Hybrid Galileo / UMTS Receiver Prototype for Mass-Market Applications

Guenter Heinrichs and Jón Winkel, *IfEN GmbH*
Christian Drewes, *Infineon Technologies AG*
Linus Maurer, *DICE GmbH & Co KG*
Andreas Springer, Rainer Stuhlberger and Christian Wicpalek, *Institute for Communication and Information Engineering, University of Linz*

Abstract—**This paper introduces a combined GNSS/UMTS receiver architecture. After a review of the state-of-the-art, a configurable GNSS/UMTS architecture is proposed. The investigated concept is based on a reconfigurable receive chain to prevent duplication of hardware, which will result in considerably lower costs. The biggest challenge in the design of Galileo receivers are the extremely tight noise figure (NF) requirements. Another key issue of integrated GNSS/UMTS receivers is the maximum tolerable UMTS transmit leakage injected into the Galileo receiver.**

I. INTRODUCTION

In the coming years the location capability of mobile phones or personal digital assistants (PDAs) will become by far market leading in the area of personal navigation applications. Market surveys forecast that the total global positioning system (GPS) receiver market for automotive and mobile phone applications could reach around 55 million units in 2005. About 73% of this market, corresponding to around 40 million units, is expected to fall into the category of mobile phone applications.

The planned global navigation satellite system (GNSS) modernization will undoubtedly further expand and improve applications for users in many fields by allowing combined use of such systems in hybrid receivers. These GNSS advances include the implementation of the Galileo system, now entering the development and validation phase under the cooperative management of the European Commission (EC) and the European Space Agency (ESA), as well as planned improvements in the U.S. counterpart, GPS.

Taking all this into account, an important step into the market for Galileo is the in-time availability of hybrid Galileo/GPS receivers in combination with cellular network positioning capabilities for consumer applications. This is the main idea behind the GAWAIN project – the development of an integrated GNSS/UMTS (Universal Mobile Telecommunications System) receiver, which provides seamless indoor/outdoor navigation and communication capability, using GPS/Galileo and UMTS for transportation and tourism (for mass market applications), combined with suited maps and information data services.

The paper will present an overview of the GAWAIN project. In order to reach the goal of an integrated GNSS/UMTS receiver, the task currently carried out is the architectural design with main emphasis on advanced UMTS radio frequency (RF)-Transceivers, advanced Galileo/GPS receiver concepts and the integrated navigation and communication concept. Preliminary results of these concepts will be presented.

II. SYSTEM OVERVIEW

To determine possible solutions of a GNSS/UMTS integration, first of all signal structures of Galileo on one hand and UMTS on the other hand have to be assessed. As already pointed out, both GNSS systems, GPS as well as Galileo, are based on DS-CDMA technology. The key parameters of the signal structures of Galileo and of UMTS will be briefly discussed within the next sections.

A. UMTS Signal Structures

Table I shows the paired frequency bands for UMTS Terrestrial Radio Access/Frequency Division Duplex (UTRA/FDD) mode [1].

TABLE I.
FREQUENCY BANDS OF THE UMTS/FDD

Operating Band	UL Frequencies UE transmit, Node B receive	DL frequencies UE receive, Node B transmit
I	1920 – 1980 MHz	2110 –2170 MHz
II	1850 –1910 MHz	1930 –1990 MHz
III	1710-1785 MHz	1805-1880 MHz
IV	1710-1755 MHz	2110-2155 MHz
V	824 – 849 MHz	869-894 MHz
VI	830-840 MHz	875-885 MHz

The UMTS air interface uses Wideband Code Division Multiple Access (W-CDMA), based on Direct Sequence Spread Spectrum (DS-SS). With DS-SS each user signal is spread by a user specific code. The most prominent advantage of DSSS-systems for cellular systems is its ability to eliminate the effect of multipath propagation by using a RAKE receiver in the mobile station. The choice of the user-specific codes employed for the spreading of the user signals greatly influences the overall performance of a CDMA system. The orthogonality among the spreading codes should be as large as possible. Otherwise the receiver will not be able to separate the different user signals due to multiple access interference (MAI).

The UMTS standard specifies a root raised-cosine (RRC) filter for pulse shaping, which determines to a large degree the spectral properties of the UMTS signals. The frequency response G_{rc} of the RRC-filter with roll-off factor α, transition type n (RRC for n=1, RC (raised cosine) for n=2) and chip duration T_C is defined by

$$G_{rc}(f)=\begin{cases} T_C & |f|<\frac{1-\alpha}{2T_C} \\ T_C\cos^n(\frac{\pi T_C}{2\alpha}\left(|f|-\frac{1-\alpha}{2T_C}\right) & \frac{1-\alpha}{2T_C}\le|f|\le\frac{1+\alpha}{2T_C} \\ 0 & |f|>\frac{1+\alpha}{2T_C} \end{cases} .$$

The pass-bandwidth of the above defined filter equals $(1+\alpha)/2T_C$, which results to 2.34 MHz for UMTS (α=0.22, T_C≈260 ns). In Fig. 1 the impulse responses of an RRC and an RC filter are shown. The RC response results due to the RRC-filtering in the transmitter and the receiver (matched filter). It is clearly visible, that only the RC response is ISI free (zero crossing exactly at multiples of T_C). An important issue for the design of the analog transceiver is the peak to average power ratio (PAR).

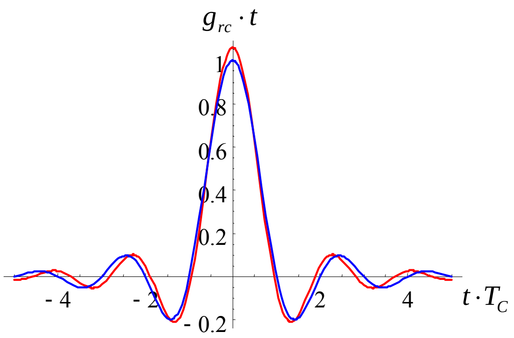

Fig. 1: RC and RRC (red line) impulse response

Due to the QPSK-like modulation format of the UMTS user signals and the fact that several user and control signals are summed up before converting them to the analog/RF-domain, the PAR can easily reach 9 dB with maximum of about 14 dB for the downlink (DL) and 4 dB with a maximum of about 6.5 dB for the uplink (UL).

B. *Galileo/GPS Signal Structures*

For consumer applications, the navigation signals transmitted at the L1 (1574.42 MHz) carrier will be the ones of highest commercial interest. Using only a single-frequency band, the receiver needs only one FE. Processing of another carrier frequency (for example, GPS L2C at 1227.6 MHz) would allow a precise correction of the ionospheric delays. Such an improvement, however, is unnecessary for consumer-oriented positioning accuracy requirements at the 10-20 meter level. Designing a single-frequency receiver is generally considered to be substantially easier and less costly than building a multiple-frequency receiver.

Three navigation signals will be available at L1 within the next few years. This includes the well-known GPS C/A code and the Galileo Open Service (OS) signals. Our working hypothesis for the Galileo OS signal foresees two components, one data-free and one data-bearing channel. Assumed parameters are shown in Table II. Further details of the Galileo signals can be found in [4].

TABLE II.
COMPARISON OF PROPERTIES OF GNSS SIGNALS AT L1 FREQUENCY

	Modulation	**Chip Rate**	**Bit/Symbol Rates**	**Code Structure**
GPS	BPSK(1)	1.023 Mcps	50 bps	Gold (1023)
Galileo OS-B	BOC(1,1)	1.023 Mcps	125 sps	4092
Galileo OS-C	BOC(1,1)	1.023 Mcps	Data-free	Tired code: 25 x 4092

The foreseen binary offset carrier (BOC) modulation of Galileo provides better multipath and receiver noise performance compared to the GPS binary phase shift keying (BPSK) modulation. However, acquisition and tracking of BOC signals requires new techniques. Several techniques have already been developed, among others the so-called bump-jumper [7]. In this project these techniques have been extensively simulated and are currently being implemented in FPGA prototypes.

In general, a BOC signal is formed in base-band by the product of two signal components: first, a non-filtered Pseudorandom Noise (PN) code having a chip rate R_C and two possible values -1 or 1 (NRZ PN sequence), then a sub-carrier, a non-filtered square wave signal[1] with frequency R_S, equal to or higher than R_C. A BOC(n,m) signal is such as $n = R_S / R_{C/A}$ and $m = R_C / R_{C/A}$, whereby n and m are not necessarily integers. We note $R_{C/A}$ as the GPS C/A code chip rate, i.e. $R_{C/A}$ = 1.023 Mcps. The effect of the square sub-carrier is to split the main lobe of the PN code spectrum into two lobes centered at $\pm 1/R_S$ from the central frequency, as shown in Fig. 2 schematically.

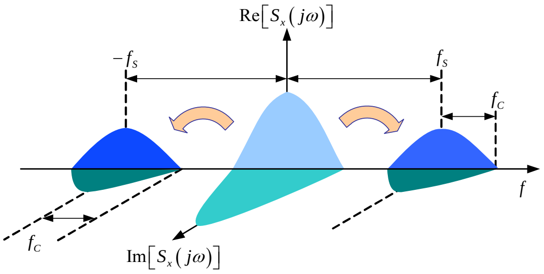

Fig. 2: Frequency Spectrum of a BOC Signal

The BOC expansion ratio, a, is defined by $a = n/m$. The spreading gain is $G = R_C / R_D$, where R_D is the data rate. When n and m are integers and $n = m$, the associated BOC(n,n) is a Manchester code. A BOC signal is usually generated in baseband and then modulates a RF carrier. Fig. 3 illustrates the L1 signal environment according to the current Galileo baseline plus current and future GPS signals.

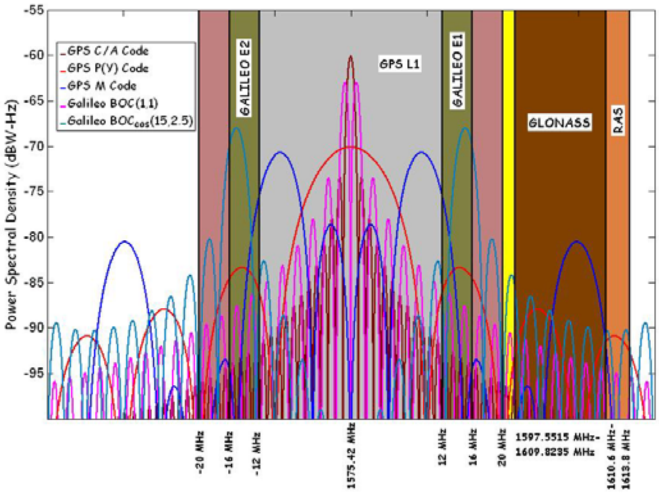

Fig. 3: Galileo L1-Frequency Spectrum

In general, each Galileo frequency will feature a pilot tone for coherent channel estimation. The signal is modulated onto in-phase and quadrature channels. The resulting symbol-rates range from 50 to 1000 sps. After forward error correction is applied the data-rates are in the range of 25 to 500 bps.

---

[1] If a sine-wave is used rather than a square-wave the signal is called a linear offset carrier (LOC) or sinusoidal offset carrier (SOC).

III. STATE-OF-THE-ART RECEIVERS

A. *UMTS Receiver Concepts*

The design of receiver concepts involves a number of challenges, including the analogue RF-FE as well as the digital back-end for base-band processing. Besides the demands for best performance, highest integration, and smallest form factor, there are also requirements for ultra low power consumption to achieve a long operation time. Those contradictions can only be solved by sophisticated architectural concepts.

Various RF-FE architectures are established, including heterodyne low intermediate frequency (IF) and direct conversion receivers (DCR) [5]. Heterodyne architectures are rarely found these days. The pre-dominant architectures use direct conversion between RF and base-band. The DCR architecture (also called homodyne architecture) is preferable, due to the fact that most of the gain and the channel selection are performed in the analog base-band section. This saves the first mixer and the first local oscillator (LO). Furthermore, the IF-amplifiers and the IF-filter (in most application an external SAW filter) can be replaced by low-pass filters and base-band amplifiers that are amenable to monolithic integration and can be designed to be reconfigurable for adaptation to different standards. Moreover, also the image problem of heterodyne receiver vanishes.

The DCR topology, however, entails several issues that do not exist or are not as serious in a heterodyne receiver [6]. The most severe problem are offset voltages which can corrupt the signal and, more importantly, saturate the following stages, since in a homodyne topology the down-converted band extends to zero frequency, and 3GPP compliant receivers need 80 dB gain. Most of this gain is contributed by base-band amplifiers. That means that even small DC offsets (in the range of several mV) at the mixer outputs may lead to DC levels sufficient to saturate the analogue-to-digital converters (ADCs). Another issue is flicker noise (or 1/f noise) which distorts spectral components around DC most. This is a critical problem for GNSS receivers, where the received signal levels are extremely low.

Within GAWAIN, a combined Zero IF/Low IF–Receiver, with a single reconfigurable front end, is proposed. With this concept it is possible to receive UMTS-signals with the Zero IF configuration and the Galileo signals with the Low-IF configuration with only one reconfigurable front end. Converting the received GNSS signal down to a low IF largely circumvents the distortions due to flicker noise. The structure of the receiver is shown in Fig. 4. Depending on what type of signal is received, the appropriate LO frequency is used and the analog and digital signal processing building blocks are properly configured.

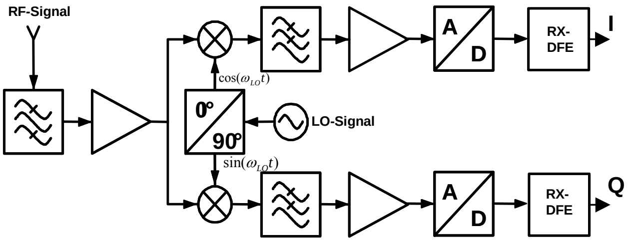

Fig. 4: Zero IF/Low IF Receiver Front-End

The main tasks of the digital front end (DFE) are channel selection and decimation. A cascaded integrator-comb (CIC) filter [8] is used to decimate the ADC output by an integer factor. Channel selection filtering and the final integer decimation are realized by wave digital filters (WDFs) [9]. A finite impulse response (FIR) filter is used to correct the pass-band droop caused by CIC and WDF and for pulse filtering according to the different standards. To correct the pass-band group delay ripple, a configurable all-pass (AP) filter is used. For the baseband interface it is necessary to receive the signals by an integer factor of the symbol and so a fractional sample rate conversion (FSRC) must be implemented. For receiving GNSS signals the DFE must include a digital down conversion from low IF to baseband.

The ADC mode, the filter coefficients and the fractional decimation factor of the FSRC must be configured accordingly to enable signal reception in either UMTS or GPS/Galileo mode.

B. *Combined Galileo/GPS Receiver Concepts*

The hybrid Galileo/GPS receiver architecture described hereafter is designed to meet the requirements of seamless indoor/outdoor navigation capability, using Galileo and GPS signals in combination with UMTS cellular network positioning.

Depending on the GNSS signal conditions, the navigation part depends more or less on the availability of so-called assistance data. The situation is sketched in Fig. 5. With decreasing carrier to noise ratio (C/N_0) the GNSS navigation becomes more and more degraded.

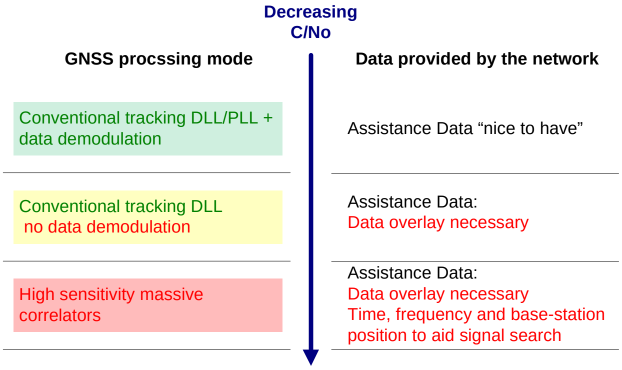

Fig. 5: Relation between GNSS processing modes and assistance data.

When the signal strength is high (green region), GNSS navigation can be performed autonomously. If assistance data are available in this case, they are nice to have since they can accelerate the initial position fix. In autonomous mode of operation, the receiver first performs code acquisition, followed by tracking, where it decodes the data overlay of the navigation message.

If the C/N_0 becomes degraded (severe multipath, tree foliage, etc.), the first process to fail is the tracking of the carrier phase (threshold at about C/N_0 = 29 dB-Hz). Unfortunately, the navigation data overlay can only be retrieved if the carrier is being tracked. Thus the navigation data overlay is required from the assistance data in this situation. However, the spreading code can still be tracked down to a C/N_0 of about 19 dB-Hz, using a non-coherent delay lock loop (DLL).

A further decrease of the C/N_0 will cause the DLL to loose lock, i.e. the tracking will break down at some point. In this case the receiver has to switch to the so-called single-shot mode. For weak-signal environments encountered in dense urban areas, however, the receiver relies on assistance data delivered through the UMTS network to aid signal acquisition. In this Assisted GPS (A-GPS) or in future A-GNSS mode (A-GPS/Galileo), particularly designed to meet the needs of location-based services, a receiver neither tracks the satellite signal nor decodes the navigation data overlay. Instead, it just performs a short "single-shot" measurement.

This single-shot measurement is similar to the acquisition process of traditional GPS receivers. Instead of tracking the signal in a conventional way, a large number of correlators simply locate the peak of the correlation function by interpolation. The aim of this process is to achieve synchronisation between the locally generated codes in the receiver and the spreading codes of all visible satellites. Clearly, while in this processing mode, the navigation data overlay cannot be retrieved from the satellite signal. The assistance data, such as defined by 3GPP, provide an estimate of currently visible satellites together with their Doppler frequency shift. They therefore significantly reduce the search space, such that mainly the code offsets of the GNSS signals are unknown. This, in turn, reduces the signal processing complexity. Furthermore, the assistance data contain the entire navigation data overlay of the satellite signals, so that data demodulation is not necessary.

An overview of the combined Galileo/GPS receiver is shown in Fig. 6. This architecture consists of a common RF-FE for all openly accessible GPS and Galileo signals in the L1-band. After sampling and ADC, the receiver performs parallel de-spreading. The received complex base-band signal is multiplied in parallel with the spreading codes of all visible satellites. For each satellite, the received signal is multiplied in parallel with the different code delay offsets. These products are then accumulated to complete the cross-correlation function.

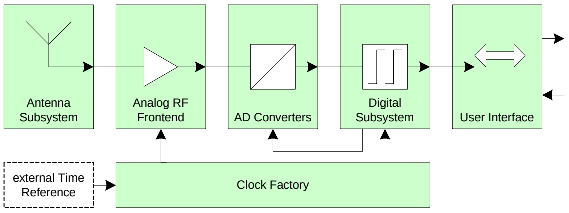

Fig. 6: Hybrid Galileo/GPS Receiver Concept

Supplementary measures for the BOC signals are necessary due to the multiple correlation peaks of the auto-correlation function. Carrier tracking is done using a phase-locked or frequency-locked loop (PLL or FLL). Coherent correlation combined with differential or non-coherent correlation will be done for the pilot and the data channel.

A hybrid Navigation solution will be implemented in order to make use of assisted data delivered through the UMTS network as well as to make use of the methods for positioning according to the 3GPP/UMTS specifications to supplement satellite-based navigation. For the tracking process and also for hardware acceleration of the A-GNSS single-shot measurements, the first digital hardware component after the ADC is an F_S /4 demodulator (F_S: sampling frequency) moving the signal frequency band down by a fixed unregulated value of a quarter of the sampling frequency. This demodulator is followed by a polyphase low-pass filter. The filter selects the desired signal band and performs a sub-sampling of the data by a factor of 2.

IV. CODE TRACKING DEGRADATION DUE TO UMTS TRANSMIT SIGNAL LEAKAGE

The continuous transmission during an active UMTS connection has to be considered carefully in the design of a configurable UMTS/NAVSAT transceiver. The allowed spurious emissions in the UMTS standard [2] do not account for the frequency bands allocated for Galileo as described in section II. Table III shows the general minimum spurious emission requirements for operation in frequency band I, which is solely considered for the work within GAWAIN.

TABLE III.
GENERAL SPURIOUS EMISSIONS REQUIREMENTS

Frequency Bandwidth	Measurement Bandwidth	Minimum Requirement
9 kHz ≤ f < 150 kHz	1 kHz	-36 dBm
150 kHz ≤ f < 30 MHz	10 kHz	-36 dBm
30 MHz ≤ f < 1000 MHz	100 kHz	-36 dBm
1 GHz ≤ f < 12.75 GHz	1 MHz	-30 dBm

According to Table III 3GPP compliant transmitters are allowed to have spurious emissions of up to -30 dBm measured within a measurement bandwidth of 1 MHz.

When the UMTS transmitter is located close to the Galileo/GPS receiver the ranging accuracy will be degraded. The achievable accuracy using a coherent DLL for the code tracking is given by

$$\sigma_{\text{celp}}^2 = \frac{B_L(1-0.25B_LT)\int_{-\beta/2}^{\beta/2} G_s(f)\sin^2(\pi f\Delta)df}{C/N_0\left(2\pi\int_{-\beta/2}^{\beta/2} fG_s(f)\sin(\pi f\Delta)df\right)^2},$$

with B_L being the noise bandwidths of the DLL in Hz, T the Integration time of the correlators in s, Δ the Correlator spacing in chip, $G_s(f)$ the spectrum of the signal, β the two-sided bandwidth in Hz, and C/N_0 the Carrier-to-noise ratio in dB/Hz.

The spectral density for BOC modulated signals is given by

$$G_s(f) = \frac{1}{nT_c}\left(\frac{\sin(\pi fT_c)\sin(n\pi fT_c)}{\pi f\cos(\pi fT_c)}\right)^2 \quad \text{for n even,}$$

$$G_s(f) = \frac{1}{nT_c}\left(\frac{\sin(\pi fT_c)\cos(n\pi fT_c)}{\pi f\cos(\pi fT_c)}\right)^2 \quad \text{for n odd.}$$

Therefore, the variance of the range is inverse proportional to C/N_0 as can be seen in the equations above. Thus, the acceptable ranging degradation of 10 % can be translated into a C/N_0 degradation of 0.83 dB.

To estimate the resulting degradation caused by the UMTS transmitter interference the following well-known equation can be used [3]:

$$\left(\tfrac{C_S}{N_0}\right)_{eff} = \frac{\tfrac{C_S}{N_0}\int_{-\beta_r/2}^{\beta_r/2} G_S(f)df}{\int_{-\beta_r/2}^{\beta_r/2} G_S(f)df + \tfrac{C_i}{N_0}\int_{-\beta_r/2}^{\beta_r/2} G_i(f)G_S(f)df}$$

C_s and G_s are the carrier power and spectrum of the Galileo/GPS signal, respectively. C_i and G_i are the carrier power and spectrum of the interferer, respectively. In this case this corresponds to the spurious emission requirements. To reduce the out of band interferences it is possible to apply filters with high enough out-of band suppression.

To obtain a first estimate of the tolerable interference we assume that the filter of the GNSS receiver is a “brick-wall” filter, i.e. the filter has 0 dB gain inside the operative band, and the interference from the UMTS terminal is wide-band with a constant power spectral density of n_I. Under the last assumption the power spectral density injected into the Galileo/GPS receiver by the UMTS transmitter can be derived in the following way:

$$\frac{C_{umts}}{N_0}\int_{-\beta/2}^{\beta/2} G_{umts}(f)G_S(f)df = \frac{n_I\beta}{N_0}\int_{-\beta/2}^{\beta/2}\frac{1}{\beta}G_S(f)df = \frac{n_I}{N_0}\int_{-\beta/2}^{\beta/2}G_S(f)df .$$

If we further assume that the RF-bandwidth β is that large that most of the signal spectrum is contained within the integration region, then the effective C_S/N_0 further simplifies to:

$$\left(\frac{C_s}{N_0}\right)_{eff} = \frac{\frac{C_s}{N_0}}{1+\frac{n_I}{N_0}} =: \alpha^2\frac{C_s}{N_0}$$

$$\Rightarrow \quad \frac{n_I}{N_0} = \frac{1}{\alpha^2} - 1 \qquad \Rightarrow \qquad \alpha^2 = \frac{1}{\frac{n_I}{N_0}+1}$$

The following Figures show the degradation of C/No (Fig. 7) and the degradation of the standard deviation of the pseudo range measurement (Fig. 8) as a function of the interfering UMTS power spectral density n_I.

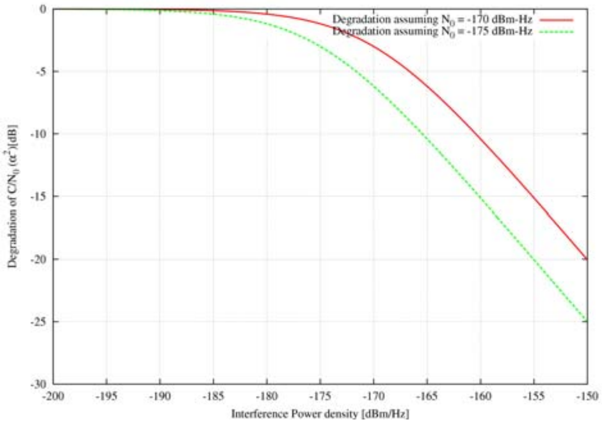

Fig. 7: Degradation of the carrier-to-noise ratio in dB as a function of the interfering UMTS spectral density (in dBm/Hz) for two values of assumed thermal noise density **(**N_0 = -170 dBm/Hz and -175 dBm/Hz).

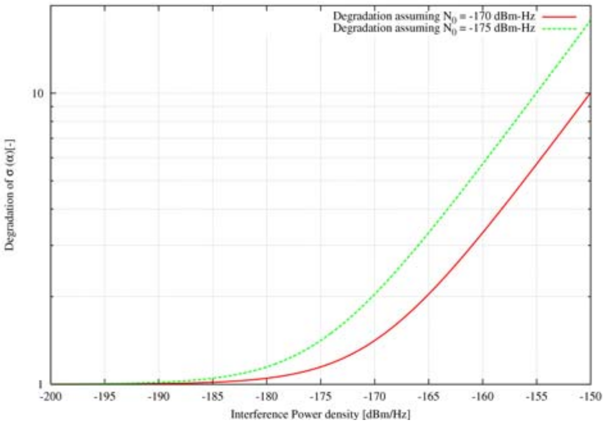

Fig. 8: Degradation of the pseudo-range accuracy as a function of the interfering UMTS spectral density (in dBm/Hz) for two values of assumed thermal noise density (N_0 = -170 dBm/Hz and -175 dBm/Hz).

Comparing the two figures above, we see that a degradation of for example 15 dB for C/N_0 will result in an increase of the standard deviation on the measurements (code and carrier) by a factor 6. To keep degradation of the standard deviation of the pseudo range measurement below 1.5 the UMTS transmit signal leakage into the Galileo/GPS band must not exceed the range of -175 dBm to -170 dBm.

V. MEASURED UMTS TRANSMIT SIGNAL LEAKAGE

We performed a leakage measurement on a UMTS demonstrator to verify if the UMTS transmitter leakage power can be suppressed to a value below -175 dBm. Fig. 9 shows the measurement setup. A signal generator (Rohde & Schwarz SMIQ) generates an UMTS signal, which is fed into the power amplifier (PA). To maximize the sensitivity of the spectrum analyzer (Rohde & Schwarz FSEA) a notch- and a SAW-filter were used. The notch-filter was tuned to the transmit frequency, whereas the SAW filter attenuated the harmonics of the transmit signal.

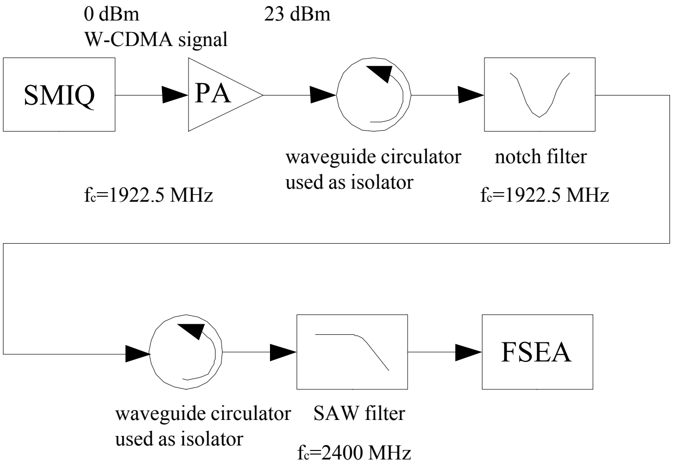

Fig. 9: Block diagram of the leakage measurement.

The measurement shows that the UMTS transmit leakage power level is around -133 dBm/Hz for all Galileo frequency bands except the E2-L1-E1 band (see Table IV). In the Galileo E2-L1-E1 band the level is around -129 dBm/Hz.

TABLE IV.
MEASURED NOISE FROM UMTS BAND I INTO THE GALILEO BANDS

Operating Band	Galileo Bandwidth	UMTS noise
E5a	1164 MHz < f < 1289 MHz	-133 dBm/Hz
E5b	1189 MHz < f < 1214 MHz	-132.7 dBm/Hz
E6	1260 MHz < f < 1300 MHz	-133.4 dBm/Hz
E2 – L1 – E1	1561 MHz < f < 1590 MHz	-129.3 dBm/Hz

Thus, a suppression of 37 dB to 42 dB is needed to keep the UMTS leakage power below -170 to -175 dBm/Hz. For the Galileo E2-L1-E1 band the needed suppression increases to approximately 41 to 46 dB.

Fig. 10 shows the frequency response of a UMTS-SAW filter, the minimum guaranteed attenuation according to the vendor specification and the three Galileo bands.

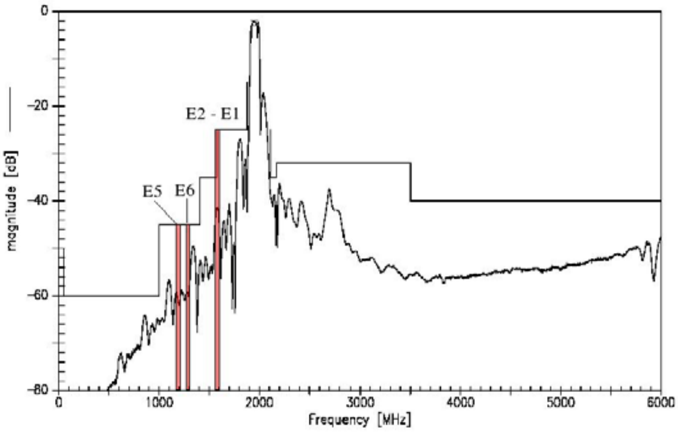

Fig. 10: Frequency response of the SAW transmitter filter

It is clearly visible that the attenuation of the SAW filter reaches a value of only 25 dB at the Galileo E2-L1-E1 band edge. With this suppression the UMTS transmit leakage reaches a level of -154 dBm/Hz, which is more than the tolerable level of -170 dBm/Hz. However, the SAW-filter suppression for the other Galileo bands is high enough to keep the UMTS transmitter leakage below -170 dBm/Hz. Thus, special measures like additional filtering must be foreseen for the Galileo E2-L1-E1 band.

VI. CONCLUSION

An important step into the market for Galileo is the timely availability of hybrid Galileo/GPS receivers in combination with wireless communications network positioning capabilities for consumer applications. This contribution shows the first development steps of the GAWAIN project based on advanced receiver concepts. The initial ideas regarding an integrated GNSS/UMTS receiver architecture were presented in order to meet the important requirements of seamless indoor/outdoor navigation. The next steps of the GAWAIN project will be related to the detailed hardware and software design of the integrated GNSS/UMTS receiver itself.

VII. ACKNOWLEDGEMENT

The investigations and developments of this work are carried out within the scope of the GAWAIN project, which is partly funded by the Directorate Information Society Technologies (IST) of the European Commission within the 5th Framework Program under IST Contract No. IST-2001-34227.

VIII. REFERENCES

[1] TS 25.213: “Spreading and Modulation (FDD)”, Release 6.0, *3GPP*, 2004.

[2] TS 25.101: "UE Radio transmission and Reception (FDD)", Release 6.4, 3GPP, 2004.

[3] John W. Betz; Effect of Narrowband Interference on GPS Code Tracking Accuracy, *ION NTM 2000*, Anaheim, CA, USA, January 2000.

[4] Hein, G., et al., "Performance of Galileo OS Signals on L1 – The New Optimized L1 OS Signal", *Proc. ENC-GNSS 2004,* Rotterdam, The Netherlands, May 2004.

[5] Springer, A., et. al., “RF System Concepts for Highly Integrated RFICs for W-CDMA Mobile Radio Terminals”, *IEEE Transactions on Microwave Theory and Techniques*, vol. 50, no. 1, January 2002, pp. 254-267 (invited).

[6] Abidi, A. A., “Direct-Conversion Radio Transceivers for Digital Communications”, *IEEE J. Solid-Sate Circuits*, vol. 30, no. 12, December 1995, pp. 1399-1410.

[7] Fine, P. and Wilson, W., “Tracking Algorithm for GPS Offset Carrier Signals”, *Proc. of the 12th International Technical Meeting ION GPS-99*, Nashville, TN, USA, September 1999.

[8] Eugene B. Hogenauer, “An Economical Class of Digital Filters for Decimation and Interpolation”. IEEE Trans. On Acoustic, Speech and Signal Processing, Vol. ASSP-29, No. 2, Apr. 1981.

[9] Alfred Fettweis, “Wave digital filters: Theory and practice”, Proc. IEEE, Vol.74, No.2, February 1986.