A DECT/BLUE TOOTH MULTI-STANDARD FRONT-END WITH ADAPTIVE IMAGE REJECTION IN 0.18 μm CMOS

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ABSTRACT

A DECT/Bluetooth multi-standard front-end with adaptive image rejection is described. The front-end is designed and simulated in 0.18 μm CMOS technology. Using a multi-band LNA with zero external components full integration of the front-end is achieved. In high image-reject DECT mode it has a $\text{NF}$ of 10 dB consuming a current of 47 mA, while in low image-reject DECT mode a $\text{NF}$ of 5 dB is obtained with a current of 39 mA. In high image-reject Bluetooth mode the front-end achieves a $\text{NF}$ of 10 dB consuming a current of 39 mA and in low image-reject Bluetooth mode it has a $\text{NF}$ of 5 dB using a current of 31 mA. Applying adaptive image rejection the power consumption is reduced 20%, the $\text{NF}$ is improved 50% and the gain improves 30%, while the chip area is negligibly increased compared to the total chip area occupied by the front-end.

1. INTRODUCTION

The wireless market is changing very rapidly. Pushed by customer requirements new standards for wireless communications are emerging fast creating a congestive radio environment with a lot of interference. So far, most of the research in the area of wireless communications is directed to obtain cost-effective front-ends dedicated to one standard, but now in order to reduce costs by hardware reuse and to increase functionality and flexibility of a front-end, designers try to develop solutions for multi-standard front-ends. Considering the frequencies used by the DECT standard (1.9 GHz) and Bluetooth standard (2.4 GHz), and the fact that their system specifications are similar, it is possible to design a DECT/Bluetooth multi-standard front-end.

Nowadays, receivers operate in very occupied radio environment. Bluetooth is located in Industrial Scientific Medical (ISM) band at 2.4 GHz, which is a free band. Thus, the level of the image signal can vary significantly. From one side the ability to provide a high image rejection ratio ($\text{IRR}$) together with high selectivity and sensitivity is crucial for a high reception quality. From the other side a front-end solution, that satisfies the specifications under the worst case conditions is very expensive. By applying adaptive image rejection, the power consumption can be reduced and a better front-end sensitivity can be achieved. Minimization of the power consumption reduces the battery size and provides a longer talk time, while better sensitivity improves the reception quality. In the case of DECT at 1.9 GHz, when high intermediate frequencies are used (in the case of high data rates and in order to reduce the contribution of the flicker noise) a high image rejection is required. By applying adaptive image rejection, a DECT front-end can handle different data rates.

Although a DECT/Bluetooth multi-standard front-end with adaptive image rejection brings the benefits as functionality, flexibility, reduction of power consumption and improvement of sensitivity, it will introduce some costs. For example: lower performance, more complexity, larger chip area and increased time to market. Therefore, this paper also investigates cost-effectiveness of the multi-standard front-end with adaptive image rejection by comparing the benefits with the costs. An analysis on the system level can not provide a definite answer. Hence, the analysis must be performed on the circuit level as it is done in this paper.

This paper is organized as follows. Architecture considerations are presented in section 2. In section 3, the design of a multi-band LNA is presented. The design of a wide-band complex mixer is presented in section 4. Cost-effectiveness is discussed in section 5.

2. ARCHITECTURE CONSIDERATIONS

The first step towards an implementation is to find a front-end architecture that has enough flexibility to accommodate the requirements of selected standards and to provide a high image rejection. A double-quadrature low-IF architecture is suitable for this purpose [1]. Problems like DC-offsets and integration of a high-frequency image-reject filter, typical for zero-IF and superheterodyne architectures, are avoided. A modified double-quadrature low-IF architecture that provides adaptive image rejection is presented in Fig.1.

![Figure 1. A double quadrature low-IF architecture with adaptive image rejection](image-url)
front-end. They can be considered as a second stage of the low noise amplifier (LNA). RF buffer 3 is a dummy circuit and its purpose is to provide symmetrical load for RF polyphase filter. Otherwise, the mismatch between I and Q paths will be too high and the IRR will be significantly degraded. The image level estimator has the task to estimate the level of an image signal and to generate the control signals E1, E2 and E3. If the image signal is strong then signal E2, E3 and E1 will enable operation of the RF buffer1, MX3 and MX4 and disable the operation of the RF buffer 2. In this way the RF polyphase filter will be in the signal path and it increases the IRR. If the image signal is weak then signals E2, E3 and E1 disable RF buffer1, MX3, MX4 and enable operation of the RF buffer2. In this way a lower IRR is obtained but the power consumption is reduced and better sensitivity is achieved because the RF polyphase filter is bypassed. The control signal E1, E2 and E3 can be also generated externally avoiding the need for the image level estimator. In that way static adaptivity will be obtained and can be used to achieve high IRR for Bluetooth and low IRR for DECT combined with increased sensitivity and reduced power consumption.

The performance (NF, gain, IIP3, IRR) of the receiver is mainly determined by the RF front-end performance. Hence, in this paper the low frequency building blocks as IF polyphase filter, VGA, ADC and image level estimator will not be considered

3. MULTI-BAND LNA

The first step towards a high performance multi-band LNA is topology selection. After a literature study, it is concluded that the lowest NF can be obtained with the LNA based on the inductively-degenerated common-source stage. The next step in the LNA design is to clearly specify design goals. The first is to find the minimum NF that a LNA can achieve with a certain power consumption, the second is to find a way to realize multi-band operation without degrading the LNA performance, compared to a single-band LNA, and the third is to make the trade of between a minimum NF and a full integration. Such fully-integrated multi-band LNA is represented in Fig. 2.

![Multi-band LNA for DECT and Bluetooth](image)

For simplicity the noise figure analysis is done for a single-ended inductively-degenerated common-source LNA, while the considerations are also valid for a differential version. The noise factor (F) of a single-ended inductively-degenerated common-source LNA can be approximated by:

\[
F = 1 + \frac{1}{g_mR_d} \left( \frac{n}{\sqrt{n+1}}Q_{Ls} + \frac{1}{\sqrt{n+1}}Q_{Lg} \right) + \frac{g_{ds}}{g_m} \cdot \frac{1}{n+1} + \frac{1}{(n+1)g_mR_d}
\]

(1)

where \(R_d\) is the source resistance (\(R_d = 50 \, \Omega\) and \(g_{ds}\) is zero bias drain conductance. The finite quality factors of the inductors \(L_g\) and \(L_s\) (\(Q_{Lg} = \omega L_g/R_g\) and \(Q_{Ls} = \omega L_s/R_s\), where \(R_g\) and \(R_s\) are series parasitic resistances of the inductors \(L_g\) and \(L_s\)), the channel thermal noise of the transistor \(M_1\) and the thermal noise from the load resistor \(R_q\) are taken into account. The factor \(n\) is the ratio of the inductances \(L_g\) and \(L_s\): \(n = \frac{L_g}{L_s}\). When analyzing (1), an important remark can be made: for a given \(g_m\), which corresponds to a certain power consumption, there is a value of \(n (n_{opt})\) that gives a minimal noise factor \(F_{min}\).

The fact that an external gate-source capacitance \(C_{gs ext}\) is used to obtain input matching (see Fig. 2) can be exploited to obtain multi-band operation. The idea is to use the same coils \((L_g\) and \(L_s\)), the same transistors \(M_1\) and \(M_2\), \(M_3\), \(M_4\) and by changing the value of the external capacitance to accommodate the LNA to operate in DECT mode or in Bluetooth mode. The reuse of coils has an advantage because in this way chip area is saved. Transistor \(M_5\) operates as a switch. It is open in DECT mode and closed in Bluetooth mode. When it conducts, it operates in the triode region. In order to reduce the resistance of \(M_5\) when it conducts, and its contribution to the noise factor, \(M_5\) is made large \((W/L = 100/0.18)\) and the highest voltage equal to the voltage supply is applied on its gate. The values of capacitors \(C_1\) and \(C_2\) must be calculated in order to satisfy matching conditions for DECT and Bluetooth. It is necessary to take into account the capacitance of the transistor \(M_5\) when it does not conduct. By the simulations it was determined that \(C_{M5} = 119 \, \text{fF}\), which originates from the gate-source and gate-drain overlap capacitances.

First, the LNA is designed to operate in DECT mode because DECT specifications are higher than Bluetooth specifications. Using a current of \(I = 16 \, \text{mA}\), \(V_{dc1,DECT} = 700 \, \text{mV}\), \(V_{opt} = 14\), \(L_g = 8 \, \text{nH}\), \(L_s = 0.57 \, \text{nH}\) and \(C_{gs,ext} = 462 \, \text{fF}\) a rather low \(NF_{min}\) of 1.3 dB can be obtained. The problem is \(L_s\), which can not be implemented as a bond-wire. Taking into account the package size and the die position in the package, inductances of approximately 3 nH can be realized as a bond-wire. The new value of the parameter \(n (n_{band})\), is obtained: \(n_{band} = 2.5\). Now, with \(n = n_{band}\), the following values for the design parameter are obtained: \(L_g = 3 \, \text{nH}\), \(L_s = 1.2 \, \text{nH}\) and \(C_{gs,ext} = 1332 \, \text{fF}\). With these design parameters a \(NF_{dec} = 2 \, \text{dB}\) is simulated, which is for 0.7 dB higher than \(NF_{min}\). This is the cost that is paid for the full integration. The operation in Bluetooth mode is obtained by applying the biasing voltage \(V_{dc1,Bluetooth}\) of 600 mV, \(I = 8 \, \text{mA}\) and \(C_{gs,ext} = 703 \, \text{fF}\). Combining \(C_{gs,ext} = 1332 \, \text{fF}\), \(C_{gs,ext} = 703 \, \text{fF}\) and \(C_{M5} = 119 \, \text{fF}\) the values for the capacitances \(C_1\) and \(C_2\) are calculated.

| Table 1. Simulation results for DECT/Bluetooth (BT) multi-band LNA |
|----------------|----------|----------|---------|---------|--------|-------|
|                | DECT     | BT       | I (mA)  |
| \(NF (\text{dB})\) | 2.25     | 2.2      | -16     | 16      |
| \(G (\text{dB})\)   | 17       | 15       | -2.7    | -14     |
| \(IIP3 (\text{dBm})\) | 1.7     | 2.7     |         |         |

Using the circuit simulator SpectreRF, the simulation results presented in Table 1 are obtained for the stand-alone multi-band LNA.
The quality factor of the integrated inductor $L_i$ is taken to be 5 and for the bond-wire inductor $L_g$ 10 at a frequency of 2 GHz, which are the realistic values considering the state of the art. Comparing the simulated $NF$ of the multi-band LNA in DECT mode with $NF_{dect}$ of 2 dB when the LNA works only for DECT, the $NF$ deterioration due to $M5$ is only 0.25 dB. Besides that, the LNA uses half power when it operates in the Bluetooth mode.

4. WIDE-BAND COMPLEX MIXER

Fig. 3 shows the block diagram of the wide-band complex mixer.

![Block diagram of a wide-band complex mixer](image)

The function of the complex mixer is to down-convert a high frequency RF signal to a lower intermediate frequency (IF), to provide a gain and a high image rejection. Since it is used in the DECT/Bluetooth multi-standard front-end, it has to provide a high $IRR$ in the band $1.8–2.5$ GHz. Thus, it is called wide-band complex mixer. The complex mixer determines a maximal image rejection that can be achieved in the double-quadrature low-IF architecture and it draws the largest part of the total current consumed by the front-end. Hence, it is considered as the core of the double-quadrature low-IF architecture. The design goal is to design a complex mixer that can provide a high image rejection with a performance ($NF$, gain and $IIP3$) similar to a common stand-alone single mixer. The increased power consumption compared to a common stand-alone single mixer is a consequence of a provided high image rejection and care is taken for the minimization of the power consumption at the circuit level.

The first step in the complex mixer design is to select a topology for a single mixer that can provide a low $NF$, a high gain and a good linearity with a low power consumption. In [2], it was shown that the folded switching mixer with current reuse is suitable mixer topology for this purpose. It is represented in Fig. 4. In this mixer topology the stage that represents voltage to current (V-I) converter and only a small amount of the DC current flows through the switching transistors, thus allowing the use of large load resistors. This is the main advantage over a conventional Gilbert cell mixer. The current reuse principle is an efficient way to have a high gain and a low noise figure with a low power [3].

![Folded-switching mixer with current-reuse](image)

In this mode, they help to reduce voltage variations at the point A. The simulation results for a stand alone mixer are given in Table 2. During the simulations the frequency of the RF signal is chosen to be 2.5 GHz, the frequency of the local oscillator is set to 2.498 GHz and local oscillator voltage swing of 600mV ($V_{lodc}$) is applied. The $NF$ is measured at intermediate frequency ($IF$) of 2 MHz and with a 50 Ω source resistance.

In order to obtain a high image rejection in the band $1.8–2.4$ GHz, polyphase filters are used as quadrature signal generator in RF and LO paths. They are implemented as two stage passive RC polyphase filters [4]. This choice is made because the implementation is straightforward and they have a very good linearity. The maximum image rejection ($IRR_{tot}$) that can be achieved is equal to the sum of the image rejection achieved in the RF path ($IRR_{RF}$) and LO path ($IRR_{LO}$).

$$IRR_{tot} = IRR_{RF} + IRR_{LO}$$ (2)

$IRR_{RF}$ and $IRR_{LO}$ depend on the mismatch between the resistors and the capacitors and on the spread of their absolute values. When performing statistical simulations it was noticed that mismatch limits achievable image rejection and spread in the absolute value shifts an image rejection curve to the left or to the right with respect to the frequency axis. In order to cope with this the RC polyphase filters are initially designed to cover the band $1.4–3$ GHz. In [4] it was shown that with the two stage RC polyphase filter, assuming the spread in the absolute value of 20% for resistors and 16% for capacitors and a mismatch of 1%, an $IRR$ of about 28 dB can be obtained in the frequency range $1.8–2.5$ GHz. Since, the LO polyphase filter is the same as the RF polyphase filter, $IRR_{tot}$ of 56 dB can be expected (see (2)). In the layout care has been taken to reduce the mismatch by placing dummy resistors and capacitors and by keeping the I and Q signal paths as much as possible the same length. The resistors are implemented as poly resistors and capacitors as MIM capacitors because they have small loses and a good linearity.
The RC polyphase filter in the RF path contributes to a high image rejection but it degrades the gain and the noise figure. The RF buffer (see Fig. 3) helps to obtain an acceptable gain and noise figure. In order to have a voltage swing of around 600 mV at the mixer switching transistors it is necessary to employ two buffers in the LO path.

The simulation results for the wide-band complex mixer are given in Table 3. The same simulation setup was used as in the case of the folded-switching mixer with-current reuse.

### 5. CONSIDERATIONS ABOUT COST-EFFECTIVENESS

Combining the multi-band LNA, wide-band-complex mixer and adding the RF buffers 2 and 3, the DECT/Bluetooth multi-standard front-end with adaptive image rejection is obtained. The simulation results of this front-end are presented in Table 4. During the simulations NF is measured at an intermediate frequency (IF) of 2 MHz.

In order to make the final conclusion related to the cost-effectiveness of the DECT/Bluetooth multi-standard front-end with adaptive image rejection the following qualitative analysis is of interest:

- The advantages of multi-standard operation are increased functionality and flexibility of the front-end, while full hardware reuse is achieved. The cost paid for the multi-standard operation is the increased NF of 0.25 dB in DECT mode due to the thermal noise of the transistor M5 in the multi-band LNA, which is negligible compared to the total NF of the front-end.
- The benefit obtained by the full integration is reduction of the assembly cost, while the cost is an increased NF of 0.7 dB compared to the LNA that achieves $NF_{wire}$ with the same power consumption but with one external inductor. The NF degradation is small compared to the total NF of the front-end.
- Commenting the simulation results presented in Table 4 the following can be said. By applying adaptive image rejection and changing the mode from a high to a low image rejection for both DECT and Bluetooth, the NF improves 50%, gain improves 30% and power consumption is reduced 20%. The reason for NF and gain improvement is bypassing of the RF polyphase filter. The power consumption is reduced because two mixers are turned off. RF buffer 2 and 3 represent the extra cost in terms of chip area paid for an obtaining adaptive image rejection. In order to evaluate this cost the following consideration is important. The RF buffers are implemented as differential amplifiers, which consist of the transistors and the load resistors. The wide-band complex mixer contains three buffers, four single mixers, two RC polyphase filters that consist of the poly resistors and the MIM capacitors. The MIM capacitors occupy large area because they have relatively low capacitance per unit area and the area occupied by RF buffer 2 and 3 is negligible compared to the area occupied by the wide-band complex mixer.

The benefits of the DECT/Bluetooth multi-standard front-end with adaptive image rejection are increased flexibility and functionality, better reception quality due to the provided high image rejection and improved performance when changing from high to low image reject mode. The costs are the increased front-end NF of 0.25 dB in DECT mode because of multi-band operation and an increased chip area due to the RF buffers 2 and 3, which are negligible in comparison with the total front-end NF and total chip area occupied by the front-end. Hence, comparing the benefits with the costs, the DECT/Bluetooth double-quadrature multi-standard front-end with adaptive image rejection looks viable when more than 40 dB IRR is required.

### 6. CONCLUSIONS

A DECT/Bluetooth double-quadrature multi-standard front-end with adaptive image rejection is presented. A novel solution for adaptive image rejection at the system level is introduced. Using a multi-band LNA with zero external components, full integration of a front end is achieved. Evaluation of the benefits brought by the multi-band operation and adaptive image rejection is performed. The major benefits are: increased flexibility and functionality, better reception quality and a performance improvement when changing from high to low image reject mode. The cost (front-end NF degradation of 0.25 dB and an increase in chip area) are negligible compared to the total front-end NF and total chip area occupied by the front-end. Hence, a DECT/Bluetooth double-quadrature multi-standard front-end with adaptive image rejection is a viable solution when a high IRR is required.

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### 7. REFERENCES


