Multiband Simultaneous Reception Front-End with Adaptive Mismatches Correction Algorithm

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Abstract— **This paper addresses the architecture of multistandard simultaneous reception receivers and aims at improving the performance-power-complexity trade-off of the front-end. To this end we propose a single front-end architecture offering lower complexity and therefore lower power consumption. In order to obtain the same performance as the state of the art receivers, a light weight adaptive method is designed and implemented. It uses a mix of two digital implemented algorithms dedicated to the correction of the front-end IQ mismatches. A study case concerning the simultaneous reception of 802.11g and UMTS signals is developed in this article.**

Keywords - multistandard simultaneous reception; adaptive systems; least mean square methods

I. INTRODUCTION

The multiple functionalities characteristics imposed to the devices of the wireless telecommunications embedded domain have lead to the development of several dedicated standards. Depending on the type of the implemented service, a decision is made concerning the type of wireless telecommunication standard. For example the 2G standards are used for the voice communication, the WiFi is used for data transfer or a more general standard, like the 3G UMTS, is used for simultaneous data and voice transfer. Meanwhile, when implementing a multiservice simultaneous treatment device, the dedicated standards stack-up is generally chosen in order to have a good power-performance trade-off.

When designing a wireless telecommunications embedded device, the main goal is the good performance-power-complexity trade-off [1]. The state of the art of the multiband simultaneous receivers is using the technique of the dedicated front-end stack-up. If we take into account the parallelization level of this type of architecture, it becomes obvious the interest of designing a unique front-end capable of simultaneously receiving two signals [2].

Such a multiband simultaneous reception single front-end architecture was proposed in [3]. A comparative study between this architecture and the front-end stack-up [4] shows a power reduction of 20% in favor of the proposed architecture, as well as a complexity gain due to the use of fewer components (image rejection filters and frequency synthesizers). Meanwhile, while evaluating the performances of the proposed architecture, we can observe an important sensitivity to the IQ mismatches of the orthogonal translations [5][6]. In fact, as shown in [3], for a level of IQ mismatches going from zero to a

realistic level [7] (1° of phase imbalance and 0.3 dB of gain imbalance) the signal's quality can be degraded up to six times.

In order to mitigate the influence of the IQ mismatches on the reception quality of the useful signal, an adaptive digital algorithm was developed. This method is context-aware and is based on a mix between an iterative light weight algorithm and a more complex SMI [8] (Single Matrix Inversion) algorithm. By mixing these two methods, we take advantage of the low consumption of the LMS (Least Mean Squares) iterative algorithm [9] and of the fast convergence characteristics of the more power greedy SMI. The results show a perfect mitigation of the effects of the IQ mismatches by the adaptive algorithm. In other words, when integrating this algorithm, the proposed architecture has the same performance as the font-end stack-up.

This paper is composed of three parts. Following this introduction, section II describes the double IQ multistandard front-end architecture. Section III details the IQ mismatches and their impact on the quality of reception when using a double IQ front-end architecture. It is also dedicated to the implementation of the adaptive mismatches correction algorithm and to the results of the entire multiband simultaneous reception structure. Finally, conclusions of this study are drawn.

II. UNIQUE FRONT-END DEDICATED TO THE MULTIBAND SIMULTANEOUS RECEPTION

A. Double orthogonal translation front-end architecture

In wireless telecommunications, the integration of IQ baseband translation structures in the receiver chain has become a common procedure [5]. It is generally used in order to reduce the bandwidth of baseband signals treated by the ADC. The orthogonal frequency translation is also used to eliminate the image frequency signal during the translation steps of heterodyne front-end architectures [6]. This image frequency rejection technique consists in using two orthogonal frequency translations stages followed by a signal processing technique. It relies on the orthogonalization of the useful signal and the image frequency band signal during the translation from the RF to base band domain. Even though the spectrums of the two signals are completely overlapped after the first frequency translation, the orthogonalization allows the baseband processing to theoretically eliminate the image frequency component while reconstructing the useful one. Starting from this monostandard image rejection architecture, the double orthogonal translation technique is implemented in a novel multistandard simultaneous reception architecture [3].
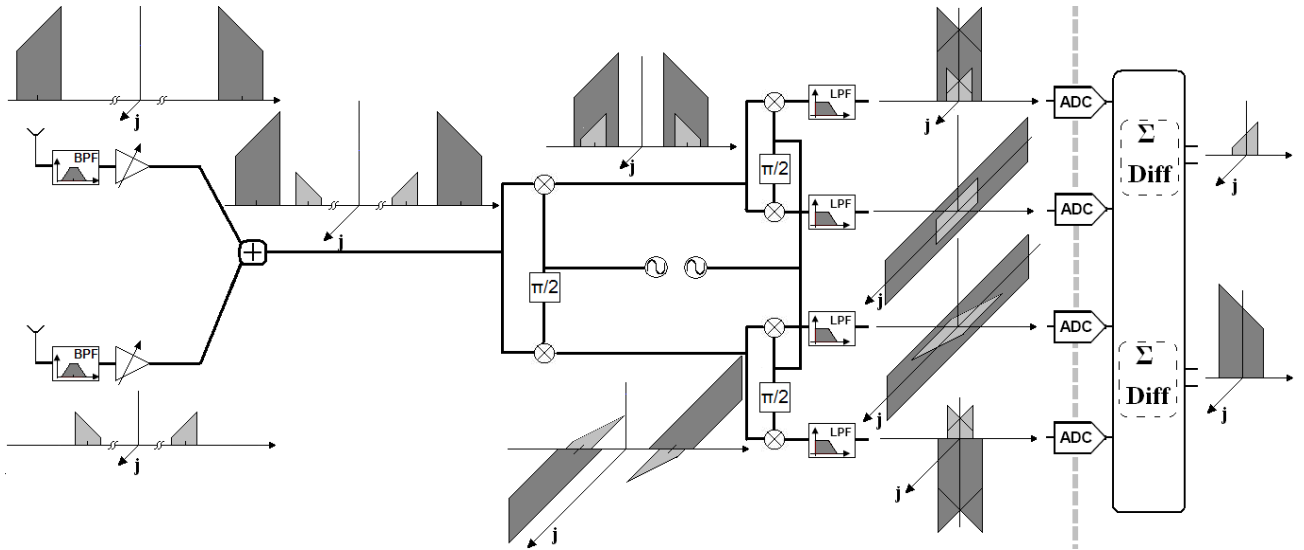
Figure 1.   Double orthogonal frequency translation front-end dedicated to the multistandard simultaneous reception.

This new architecture considers the image band signal as a useful signal. In order to fulfill this condition the local oscillator used during the first of the two orthogonal translations is ably dimensioned. Its frequency is set in such a manner that each of the two useful signals has a spectrum that occupies the image frequency band of the other.

The architecture and the spectrum evolution of such a receiver, able of treating simultaneously two standards, are developed in Fig. 1. As it can be observed, the parallelization of the input stages imposes the use of two dedicated antennas, two dedicated RF band filters and two dedicated LNAs. The gain control stage is realized by the input stages, each LNA being dedicated to the gain control of one of the signals. Once separately filtered and amplified, an addition of the two signals is made. The output is then processed by a double orthogonal translation structure. As the frequency of the first oscillator is chosen in such a manner that each of the two signals occupies a spectrum in the image band of the other, a complete overlapping of the spectrums can be observed in the intermediate frequency domain. After the second orthogonal frequency translation and after the digitalization of the four resulting signals, two basic processing chains are implemented. Each of them reconstructs one of the two useful signals, while rejecting the other.

The choice of the standards used for the study case is WLAN (802.11g) and WCDMA-FDD, representitive of the OFDM and CDMA techniques, as well as for the severe constraints they impose. Several simulation of the structure presented in Fig. 1 were performed using the ADS software provided by Agilent Technologies [3]. One of this series of simulations concerns the BER (Bit Error Rate) evolution of the two study case standards when being simultaneously received either by a structure using the heterodyne front-end stack-up architecture or by the proposed double IQ architecture. The blocks used during the simulations have the same typical metrics in both cases. The performance of the two architectures during the simultaneous reception of the two standards is almost identical. Meanwhile, these simulations do not take into account the orthogonal mismatches of the IQ translation blocks.This sensible matter concerning the mitigation of the IQ mismatches impact is amply treated in section III.

B.   *Comparative power-complexity study*

One of the most important issues when designing a radiofrequency front-end is the performance-power-complexity trade-off [1]. This section is therefore dedicated to a comparative overall power-complexity evaluation between the heterodyne front-end stack-up and the proposed architecture. Table 1 presents the results of a bibliographic study, concerning the state of the art of the blocks used by the two structures [4]. It summaries the numbers of elements used by each structure, as well as their individual power consumption along with the supply voltage. We can then conclude that the proposed architecture needs fewer components than the front-end stack-up as it doesn't need image rejection filters and it uses two times less frequency synthesizers. Therefore, the complexity comparison is favorable to the proposed structure, especially because the image rejection filters are not on-chip integrated elements. For our study case and for the power consumption levels presented in Table 1 the overall consumption comparison shows that our structure consumes

TABLE I.   BASIC ELEMENTS USED BY THE TWO ARCHITECTURES

	Stack-up	Double IQ	Power//Supply
	Quantity	*Quantity*	*mW//V*
LNA UMTS	1	1	7.2//1.8
LNA WLAN	1	1	8//1
RF Filter	2	2	-
IF Filter	2	0	-
Mixer	6	6	5.6//-
RF-Frequency Synthetizer	2	1	42//3
IF-Frequency Synthetizer	2	1	20//-
Baseband-Amplifier WLAN	2	4	10//-
Baseband-Amplifier UMTS	2	0	5//-
ADC WLAN	1	4	12//2.5
ADC UMTS	2	0	11//1.8

216 mW while the state of the art architecture uses 284 mW. This means a 20 % of gain in favor of the single front-end structure assessed in this paper.It can be observed that the power reduction comes essentially from the use of two times less frequency synthesisers, while using the same number of other components.

III. ADAPTIVE ALGORITHM DEDICATED TO THE CORRECTION OF ORTHOGONAL MISMATCHES

This section is addressing the impact of the orthogonal mismatches on the quality of the useful signal in a multiband double orthogonal translation structure. It also presents a dedicated adaptive MMSE (Minimum Mean Square Error) algorithm used to mitigate this impact.

A. IQ mismatches

The double orthogonal translation technique allows a theoretically perfect rejection of the image band signal for a case study where the quadrature mounted mixers are perfectly matched – no phase or gain mismatch. Nevertheless, design and layout defaults, such as different line lengths between the two branches and non identical gain of the mixers, generate phase and respectively gain mismatches [5]. Therefore, in a real case scenario where the gain and the phase mismatch can go up to 0.3 dB and respectively 1 degree [7], the image band signal is not completely rejected. In fact the metric used to quantify this rejection, the image rejection ratio (IRR), depends on the gain and phase mismatches between the two branches of the IQ translation structures [6]. While evaluating the IRR of the double orthogonal translation, we choose to ignore the IQ mismatches of the block used to translate the signal in the base band domain because of the low frequency of their input signal. Supposing that the first IQ stage has a gain mismatch ΔA and a phase mismatch $\Delta\theta$, the final IRR can be modeled by the equation:

$$ IRR\,(dB) = 10\log\left[\frac{1+(1+\Delta A)^2 + 2(1+\Delta A)\cos(\Delta\theta)}{1+(1+\Delta A)^2 - 2(1+\Delta A)\cos(\Delta\theta)}\right] \quad (1) $$

For the levels of phase and gain mismatch of 1° and 0.3 dB respectively, the theoretical IRR rejection is 28.97 dB. In the followings we assume that the mismatches of the orthogonal translation blocks integrated in the multiband simultaneous reception architecture can reach this level. Therefore the 28.97 dB of IRR represent the minimum rejection that the complementary signal undergoes when one of the signals is received. For our study case - simultaneous reception of UMTS and WLAN – this level of rejection is clearly not sufficient. In fact, the worst case scenario implies a WLAN signal having a -80 dBm power level and a UMTS signal with a -30 dBm power level at the antenna. For this case we consider an automatic gain control stage (AGC) that amplifies of 30 dB the signal on the WLAN dedicated branch and of 0 dB the signal on the UMTS dedicated branch. For these given conditions the WLAN quality of service imposes that the front-end rejects the complementary UMTS signal under the power level of the thermal noise on the WLAN dedicated branch. This means an IRR of 41 dB that has to be realized by the double orthogonal
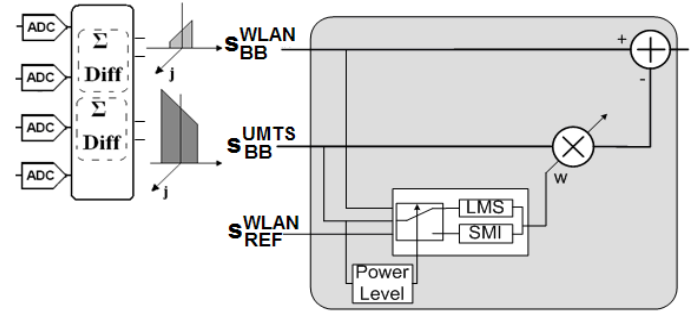

Figure 2. Digital context-aware method used to mitigate the influence of IQ mismatches in a double orthogonal translation receiver.

translation structure in order to have the same performances as the front-end stack-up architecture. For the scenario presented above, several simulations show a normalized WLAN BER that can go from 1 to 6 when the phase and gain mismatch go from 0 to 1° and 0.3 dB respectively [3].

B. Adaptive digital Algorithm

In order to mitigate the influence of the IQ mismatches on the quality of the signals processed by the proposed receiver structure, a digital adaptive method has been implemented. It is composed of a mix between a light power consumption iterative LMS algorithm and a power greedier SMI algorithm. The scenario considered here involves a continuous reception of a WLAN signal while the UMTS signal at the antenna has a random power level. It is also supposed that the IQ mismatches have a slow variation during the reception.

Based on (1) and on the system model presented in [3], the two signals s_{BB}^{WLAN} and s_{BB}^{UMTS}, obtained after the digital demodulation presented in Fig. 1, can be modeled by:

$$ s_{BB}^{WLAN} = \alpha \cdot s_{RF}^{WLAN} + \beta \cdot s_{RF}^{WLAN\,*} \quad (2) $$

$$ s_{BB}^{UMTS} = \alpha \cdot s_{RF}^{UMTS} - \beta \cdot s_{RF}^{WLAN\,*} \quad (3) $$

where s_{RF}^{WLAN} and s_{RF}^{UMTS} are the baseband translation of the RF signals at the output of the automatic gain control stages. The α and β coefficients depend directly of the gain mismatch ΔA and of the phase mismatch $\Delta\theta$:

$$ \alpha = \frac{1 + (1+\Delta A)\cdot e^{-j\Delta\theta}}{2} \quad (4) $$

$$ \beta = \frac{1 - (1+\Delta A)\cdot e^{j\Delta\theta}}{2} \quad (5) $$

The α/β ratio is directly proportional with the IRR, as it represents the attenuation of the image band signal compared to the useful baseband signal. In the followings, we choose to focus on the reception of the WLAN signal and to consider the UMTS signal as interference, the UMTS dedicated method being analog to that used for the WLAN. For this study case, the adaptive correction method is estimating β by a weight w.
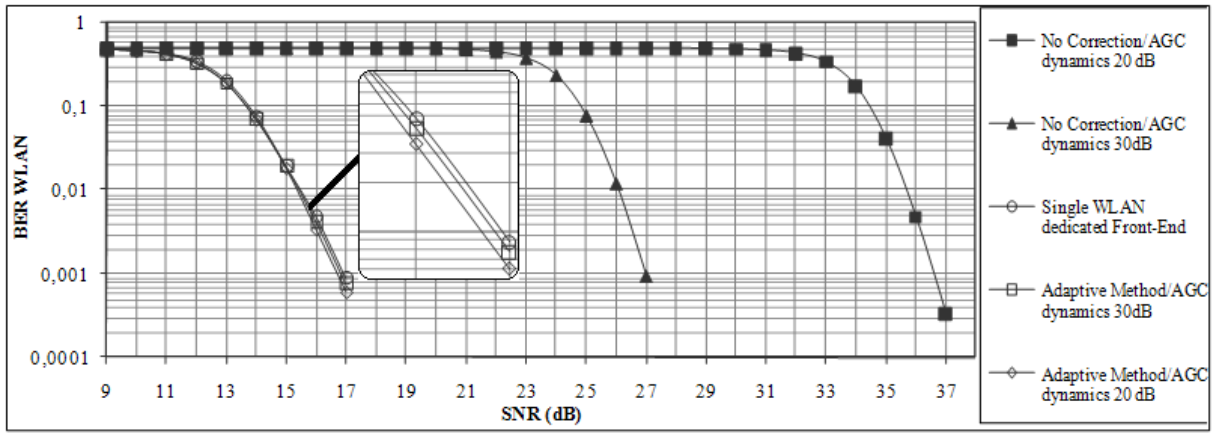
Figure 3. WLAN BER evolution during a multiband simultaneous reception for different values of the gain control and for two configuration depending on the implantation of the adaptive IQ mismatches corection method.

In order to do this estimation it uses the two signals from the output of the digital demultiplexing stage and a known training sequence – two long preamble symbols of the WLAN signal. Once the estimation is finished, the weight is multiplied with the s_{BB}^{UMTS} signal and the result is subtracted from s_{BB}^{WLAN}, as shown in Fig.2. In this manner, the interfering s_{RF}^{UMTS} component of the s_{BB}^{WLAN} signal becomes insignificant.

The estimation is realized by a context-aware method using either a LMS or a SMI algorithm [8][9]. The LMS algorithm is an iterative method that uses the MMSE technique in order to minimize the difference between the received signal and a training sequence. For our study case, each of the iterations implies the following operations:

$$s_{OUT}(n) = s_{BB}^{WLAN}(n) - w(n) \cdot s_{BB}^{UMTS}{}^{*}(n)$$
$$error(n) = s_{OUT}(n) - s_{REF}^{WLAN}(n) \qquad (6)$$
$$w(n+1) = w(n) + \mu \cdot error \cdot s_{BB}^{UMTS}{}^{*}(n)$$

where s_{REF}^{WLAN} is the training sequence of the WLAN signal and μ is the algorithm step size. A trade-off has to be made when choosing μ because a large step size leads to a bad estimation precision while a small one leads to a slow convergence of the algorithm. Simulations show that the algorithm manages to mitigate the influence of IQ impairments. In addition, for a continuous WLAN and UMTS simultaneous reception, LMS manages to adapt to the slow IQ impairments variation.

The major drawback of this algorithm is the small precision of the evaluation to the absence or to the week power level of the complementary UMTS signal. But this is not a major problem for this input power level case. The real inconvenient is the fact that, if the power level on the UMTS dedicated branch changes from -107dBm to a significant level, the LMS algorithm has to converge once again in order to offer a good precision. Simulation shows that, in order to converge to an estimation of β allowing a supplementary 20 dB of IRR, the algorithm needs up to 10000 samples. Knowing that the two WLAN preamble symbols provide 128 samples of training sequence per frame, it takes up to 80 frames for the algorithm
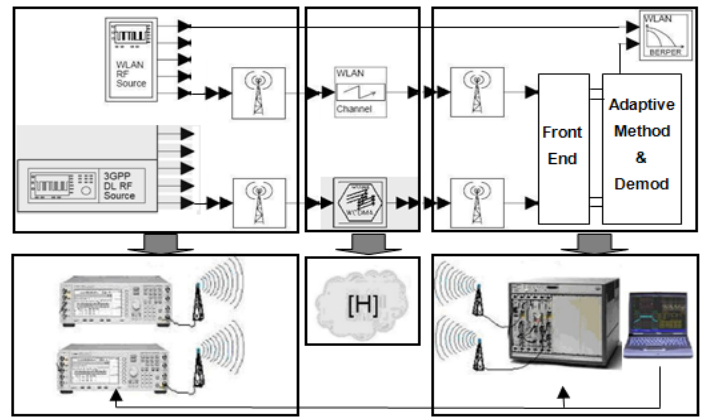

Figure 4. Radiofrequency platform integrating two front-end models dedicated to the multiband simultaneous reception: the stack-up architecture and the proposed double orthogonal translation structure.

in order to grant a sufficient precision. We conclude that this algorithm can provide an adaptive mitigation of the influence of the IQ impairments, but it cannot manage an arbitrary power variation of the complementary signal.

In order to overcome this sensitivity of the LMS algorithm to the absence of signal at the output of the UMTS dedicated branch, a solution is the use of this adaptive algorithm only when the complementary signal sbb_{UMTS} has certain power level. But this means that during the absence of the UMTS signal, the algorithm can not adapt the w estimation to the variation of the IQ mismatches. Therefore, each time the UMTS signal power changes from an insignificant to a consistent level, the LMS has to converge in order to evaluate once again the IQ mismatches that could have changed during the absence of the UMTS signal. The solution that has been choose in order to adapt to this UMTS signal fluctuating power level is to use a SMI algorithm [8]. The advantage of this algorithm is its estimating performance when using a relatively small training sequence – 128 samples of the two WLAN preamble symbols for our study case. Compared to the continuous estimation approach of the LMS algorithm, the SMI has a block adaptive approach. Instead of using an iterative approach in order to estimate w, it uses the entire training

sequence for a matrix inversion operation. Simulations show that a training sequence of 128 samples is sufficient for the SMI algorithm in order to realize a supplementary 20 dB rejection of the UMTS complementary signal. However, the main drawback of this type of algorithm is its complexity and power consumption compared to the LMS. By consequence, the optimum solution for an adaptive IQ mismatch correction algorithm is a context-aware method depending on the power level P_{UMTS} of s_{BB}^{UMTS}:

- If the current P_{UMTS} is bigger than a choosen detection level, the decision on which algorithm to be activated depends on the P_{UMTS} level of the previous frame:

  o If it was smaller than the detection level, the SMI is activated in order to find the optimum w weight by using only one 128 samples training sequence.

  o If it was bigger than the detection level, the LMS algorithm is activated in order to be able to adapt to the IQ mismatches slow variation.

- If P_{UMTS} is smaller than a trigger level, none of the two algorithms is activated in order to estimate the w weight.

This context-aware adaptive method was implemented using Matlab software. In order to have more eloquent results, it was incorporated in a co-simulation platform which also includes the UMTS and WLAN transmission sources, as well as the model of the analog double orthogonal front-end. This platform is composed of two E4438C Signal Generators, of a 89600 Vector Signal Analyzer and it uses the Advanced Design System software, all provided by Agilent technologies [10]. The measurements were made by using a line of sight channel close to the AWGN conditions. During this measurements campaign we focused on the WLAN reception while the UMTS signal is considered as interfering. In order to validate the context awareness of the adaptive method, the source generating the interfering signal is arbitrarily turned on. The power level for this source is chosen in such a manner that the UMTS interfering signal has a power level of -30 dBm at the input of the receiver. Fig.3 presents several BER evolutions as function of the WLAN signal's SNR (Signal to Noise Ratio). These results reveal that, for different levels of the gain control and therefore of the interfering signal, the influence of the IQ mismatches is mitigated by the digital adaptive method. In fact the performance of a single WLAN dedicated front-end and that of the proposed multiband simultaneous reception structure are practically identical when the adaptive method is used. In the same time, we can observe a shift between the curves characterising the BER evolution when the adaptive method is implemented and when the multiband receiving structure doesn't use any digital correction method. This shift can go up to 20 dB, depending on the attenuation of the UMTS interfering signal by the gain control stage.

Finally the proposed adaptive method manages to offer up to a supplementary 20 dB of the complementary signal rejection when implemented in a multiband double orthogonal translation structure. In other words, our structure has the same performance as the front-end stack-up structure [2], independently of the IQ mismatches.

IV. CONCLUSIONS

This article is focused on a novel context-aware adaptive method dedicated to the mitigation of the IQ mismatches impact in a multiband double orthogonal translation front-end. The theoretical results related to this digital processing technique were validated by measurement. During this measurement campaign, a performance comparative study is realized between the front-end stack-up receiver and the single front-end multiband receiver integrating this digital adaptive method. For this purpose, the radiofrequency platform is integrating a real communication channel and realistic models of the two multiband simultaneous reception front-ends compared here. The reception measured performances are practically identical when the two structures are used. This implies that, when integrating the adaptive method, the proposed single front-end architecture has the same performance as the dedicated front-end stack-up. If we also take into account the complexity gain as well as the 20% of power reduction, the proposed receiver structure offers a significantly improved performance-consumption-complexity trade–off when compared to state of the art of the multistandard simultaneous reception architecture.

The follow-ups of this work would consist in a power-performance study concerning the length optimization of the training sequence used by the SMI algorithm.

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