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Analysis and Compensation of RF Impairments for Next Generation Multimode GNSS Receivers

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Abstract—**Global Navigation Satellite System (GNSS) receivers require solutions that are compact, cheap and low-power, in order to enable their widespread proliferation into consumer products. Furthermore, interoperability of GNSS with non-navigation systems, especially communication systems will gain importance in providing the value added services in a variety of sectors, providing seamless quality of service for users. An important step into the market for Galileo is the timely availability of these hybrid multi-mode terminals for consumer applications. However, receiver architectures that are amenable to high-levels of integration will inevitably suffer from RF impairments hindering their easy widespread use in commercial products. This paper studies and presents analytical evaluations of the performance degradation due to the RF impairments and develops algorithms that can compensate for them in the DSP domain at the base band with complexity-reduced hardware overheads, hence, paving the way for low-power, highly integrated multi-mode GNSS receivers.**

I. INTRODUCTION

Galileo is Europe's initiative for a state-of-the-art *Global Navigation Satellite System* (GNSS), providing a highly accurate, guaranteed global positioning service under civilian control. It will be interoperable with GPS and GLONASS, the two other global satellite navigation systems currently in use. According to the European white paper "*European transport policy for 2010: time to decide*", GNSS is identified as a critical technology. GPS, Galileo and GLONASS are tightly designed to be autonomous systems. However, by careful combination of the signals from the three GNSS systems a new world of possibilities unfolds for applications designers. Furthermore, interoperability with non-navigation systems, especially communication systems (GSM, UMTS, WLAN, Bluetooth, TETRA, etc.) will become of high importance in providing the value added services in variety of sectors, delivering seamless quality of service for users. In the near to medium-term future, the market for satellite navigation technology is expected to experience major growth. Market research indicates that current global annual revenues from GNSS products and services is about US$20- 40 billion and this figure is expected to reach US$100 billion in 2010 and over US$250 billion by 2020 [1].

The user terminal will play a central role in all these developments and applications. The timely availability of low-power and low-cost hybrid receivers is a factor of great importance in the successful placement of Galileo in the consumer sector. To enable the deployment of GNSS capabilities into consumer products, an integrated receiver should minimize the number of off-chip components, particularly the number of expensive passive filters [2]-[4]. However, receiver architectures which provide high levels of integration like the zero-IF and low-IF topologies suffer from RF impairments which hinder their widespread use [5]-[7]. For future GNSS multimode receivers a hybrid zero-IF/low-IF architecture is envisaged.

The main purpose of this paper is to analyze the influence of the RF impairments on the GNSS receiver's performance and propose novel efficient low-complexity means of dealing with them in the DSP domain. This will provide an enhanced performance and increased integration as coarser RF components which are amenable to high levels of integration will be made possible leading the way to software (digitally) defined multimode GNSS receiver.

The paper is organized as follows: Section II outlines the background on the system architecture for Galileo. Section III investigates RF impairments and their influence and outlines solutions to mitigate them. Simulation results are also given in this section. Concluding remarks are given in Section IV.

II. SYSTEM ARCHITECTURE

A. Galileo Signal Structure

Galileo includes three signal bands namely E5, E6 and L1 with respective centre frequencies of 1191.795 MHz, 1278.750 MHz and 1575.420 MHz. This is depicted in Table I. For consumer applications, the navigation signals

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transmitted at the L1 and E5 carriers will be the ones of highest interest.

TABLE I. GALILEO SIGNAL BANDS

Carrier	*Centre Frequency*	*Modulation*	*Multiplex Scheme*
E5	1191.795 MHz	BPSK(10)	AltBOC(15,10)
E6	1278.750 MHz	BPSK(5), BOCcos(10,5)	Constant Envelope
L1	1575.420 MHz	BOC(1,1), BOCcos(15,2.5)	Constant Envelope

B. Binary Offset Carrier Modulation

A *Binary Offset Carrier* (BOC) modulated signal $s_{BOC}(t)$ is generated at the baseband by the product of the navigation data, a non-filtered *Pseudo Random Noise* (PRN) code with a chip rate f_c having values {±1} and a non-filtered square-wave signal, $\mathrm{sgn}[\sin(2\pi f_s t)]$,with frequency f_s, which can be equal to or greater than f_c, acting as a carrier. This is shown in Fig. 1 where f_b is the data rate.

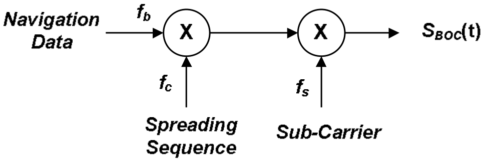


Figure 1. Principle of BOC modulation

The effect of this square carrier is to split the main lobe of the PRN spectrum into two lobes centred at ± f_s from the central frequency. The BOC type signals are usually expressed in the form BOC(f_s, f_c), whereas in the GNSS nomenclature they are expressed as BOC(n,m) where n and m stands for the normalization of the carrier frequency and the code rate by the reference frequency of 1.023 MHz. For example a BOC(10,5) signal has actually a sub-carrier frequency of 10x1.023 MHz and a spreading code chipping rate of 5x1.023 MHz. A particular case of this signal, when n and m are integers and $n = m$, is the well know Manchester code.

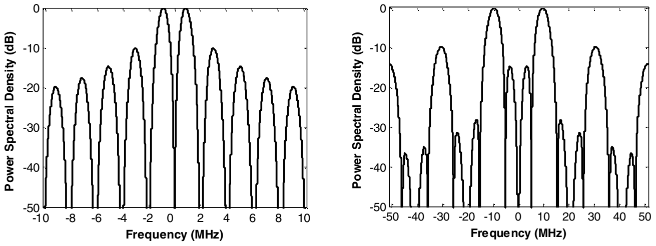
In order to minimize the interference between the Galileo and the current and future GPS signals on the L1 band a slight modification is introduced to the BOC modulation. The sine phasing modulation is replaced by a cosine phasing. The sine BOC (BOCsin) modulation has lobes with more power on the inner side whereas cosine BOC (BOCcos) has lobes with more power on the outside, which reduces the interference with the GPS signals. According to [8], the BOCcos(15,2.5) signal improves the spectral separation with respect to the GPS M-code by about 3.8 dB in comparison to its sine counterpart. The P*ower Spectral Density* (PSD) of a generic BOCsin(f_s, f_c) can be expressed as [9]:

$$s_{BOC\sin}(fs,fc)=fc\left(\frac{\sin\left(\dfrac{\pi f}{2f_s}\right)\sin\left(\dfrac{\pi f}{f_c}\right)}{\pi f\cos\left(\dfrac{\pi f}{2f_s}\right)}\right)^2 \tag{1}$$

The PSDs of various combinations of m and n proposed for Galileo are shown in Fig. 2. BOC modulation presents features allowing for an improvement of the acquisition and the tracking performance, while opening different implementation strategies for the demodulation chain within the receiver with different complexity costs. The *Alternative BOC* (AltBOC) is a slight modification to the BOC modulation intended to allow different channels in the lower and upper main side lobes [10]. Intuitively the idea is to perform the same process as in the BOC modulation with the exception of multiplying the baseband signal with a complex rectangular sub-carrier which is a complex exponential given as $sign(e^{j2\pi f_s t})$. Using the Euler formula this can be written as $v(t)=sign[\cos(2\pi f_s t)+j\sin(2\pi f_s t)]$. Having two baseband signals $x_1(t)$ and $x_2(t)$, the modulation can be expressed as:

$$s_{AltBOC}(t)=x_1(t)v(t)+x_2(t)v^*(t) \tag{2}$$

In this way the signal spectrum is not split up, but only shifted to higher and lower frequencies [10]. The goal of the AltBOC modulation is to generate in a coherent manner the E5a and E5b bands which are respectively modulated by complex exponentials or sub-carriers to form the E5 signal, which can be received as a wideband BOC-like signal.



(a) BOC(1,1) (b) BOC(10,5)

Figure 2. Power Spectral Density of BOC modulations

C. State-of-the-art Receivers

There is a drive to develop multi-mode receivers capable of processing Galileo, GPS and wireless communications. By observing commonalities between them one can identify a synergy for multi-modal operation. The RF front-end is the main bottleneck with a number of centre frequencies and bandwidths to deal with. Initially a receiver utilising multiple RF front-ends with a common DSP is envisaged as shown in Fig. 3. Feasibility of such a receiver is carried out in [11]. Integration and off-chip component reduction in the RF part is a key research area. Zero-IF and low-IF receiver topologies offer high levels of integration. However, suffer from RF impairments. It is because of these RF impairments that the receiver described in [11] is based on the super-heterodyne topology. There are a number of drawbacks with such a topology: the external component count, power consumption and lack of amenability to high levels of integration when compared to the low-IF and zero-IF counterparts.

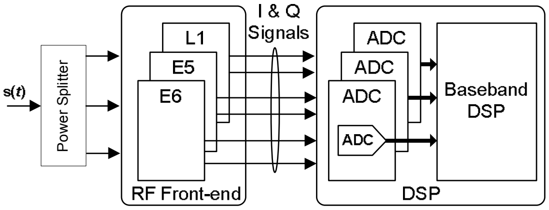
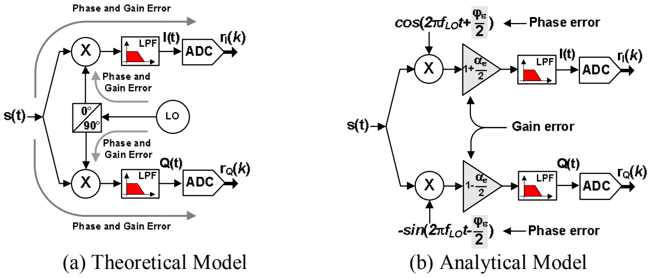


Figure 3. Possible Multimode Galileo Receiver Block Diagram

III. RF IMPAIRMENTS

Receiver architectures that utilize *IQ*-signal processing are vulnerable to mismatches between the *I* and *Q* channels. Sources of *IQ*-imbalances in the receiver are: the RF splitter used to divide the incoming RF signal equally between the *I* and *Q* paths which may introduce phase and gain differences as well as the differences in the length of the two RF paths can result in phase imbalance. The quadrature 90° phase-splitter used to generate the *I* and *Q Local-Oscillator* (LO) signals that drive the *I* and *Q* channel mixers may not be exactly 90°. Furthermore, there might be differences in conversion losses between the output ports of the *I* and *Q* channel mixers. In addition to these, filters and ADCs in the *I* and *Q* paths are not perfectly matched. The effects of these impairments on the receiver's performance can be detrimental. A model of a quadrature downconverter with the *I*/*Q*-phase and gain mismatch contributions by various stages is shown in Fig. 4(a), whereas Fig. 4(b) shows the analytical model used with all the phase and gain mismatches accumulated and represented by the erroneous LO signals.



(a) Theoretical Model (b) Analytical Model

Figure 4. RF Impairment contribution through the various stages

The *IQ*-impairments can be characterized by two parameters: the amplitude mismatch, α_ε and the phase orthogonality mismatch, φ_ε between the *I* and *Q* branches. The amplitude-imbalance, β in decibels is obtained from the amplitude mismatch, α_ε as:

$$\beta = 20\log_{10}\left[(1+0.5\alpha_\varepsilon)/(1-0.5\alpha_\varepsilon)\right] \quad (3)$$

The following is an outline analysis to show the effects of RF-impairments on the receiver's performance. Consider the incoming GNSS receiver input signal $s(t)$ at L1 band consisting of the wanted signal $u(t)$ at f_{RF} and unwanted image signal $i(t)$ at f_{IMG} where $f_{IMG} = f_{RF} - 2f_{IF}$.which can be expressed as:

$$s(t) = \Re\left\{u(t)e^{j2\pi f_{RF}t}\right\} + \Re\left\{i(t)e^{j2\pi f_{IMG}t}\right\} \quad (4)$$

where $u(t)$ and $i(t)$ are the complex envelopes of the wanted and image signals respectively. To simplify the analysis, whole phase and gain imbalances between the *I* and *Q* channels are modelled as an unbalanced quadrature downconverter. The erroneous complex LO signal, $x_{LO}(t)= I_{LO}+jQ_{LO}$, is given as:

$$x_{LO}(t) = e^{j2\pi f_{LO}t}(g_1 e^{j\frac{\varphi_\varepsilon}{2}} - g_2 e^{-j\frac{\varphi_\varepsilon}{2}}) + e^{-j2\pi f_{LO}t}(g_1 e^{-j\frac{\varphi_\varepsilon}{2}} + g_2 e^{j\frac{\varphi_\varepsilon}{2}}) \quad (5)$$

where $g_1=(1+0.5\alpha_\varepsilon)$, $g_2=(1-0.5\alpha_\varepsilon)$. Fig. 5 shows the downconversion from the L1 carrier frequency to baseband. As shown in Fig. 5, the received signal $s(t)$ is quadrature mixed with the non-ideal LO signal, x_{LO}, and low-pass filtered resulting in received IF signal. Following this, another mixer stage takes care of the final downconversion from IF to baseband. As this conversion stage takes place in the digital domain, the *I* and *Q* channels are matched, hence, ideal mixing is assumed leading to the baseband signal $r_{BB}(k)$. The complex baseband equation for the *IQ*-imbalance effects on the ideal received signal $r_{BB}(k)$ is given as:

$$r_{BB}(k) = u(t)\overbrace{(g_1 e^{-j\frac{\varphi_\varepsilon}{2}} + g_2 e^{j\frac{\varphi_\varepsilon}{2}})}^{h_1} + i^*(t)\overbrace{(g_1 e^{j\frac{\varphi_\varepsilon}{2}} - g_2 e^{-j\frac{\varphi_\varepsilon}{2}})}^{h_2} \quad (6)$$

where (•)* is the complex conjugate.

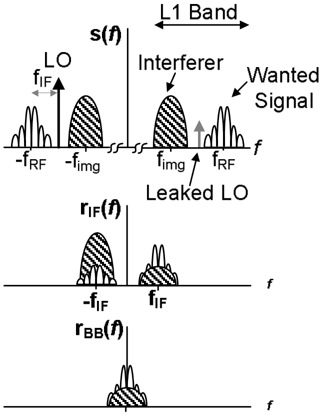
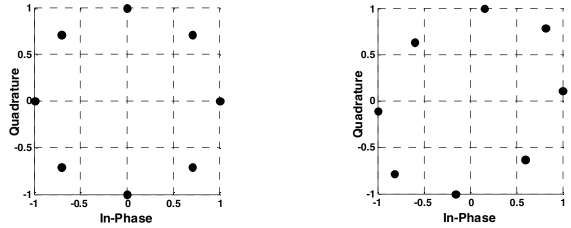


Figure 5. RF-to Baseband downconversion with RF impairments

The effect of *IQ*-impairments on the constellation diagrams of AltBOC modulated signals with a phase error of 15° and an amplitude imbalance of 3 dB is depicted in Fig. 6.



(a) Ideal (b) Erroneous

Figure 6. Constellation Diagrams for AltBOC (a) ideal, (b) erroneous [φ_ε=15°, β =3 dB]

Our proposed solution for dealing with these RF impairments is depicted in Fig. 7 [12]. *Digital Impairment Mitigation Block* (DIMB) processes the digitised L1/E5 and E6 *I* and *Q* signals and estimates the RF impairments in the respective RF front-ends and compensates for them in real-time. The idea behind the proposed approach is based on the simple observation that in the absence of the RF impairments the *I* and *Q* channels are orthogonal to each other and no correlation exists between them. However, as shown before in the presence of RF impairments there exists a correlation between the *I* and *Q* as well as the desired and the image channels.

For a zero-IF topology the inputs to the DIMB are the *I* and *Q* signals whereas in the case of the low-IF topology they are $+f_{IF}$ signal and $-f_{IF}$ signal downconverted from the IF to the baseband. Figure 8 shows a possible implementation of the DIMB [12]. The filter block consists of two-taps, w_1 and w_2.

The output signals c_1 and c_2 can be expressed as a function of desired and interfering signals $u(k)$ and $i(k)$ as:

$$\begin{aligned} c_1(k) &= (1 - w_1 h_2) u(k) + (h_1 - w_1) i(k) \\ c_2(k) &= (h_2 - w_2) u(k) + (1 - w_2 h_1) i(k) \end{aligned} \tag{7}$$

where h_1 and h_2 are given in (6). When the filters converge, i.e. $w_1 = h_1$ and $w_2 = h_2$ then the source estimates become:

$$\begin{aligned} c_1(k) &= (1 - h_1 h_2) u(k) \\ c_2(k) &= (1 - h_2 h_1) i(k) \end{aligned} \tag{8}$$

As can be observed from (8) the influence of the RF impairments have been removed. Interestingly, both the desired channel $u(k)$ and the interfering channel $i(k)$ are recovered simultaneously. The coefficient update can be done with any adaptive algorithm depending on the desired performance with least-mean-square and recursive-least-squares algorithms being the most obvious ones resulting in different convergence speeds and computational complexities.

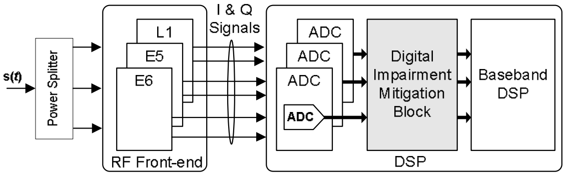


Figure 7. Proposed Solution

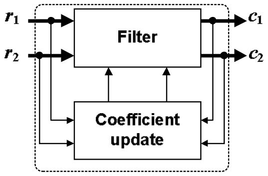
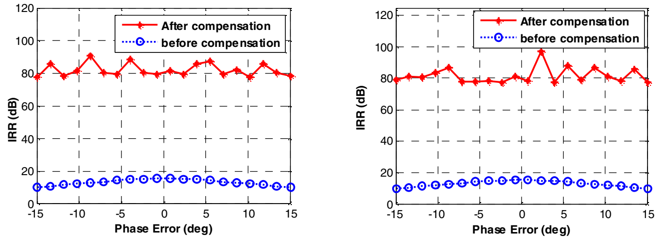


Figure 8. Possible Digital Impairment Mitigation Block

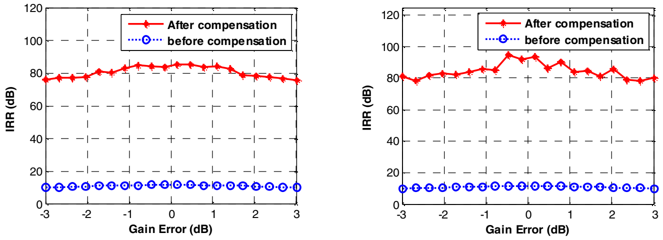
The performance of the proposed approach is analysed considering BOCsin(1,1) and AltBOC(15,10) signals with ideal symbol rate sampling. To examine the performance *Image-Rejection Ratio* (IRR) is defined as the ratio between the image signal to the desired signal e.g. h_2/h_1. For all simulations, the interfering signal is assumed to be 20 dB stronger than the desired one. Fig. 9 (a) – (d) depict the simulation studies for IRR before and after the DIMB for (a), (b) various phase error and (c), (d) for varying gain errors. As can be observed the results look promising and the use of DIMB has improved the IRR performance by about 60 dB.

IV. CONCLUDING REMARKS

Portable, consumer GNSS receivers require solutions that are compact, cheap and low-power. To popularize and make possible widespread deployment of GNSS capabilities in consumer products, an integrated receiver should minimize the number of off-chip components. Furthermore, interoperability of GNSS with non-navigation systems, especially communication systems will become of high importance. An important step into the market for Galileo is the timely availability of these low-power and low-cost hybrid multi-mode terminals for consumer applications. Receiver architectures that offer high levels of integration are susceptible to RF impairments. In this paper we have mathematically analyzed the RF impairments pertaining to the Galileo signals and proposed a possible solution that deal with them. We have also demonstrated through simulations the validity of our proposed solution with improvement in the IRR performance of 60 dB.



(a) BOC(1,1) (b) AltBOC(15,10)



(c) BOC(1,1) (d) AltBOC(15,10)

Figure 9. IRR before and after compensation for varying gain and phase errors

REFERENCES

[1] PriceWaterhouseCoopers, "Inception Study to Support the Development of a Business Plan for the GALILEO Program", Study for EC, November 2001.

[2] L. Maurer, Springer, A., Stuhlberger, R., Wicpalek, Ch., Heinrichs, G., Winkel, J., Drewes, Ch., " On the design of a configurable UMTS/NAVSAT Transceiver", IST Mobile & Wireless Communications Summit, Dresden, Germany, 19 - 23 June 2005.

[3] G. Heinrichs, J Winkel, C Drewes, L Maurer, A, "A Combined GNSS/UMTS Receiver Architecture for User Equipment Positioning", IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, vol: 4, pp. 2405- 2409, September 2005.

[4] D.K. Shaeffer, Shahani, A.R. Mohan, S.S, et al., "A 115-mW, 0.5-µm CMOS GPS receiver with wide dynamic-range active filters", IEEE Journal of Solid-State Circuits, vol.33, issue. 12, pp. 2219- 2231, December 1998.

[5] J. Crols and M.J. Steyaert, "Low-IF Topology for High Performance Analog Front Ends of Fully Integrated Receivers", IEEE Trans. on Circuits and systems- II: vol. 45, no.3, pp. 269-282 March 1998.

[6] B. Razavi, "Design Considerations for Direct-Conversion Receivers", IEEE Trans. On Circuits and Systems-II: Analog and Digital Signal Processing, vol.44, No, 6, pp. 428-435, June 1997.

[7] M. Valkama, M. Renfors, and V. Koivunen, "Advanced methods for I/Q imbalance compensation in communication receivers," IEEE Trans. Signal Processing, vol. 49, pp. 2335–2344, Oct. 2001.

[8] GW Hein, M Irsigler, JA Rodriguez, T Pany, "Performance of Galileo L1 Signal Candidates", Proceedings of the European Navigation Conference ENC GNSS, May, 2004.

[9] J. Betz, "Binary Offset Carrier Modulations for Radionavigation," Journal of the Institute of Navigation, vol. 48, pp. 227–246, 2001.

[10] G. Hein, J. Godet, J. Issler, J. Martin, P. Erhard, R. Lucas-Rodriguez and T. Pratt "Status of Galileo Frequency and Signal Design", Proc. ION-GPS pp. 266-277, September 2002.

[11] W. De Wilde , Sleewaegen, J.-M., Van Wassenhove, K., Wilms F. "A first-of-a-kind Galileo receiver breadboard to demonstrate Galileo tracking algorithms and performances". Proceedings of ION GPS, Long Beach, California, USA, 21-24 September 2004.

[12] E. Cetin, I. Kale, R. C. S. Morling and A. Dempster "Satellite Radio Navigation Receivers", UK Patent, GB0603038, Filed: 15 Feb. 2006.