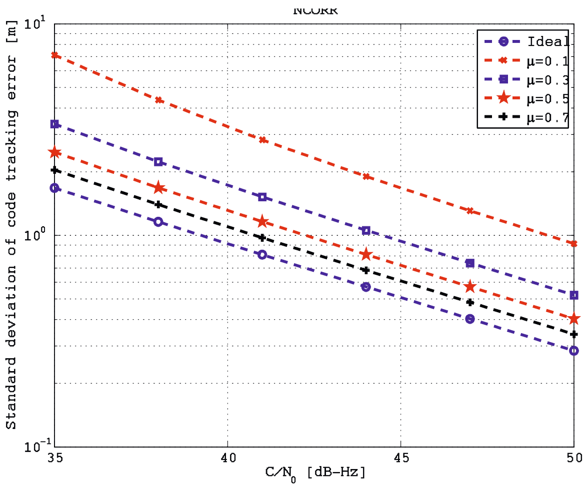

Figure 1: Code tracking error standard deviation versus C/N0.

The effect of different power switching intervals on GNSS signal acquisition, tracking and navigation data decoding performance is also evaluated in a Galileo E1 signal Simulink simulator built at the Department of Electronics Communications Engineering in Tampere University of Technology, Finland. The simulator is freely available under an open-access license term at[7] and the details of each block of the simulators can be found in[8-10]. The simplified simulation block diagram is shown in Fig. 2. The transmitter generates the Composite Binary Offset Carrier (CBOC)-modulated E1 signal[11] at Intermediate Frequency (IF). After the transmitted signal passed through a wireless channel, the signal is captured by the receiver and filtered by a front-end filter. A switching block is implemented to simulate the power on/off modulator. The duty cycle of the switch is 50%, which means that it switches between on and off every T ms, where the switching time T is user defined and it is assumed to be smaller than the correlation period. The signal acquisition and tracking blocks are incorporated in the receiver block. The simulations at the acquisition and at the tracking stages are executed separately, which means that the acquisition decision does not affect the tracking. This particular architecture (separate execution of acquisition and tracking) was chosen to ensure that the tracking statistics do not depend on the acquisition performance. SinBOC(1,1)-modulated E1B (i.e., Galileo data channel) and E1C (Galileo pilot channel) signals are used as local replicas in acquisition and tracking. The correlation period for Galileo E1 signal is 4 ms, which is also the data bit duration for the Galileo E1B signal. A Narrow Correlator (NCORR) discriminator is used in the implementation as a standard Delay Locked Loop (DLL)[12] with Early-Prompt correlator spacing of 0.07 chips (chip rate is 1.023 MHz).

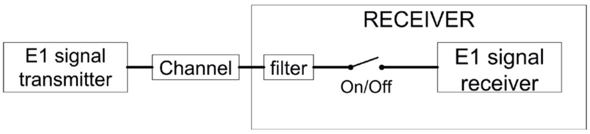

Figure 2: Simplified block diagram of the baseband simulator.

All the simulations are conducted with infinite front-end filter bandwidth in a single path scenario in order to ignore the effect of limited bandwidth and multipath and to illustrate the best achievable performance with an on/off architecture. The statistics are computed with 1000 observations for each particular C/N_0. The acquisition utilizes Fast Fourier Transform (FFT)-based acquisition technique. The acquisition detection is implemented according to the Constant False Alarm Rate (CFAR) algorithm as described in[13]. The acquisition threshold is set to 1.3, because this value is proved to give a good tradeoff between detection and false alarm probabilities. The code tracking errors are computed after every 4 ms coherent integration period. The Root-Mean-Square (RMS) is computed at each particular C/N_0 level. The bits are detected by taking the sign of the in-phase correlator output.

The simulation results of receiver performance in terms of acquisition, code tracking and bit detection are shown respectively in Figs. 3, 4 and 5. It can be seen that the receiver performance with power reduction ("PR" in the plot) front-end structure is significantly worse than those without PR. In both acquisition and code tracking, the PR causes at least 3 dB losses with 50% duty cycle (i.e., $\mu = 0.5$). Among the studied switching time ("ST" in the plot) intervals, the switching time at 3 ms and 4 ms, in general, show the worst performance. This is due to the fact that the Galileo E1 receiver block does the coherent integration for 4 ms just because the code length of Galileo E1 signal is also 4 ms. When the switching time is 3 ms or 4 ms, every other integration only gets a little portion of the signal or even only noise, which degrades the performance. The performance with front-end working at 50% of the correlation period (4 ms/ST=even number) are quite similar and incur a minimum loss of 3 dB. This is because the power of E1 is halved in every correlation period in all these cases, which causes 3 dB in every correlation period. Similar results are obtained for bit detection performance analysis. The 4 ms switching interval severely degrades the bit detection performance due to the absence of useful signal information in every other integration. The bit detection is much better with switching interval 1, 2 or 3 ms since there is some useful signal energy present in every integration period. The performances of bit detection with other studied switching times have quite similar performance.

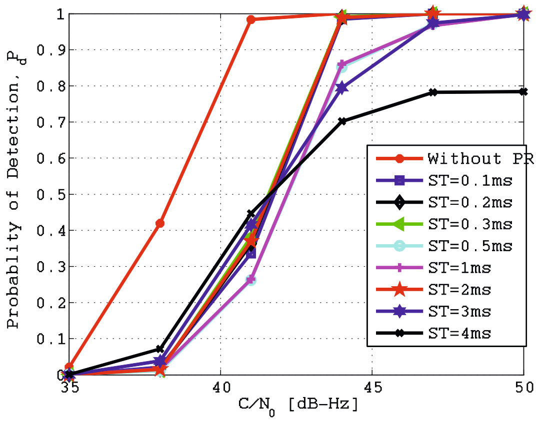

Figure 3: Detection probability at the acquisition stage.

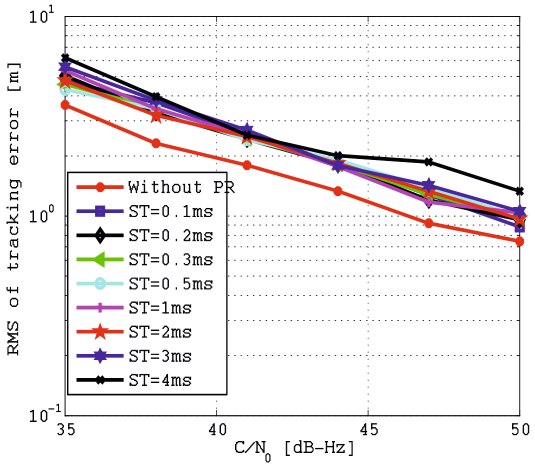

Figure 4: Code tracking error at the tracking stage.

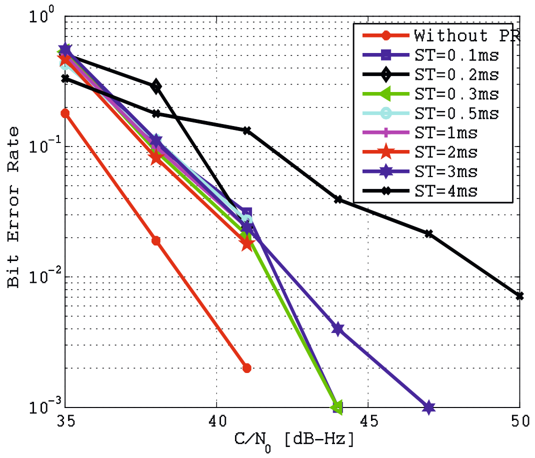

Figure 5: Bit error rate at the bit detection stage.

4. Challenges and opportunities

It can be seen from the results presented in the earlier section that the implementation of a power modulator decreases the received signal energy, which consequently keep the C/N_0 in the acquisition and tracking stage below the required threshold at some point. This particular phenomenon introduces a new challenge to the conventional GNSS receiver as they now require much sophisticated algorithms to compensate for the loss in C/N_0. A good selection of acquisition/tracking algorithms could help to compensate the C/N_0 losses due to power reduction.

The results above also show that the C/N_0 loss can be even higher depending on the alignment between the active signal and the correlation period. Therefore, in a practical implementation, we would suggest that the switching time should keep the ratio between the correlation period and the switching period as an integer in order to maintain constant phase with respect to the code.

Although the power modulator saves the power by sacrificing the performance on the conventional GNSS receiver, it also intrinsically offers an opportunity for interference mitigation. The GNSS signal may expose to potential interferences from other services sharing the same frequency range, for example, the pulsed interference originated from systems such as Distance Measuring Equipment (DME). Depending on the length of the interference on/off cycle, the power modulator could blank the pulsed interference by adjusting the switching time, as mentioned in[14].

The single frequency receiver can save up to 50% of the power consumption with 50% duty cycle with a trade-off of 3 dB power loss in terms of the received signal energy. This concept of power reduction can also be utilized in a dual-frequency receiver by switching the control of the baseband receiver between the two operating frequencies, as mentioned in[5]. As illustrated in[5], each chain in dual-frequency RF section can work alternatively so that the power consumption in dual-frequency receiver could be kept as low as possible.

5. Conclusions

It was shown that the power consumption can be reduced by switching the front-end operational power on and off with certain duty cycle (for example, 50% duty cycle) at the cost of corresponding loss in the received signal energy. However, the hardware implementation issues of such a power switching architecture for a GNSS receiver are still to be studied in future. The effect of power on/off front-end structure on the receiver's baseband performance is analyzed both from the theoretical point of view and via signal simulations. According to the results obtained at different signal processing stages, there is a loss of around 3 dB in terms of C/N_0 with 50% duty cycle as compared to the traditional receiver without having any power reduction. We conclude that the power switching interval should keep the ratio between the correlation period and the switching period as an integer in order to maintain constant phase with respect to the code for an optimized performance.

Acknowledgment

The authors would like to thank Graduate School in Electronics, Telecommunications and Automation (GETA) and Tampere Doctoral Programme in Information Science and Engineering (TISE) for their support. This work has also been supported by the Academy of Finland and European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement number 227890 (GRAMMAR project), which are gratefully acknowledged.

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