SDR Analog Front-End Architecture For Simultaneous Digitalization of Data Transmission and Navigation Signals

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***Abstract*—In the last years, an increasing interest of the market in devices able to integrate navigation and communication technologies has been noticed. Software Defined Radio technology helps in a tight integration of all possible radio signals into one, completely reconfigurable, universal device. In this work the problem of the parallel acquisition and demodulation of Galileo, Satellite UMTS (S-UMTS) and IEEE 802.11b local wireless LAN has been faced through the usage of a multi-stage super-heterodyne analog front-end able to overlap the different signals into a reduced bandwidth. In this way it is possible the usage of low-cost components both for the analog heterodyne front and for the A/D Converter.**

I. Introduction

In the last years, an increasing interest of the market in devices, able to integrate navigation and communication technologies, has been noticed. In fact, nowadays, it is easy to find palms or mobile phones that integrate GNSS (Global Navigation Satellite Systems) navigators, such as GPS or the future European Galileo, or that can be easily equipped with, through additional gears. The handling of multiple signals and standards increases both the complexity and the cost of the receiver. In fact, if the user would like to use simultaneously a navigation and a data transmission system, in the mobile device a receiver for each considered signal has to be integrated.

Software Defined Radio technology helps in a tight integration of all possible radio signals into one, completely reconfigurable, universal device. In fact, thanks to the architecture of the SDR baseband processors, it is possible to perform parallel processing of different signals. Unfortunately the Analog-to-Digital (A/D) Conversion represents always one of the most sensitive part of the device. It is evident that the more standards are considered in the simultaneous signal acquisition, the more will be the bandwidth of the digitized signal. A solution could be to use parallel demodulation banks, but in this case each branch should be equipped with a dedicated A/D. Conversely, it is not possible to digitize the whole signal with a single A/D because physical electronics limits are still restricting the capabilities of A/D Converters, both in terms of number of samples per seconds and in terms of bits per sample.

Some communication and navigation transmissions are characterized by a significative property: they are modulated with Spread Spectrum techniques. In the following it will be shown that this fact can help in reducing the overall digitized bandwidth. By exploiting the same strategy of Code Division Multiple Access (CDMA) systems, it is possible to design specific multi-stage, sequential, not parallel, super-heterodyne analog front-end able to overlap the different signals into a reduced bandwidth. In this way it is possible the usage of low-cost components both for the analog heterodyne front-end and for the single A/D Converter. In the present work three different signals have been chosen to test the integration strategy. In particular we consider the Galileo E6 signal, as representative of GNSS systems, the Satellite UMTS (S-UMTS) for the global communication systems and the IEEE 802.11b Wireless LAN (WLAN) for the local data transmission systems.

The proposed system has been extensively tested in a completely simulated framework, developed in an hybrid Matlab/C++ environment and results have been pointed out in terms of cross-interference. For each single system, different parameters have been considered: Bit Error Rate in the case of WLAN and S-UMTS and degradation of conventional S-Curve, used to check the goodness of the code tracking/ranging module, in the case of Galileo navigation system.

Results prove that the considered integration strategy is an interesting low-cost and market-ready solution for SDR devices.

II. Software Radio Technology

The Software Radio Technology [1] is nowadays considered a fact. Different companies are now commercializing SDR products, especially for the military JTRS-compliant market [2] or civil GSM base stations based on SDR reconfigurable technology [3].

Under this framework the usage of GNSS systems is considered essential to provide location awareness and precise timing services to the SDR module. In fact there is an increasing attention of the GNSS research community in such systems as demonstrated by [4].

SDR is a very flexible platform for the management of multiple standards, such as GNSS and communication ones, but one of its main limit is the possibility to use only one standard/bandwidth per time. In fact, while the software part of the device is able to perform parallel hardware operations (thanks to FPGAs for example), the analog front-end is able to manage only a limited bandwidth (and often only one standard is associated to a single band). Current products are hence still based on different, dedicated analog front-ends for GNSS and communication systems. This fact is due to the ultra-wide bandwidth that have to be considered and digitized for the parallel demodulation of multiple signals. Current Analog-to-Digital Converters (A/DCs) can achieve sampling speeds no larger than 1 Gigasamples-per-second with a medium resolution of 8 bits. It implies that the maximum acquired bandwidth can be 500 MHz, according to the Nyquist sampling theorem. These kinds of A/DCs are also extremely expensive for mass market applications, hence a low-cost solution should be considered.

III. PROPOSED METHOD

The proposed method can be considered an extension of the one presented in [5]. In fact the same super-heterodyne demodulation strategy has been followed. The novelty is in the further integration of a local data transmission system such as IEEE 802.11b Wireless Local Area Network (WLAN). This system has been chosen because it is one of the most common data transmission system in the market. In the last years a wider number of producers have introduced WLAN receiver in Smartphones and palms, such as Nokia, Q-tek and recently Blackberry.

The proposed system is based on a three-stages demodulation and filtering analog/numerically controlled radio frequency front-end, as shown in Figure 1. The three local oscillators are used to overlap the three signals in the frequency domain. The overlapping is possible through the usage of Image Bandwidths. The Filtering stage is used to reduce the interferences. A more detailed explanation of the so-called *Frequency Plans* will be found in the following (see Section IV).

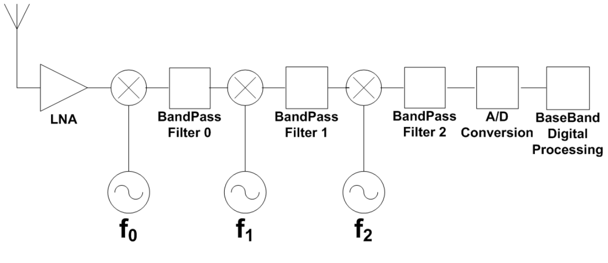

Fig. 1. Proposed Three-stages Architecture

The problems that arises in such a system are due the extremely increased bandwidth (WLAN works with a 2.4Ghz carrier frequency) and to the different Signal-to-Noise Ratio achievable with a local system instead of a satellite one. Fortunately the spread-spectrum codes that characterize each involved communication system can be exploited to maintain good performances.

A. Galileo

The GPS system modernization phase and the Galileo system development will increase signal availability and hence GNSS system-based applications. This surprising evolution of GNSS applications, mostly due to a large commercialization of GNSS-receiving technology, has led to stringent requirements for GNSS receivers, particularly in regard to their accuracy. In fact GNSS systems are of enormous benefit to myriad of military, civil, commercial, and scientific users around the world; different fields of application will benefit of this evolution, like car navigation, automatic position reporting during emergency mobile phone calls, monitoring of Earth crustal deformations.

Galileo system, like GPS, will be divided in three segments: the Space Segment, that comprises the satellites, the Control Segment, that deals with the management of the satellite operations, the User Segment, that covers the activities relative to the user equipment.

Each satellite broadcast navigation information by using the multi-user CDMA technique. In particular, on the basis of the 2000 World Radio-communication Conference (WRC), the Galileo frequency plan comprises five sub-bands, four in L band and one in C band, E5, E6, E2, E1 and C [6], [7].

As already said, Galileo, as GPS, uses the DS-CDMA to implement the multiple access. Each satellite has assigned a pseudo-random noise (PRN) code which can identify it. In particular the PRN codes are Gold sequences. In a common receiver, the incoming signal is sent to an Intermediate Frequency (IF) demodulator and than to a non-coherent Delay Lock Loop (DLL) [8]. It is based on the correlation between the received signal and three locally generated code replicas: Early (E), Prompt (P) and Late (L). The distance between the replicas (spacing) is a basic feature in precision positioning. A discriminator is used to find the correlation maxima: it is an error function, that depends on the correlation function, which shows that, when the error is greater then zero, the replica must be delayed, otherwise the replica must be anticipated. If the error function is equal to zero the signal has declared synchronized.

The chosen discriminator function in this paper is the Early Minus Late Envelope Normalized Function (EMLEN) and it is described by equation 1.

$$D = \frac{\sqrt{I_E^2 + Q_E^2} - \sqrt{I_L^2 + Q_L^2}}{\sqrt{I_E^2 + Q_E^2} + \sqrt{I_L^2 + Q_L^2}} \qquad (1)$$

where I_E, I_L, Q_E and Q_L represent the early and late correlation values for the in phase and quadrature component of the received signal. From the receiver point of view the discriminator's output is the feedback signal which control the local code replica as shown in Figure 2. The S-curve is a characteristic signature of the tracking code block, that relates the discriminator output and the shift of the local replica [9], and its shape looks different according to the chosen discriminator function. The performance estimation of different tracking loops in noisy environment is often made by showing the similarity between the S-curve deriving from the loop and the theoretical first order model, that represents the ideal case without any distortion.

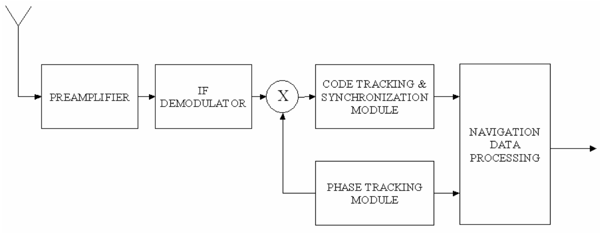

Fig. 2. Classical DLL GNSS Receiver

In the present paper the S-function, as a measure for determining the degradation performances introduced by the proposed method, has been chosen.

B. S-UMTS

The satellite component of UMTS (S-UMTS) will play an important role in providing worldwide access to UMTS services. Because satellite systems have the advantage of fast deployment, flexible use, and global coverage, satellites are able to provide telecommunication services in areas where terrestrial networks are economically or technically not feasible, such as the rural areas.

The satellite component of the system has been designed to be compatible with the Terrestiral-UMTS (T-UMTS) network.

As is known, the 3GPP T-UMTS proposal encompasses two operating modes: W-CDMA, associated with frequency division duplex (FDD), and TD-CDMA, associated with time division duplex (TDD). The two operating modes were adapted to the satellite environment, which resulted in the two proposals identified: as Satellite W-CDMA (SW-CDMA) and Satellite Wideband Code and Time Division Multiple Access (SW-CTDMA) [10]. For what concerns SW-CTDMA, it may be a suitable solution for regional systems adopting geostationary or elliptical orbits when the terminal peak effective radiated power (EIRP) can be relatively large. More details can be found in [11]. SW-CDMA represents an adaptation of the T-UMTS WCDMA proposal [12]. SW-CDMA is based on wide-band direct-sequence CDMA technology, with a basic chip rate of 3.84Mchip/s and a half rate option at 1.92Mchip/s, which may be more suitable in a multi-operator environment where bandwidth limitations may arise. SW-CDMA uses FDD and has a flexible carrier spacing of 4.4-5.0MHz with a carrier raster of 200 KHz.

The physical layer offers services to higher layer. These services are denoted as transport channels. A transport channel is defined on the basis of the data transferred over the air interface. The transport channels can be classified into two main groups:

- Dedicated channels, using inherent addressing of User Equipment (UE);
- Common channels, using explicit addressing of UE, if needed.

Various kinds of transport channels can be found [10], [12]. To each transport channel, there is a corresponding transport format (TF) set, determining the possible mappings, encoding, interleaving, etc, of a particular transport channel. The physical layer takes in charge the conversion of transport channels into physical signals to be sent on air. In the present paper three down-link transport channel only, with $2.5MHz$, $7.5MHz$ and $12.5MHz$ baseband subcarriers, each one characterized by a $5MHz$ bandwidth, have been considered in the simulations. The down-link service for the ITM-2000 regulation is allocated in the $2170-2200MHz$ bandwidth.

C. Wireless LAN

WLAN is a very common data transmission system. Due to the availability of very-low cost components it is becoming the lead standard also for setting up LAN in domestic environments. It was firstly standardized by IEEE under the name of IEEE 802.11 and further extended by adapting the communication modalities and the offered services [13]. The potentiality of this standard resides in the different kind of connections possible: Peer-to-Peer or communication through access points with a local Ethernet network.

In the present paper a particular extension of the WLAN standard has been considered: the IEEE 802.11b. This standard is characterized by a physical level working in the *Industrial Scientific and Medical* (ISM) bandwidth, with a carrier frequency of $2.44GHz$. The transmitted signal power can reach $100mW$ covering until $30m$ in indoor and $100/150m$ in outdoor.

A CDMA grants the access to the communication channel to multiple users. Two different kinds of CDMA techniques are foreseen by the standard in order to codify each user's information: Frequency-Hopping Spread Spectrum (FH-SS) and Direct Sequence Spread Spectrum (DS-SS). DS-SS is the most used one and for this reason has been chosen for the present paper. Under this assumption two PN fingerprints are possible and they are chosen depending on the available bit-rate, as shown in Table I.

TABLE I
IEEE 802.11B PHYSICAL LAYER CHARACTERISTICS

Bit-Rate [Mb/s]	PN Coding	Modulation
11	CCK	DQPSK
5.5	CCK	DQPSK
2	Barker	DQPSK
1	Barker	BPSK

In the present paper the assumption of transmissions at maximum bit-rate has been made. For this reason the most interesting characteristic is the Complementary Code Keying (CCK), which is a Poly-Phase code based on four symbols $\{1, -1, +j, -j\}$ [14]. The complex code is foreseen to be, for the 802.11b, 8 chips long with a chip-rate of $11Mchip/s$. The frequency allocation (and hence the channel allocation) is different from country to country. In most part of the Europe 13 partially super-imposed channels, each one with a $22MHz$ bandwidth, are in use in the regulatory plans. In order to verify the interference due to the proposed integration method, three non-overlapped channels have been used in the present paper, i.e. channels 1, 7 and 13 with carrier frequency $2412MHz$, $2442MHz$, $2472MHz$ respectively.

IV. FREQUENCY PLANS

By tuning properly the three local oscillators and the respective filters showed in Figure 1, it is possible to obtain different *Frequency Plans* (FPs), i.e. different ways of overlapping of the three considered communication systems. In the present paper three FPs have been tested (see Table II).

TABLE II
LOCAL OSCILLATOR FREQUENCIES

Plan ID	f_0 [MHz]	f_1 [MHz]	f_2 [MHz]
FP1	$1820MHz$	$452.5MHz$	$52.5MHz$
FP2	$1835.5MHz$	$452.5MHz$	$68MHz$
FP3	$1841MHz$	$455MHz$	$71MHz$

In Figure 3, 4 the frequency behavior for the three standards is shown. In FP1 there is overlapping of the satellite signals only. This configuration is similar (except for the presence of the WLAN signal) to the one presented in [5]. More interesting FPs are the other ones, where an increasing superimposition of the WLAN signal with the satellite ones is present, as shown in Figures 3 and 4.

As it is possible to see all the tested FPs have the property to reduce enormously the bandwidth required at the A/D conversion. In fact by using a single IF demodulation stage the occupied bandwidth would be about $1.3GHz$ while through the proposed method no more than $200MHz$ are needed.

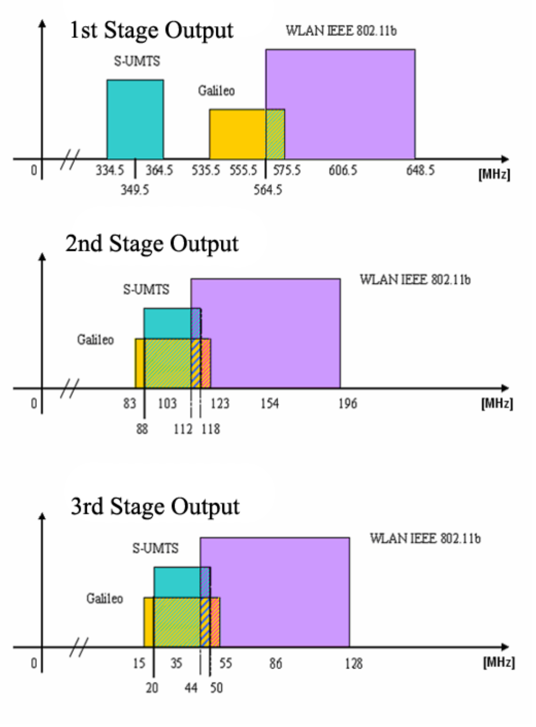

Fig. 3. FP2 Frequency Plan

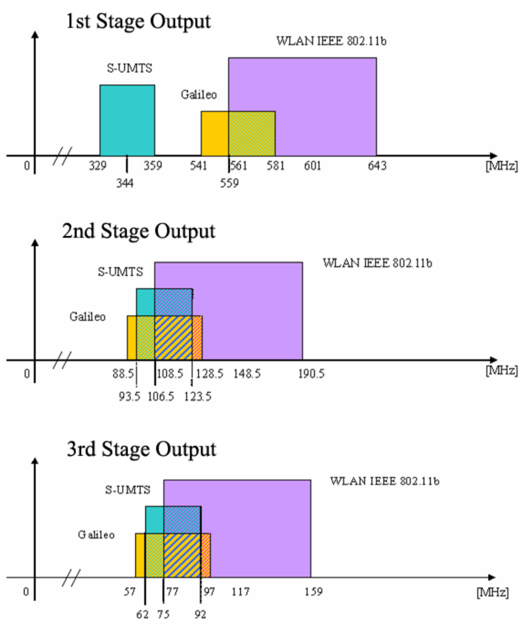

Fig. 4. FP3 Frequency Plan

V. SIMULATION AND RESULTS

In order to test the proposed integration method a complete simulation architecture has bee set up. The used simulation languages are Matlab©/Simulink© and C++ and the complete simulation architecture in Figure 5 is shown.

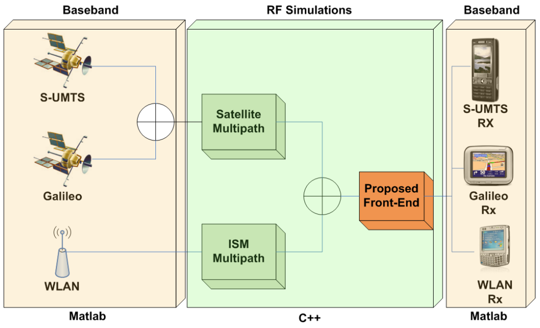

Fig. 5. Hybrid Matlab©/C++ Simulation Architecture

Matlab© has been used for the baseband signal generation and reception while C++, due to its efficient usage of the computational resources has been used for radio frequency simulations. Each signal has been separately tested and the performances of each receiver has been verified, in order to realize simulations comparable with the real systems. The second step has been the simulation of the whole integration procedure in terms of S-curves for Galileo and BER for the communication systems.

A. Results

As expected the most interesting FP is the number 2, where a small overlapping of the three systems is performed. In fact there are no problems on the overlapping between Galileo and S-UMTS because Galileo receiver perceives S-UMTS as a narrow-band jammer whose code orthogonality grants a reduced effect on the synchronization performances. Problems arise when the WLAN signal is partially overlapped to other ones. In FP3 these problems are reduced because an entire WLAN channel is overlapped and in this case too the orthogonality of the PN codes is assured. In FP2 only a sub-portion of the WLAN channel is superimposed and hence the perceived noise, generated by the non-orthogonality of the codes, is higher respect to the other plans.

Figures 6 and 7 show typical S-curves obtained in FP2 and FP3.

In the performed simulations 8 in-view Galileo Satellites, whose identification numbers are 2, 3, 4, 5, 6, 7, 9 and 10, have been considered. The performances in the central part of the S-curves can be considered good for all the FPs, while in the two sides the effects of the non-orthogonality of the PN codes are clearly visible in Figure 3 for FP2.

A performance reduction can be noticed, in FP2, for communication systems too. In fact both WLAN and S-UMTS suffer for an increased BER. But while the worsening for WLAN is in the order of 10^{-4} (see Figure 9), S-UMTS BER aggravation is much more higher, due to the extremely lower received power respect to the WLAN signal. In fact from Figure 8 it is possible to evict the typical BER behavior for each simulated channel.

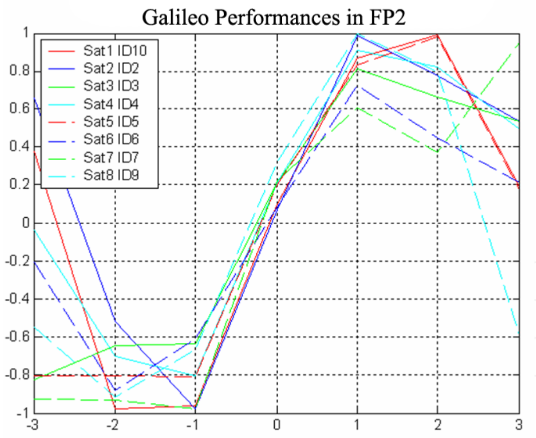

Fig. 6. Typical S-curve for FP2

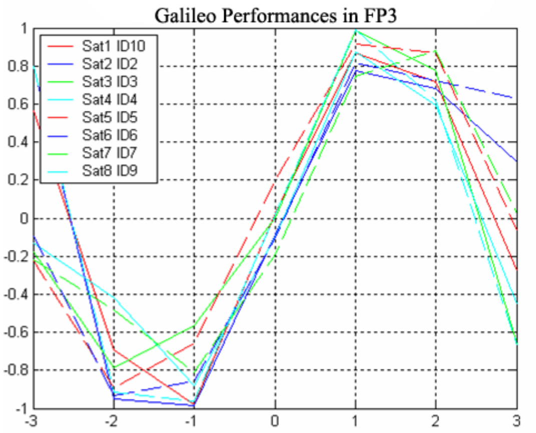

Fig. 7. Typical S-curve for FP3

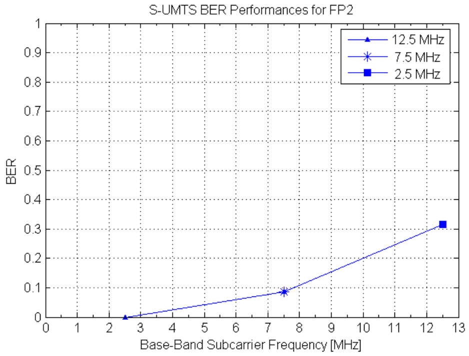

Fig. 8. S-UMTS Achieved BER for FP2

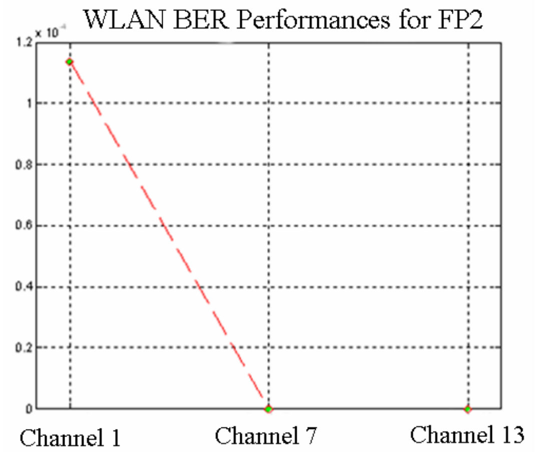

Fig. 9. WLAN Achieved BER for FP2

BER is higher and higher the more the S-UMTS channel is overlapped to the WLAN channel. But this performances are referred to the physical bits, without any information protection system. A further FEC coding, joined to typical ARQ included in packet networks could reduce the errors on higher levels.

In the other two FPs this problem is not present and they can be considered suitable solutions for the simultaneous acquisition also in presence of multipath fading and AWGN noise. In fact the BER obtained in these two cases can be considered negligible.

VI. CONCLUSIONS

In the present paper a novel method for integrating local and satellite communication and navigation systems has been presented. After a brief overview on the involved transmission systems, the proposed integration strategy based on a multi-stage super-heterodyne analog front-end has been presented. Results obtained in a completely simulated framework prove that the integration strategy implies a negligible cross-interference among the involved signals.

Future works will be devoted to introduce new standards and in a further reduction, in the already designed FPs, of the final bandwidth to be digitized.

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