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System level design for zero-IF UE W-CDMA receiver frontend using the available RFICs in the market

By

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Abstract:

Since the zero-IF architecture is attractive for its numerous advantages, the work presented here has its focus on direct conversion (zero-IF) receiver front-end architecture for the wideband code division multiple access (W-CDMA), frequency domain duplex (FDD) operation mode, where a full system-level design for the user equipment (UE) is performed. According to the RF requirements for the FDD mode, the used components used in the system are to be fetched and engineered. Performance analysis and simulation of the over all systems are achieved. The final system can be used in 3G mobile phones.

Keywords:

Zero-IF, W-CDMA, Handheld, Receiver

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1. Introduction:

Of the various architecture options available for a 3G mobile systems, the zero-IF receiver type is probably the most attractive. In general, the zero-IF architecture offers the considerable advantage over the classical alternative of the superheterodyne in having reduced number of blocks, where mixer, IF amplifier, IF filter and image-rejection filter blocks were saved in the receiver. This makes it suitable for integration on-chip with minimum required area. Another effective advantage of the direct-conversion architecture is eliminating the image problem in the receiver which makes the frequency planning of the receiver too simple. Also in the transmitter, the direct conversion approach is used with little components and hence, less power is consumed.

Contrary, the drawbacks of a zero-IF approach and their solutions may be summarized as follows:

Even Order Distortion becomes problematic in homodyne down-conversion. These even order distortions arise from the asymmetry in the LNA and mixer circuits (due to mismatch, the circuits are not perfectly balanced ...). This gives a DC component and an IP2 component around the DC. To avoid that either a balanced (differential) LNA and mixer are used, or a filtering mechanism (e.g. HPF or RC coupling) is used in the baseband to suppress this DC offset. But antennas and duplexers are usually single ended because they must operate with single-ended power amplifiers at the transmit path, so a conversion from single ended to differential is required if differential LNA and mixer were used. Such converters (transformers/ baluns) exhibit several dBs of loss at high frequency, directly raising the overall noise figure. In addition to that, differential LNAs require higher power dissipation than single-ended LNAs to achieve a comparable noise figure. On the other hand, due the spread-spectrum nature of the air interface suited, a few kHz of the channel can be wasted with no significant drop in the data rate, that is, it is possible to use RC coupling in the receiver baseband to filter out the DC offsets and some of the other 2nd order products without significant impact on the sensitivity. However, a relatively high IIP2 value is required but still better than the requirement for a narrow-band system such as GSM.

DC Offset due to self mixing, which arises from the leakage from the VCO to LNA and to the RF port of the mixer, and the leakage. These leakage signals are due to the finite isolation between corresponding ports (due to e.g. capacitive/ substrate/ bond wire coupling). Again the RC coupling (HPF) in the baseband is a good solution to such DC offset.

The baseband flicker (1/f) noise becomes an issue because the demodulated signal spectrum extends to the DC. This can be solved by introducing higher gain in the RF, e.g. by using double stage LNA or using an active mixer, and also the high-pass filtering of the down-converted signal will decrease the flicker noise [1].

2. System Requirements:

The W-CDMA standard has been developed by the Third Generation Partnership Project (3GP) as a standard for third generation digital mobile phone applications. A FDD scheme is specified with the transmitter and the receiver operating simultaneously. For the band I in the W-CDMA air interface, the UE receiver operates from 2110 to 2170 MHz and the UE transmitter from 1920 to 1980 MHz, with 5-MHz wide channels. The signal power at sensitivity for the lowest data rate is -117 dBm. In-band interferers are specified at 5- and 10-MHz offsets from the desired channels. A two-tone intermodulation test is specified using interferers at 10- and 20-MHz offsets. Out-of-band interferers are specified from 1 MHz to 12.75 GHz. The power levels of the interferers range from 56 to 15 dBm depending on their frequency offsets from the desired channel. The sensitivity and interference tests are conducted with the transmitter active. For class-III operation, the transmitter output power is 24 dBm for the sensitivity test.

The RF requirements for the UE transceiver, such as NF, IIP2, IIP3 ... etc, are extracted from the given specs applying receiver sensitivity test, receiver selectivity test, two-tone IMD test and others. The following table summarizes the extracted specs [2]-[4].

TABLE (1): ZERO-IF W-CDMA RECEIVER FRONTEND EXTRACTED SPECS

Specification	Limits
Sensitivity	≤ -117 dBm
Selectivity	≥ 33 dB @ ± 5 MHz (ACS) ≥ 43 dB @ ± 10 MHz
Linearity	IIP2: 8 à 47 dBm IIP3: -21.3 à -8 dBm
Noise	SNR ≥ -18.9 dB NF ≤ 7.9 dB (Phase Noise) _{LO} ≤ -128.9 dBc/ Hz
Gain	Gain: 22 à 95 dB
Power	P _{in} : -117 à -25 dBm

3. System Design and Components Fetching:

The block diagram of the entire receiver is shown below in Fig. 1. Now, we are targeting to implement the RF frontend portion only (i.e. from the antenna to the demodulator) that satisfies the extracted specifications, using the available ICs in the international market.

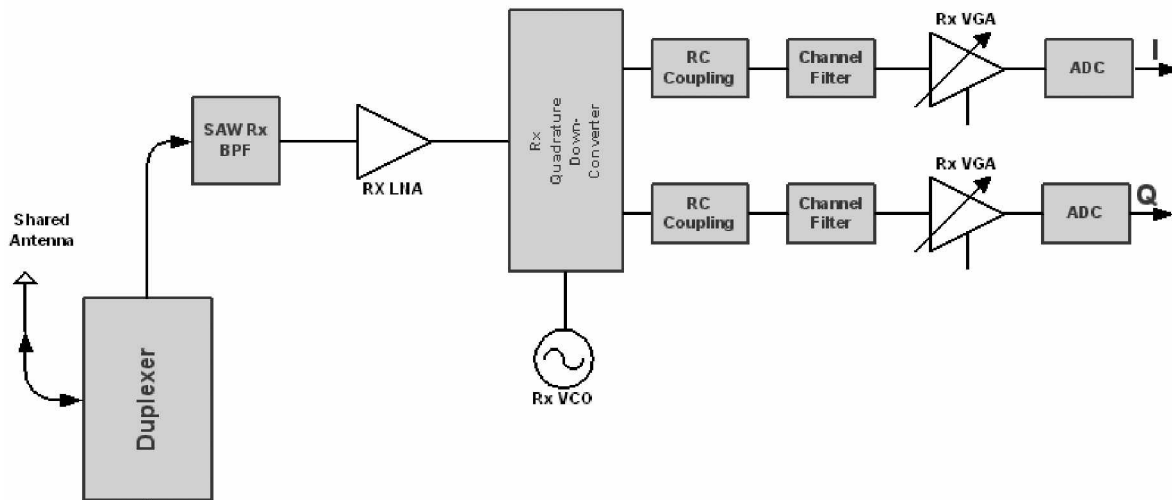


Figure (1): Block diagram of a zero-IF W-CDMA receiver frontend

3.1 Duplexer Selection:

The duplexer is a device that isolates the receiver from the transmitter while permitting them to share a common antenna. It must provide sufficient isolation to prevent receiver desensitization. In our case it is typically 55 dB.

The chosen duplexer is *SAYDTIG95AA0B00* by *muRata*, which provides 2 dB insertion loss from the antenna to the receiver (2110 à 2170 MHz), 1.5 dB insertion loss from the transmitter (1920 à 1980 MHz) to the antenna and about 60 dB isolation between the transmitter and the receiver. Fig. 2.

3.2 Rx SAW Filter Selection:

The surface acoustic wave (SAW) filter has tiny dimensions compared to distributed filters. So, it's optimum for UE mobiles. In our case, it must select the receiver band, 2110à2170 MHz, with as small as possible insertion loss and provide as large as possible attenuation in the transmitter band, 1920à1980 MHz, killing the Tx leakage.

The chosen Rx SAW band-pass filter (BPF) is the 855937 by *TriQuint* and it has the frequency response depicted in Fig. 3 that shows that it contributes about -3 dB in the losses and provides a good out-of-band attenuation. It also provides about 45 dB attenuation to the noise of the associated transmitter signal, which will help in avoiding the desensitization of the receiver by the transmitter interferer.

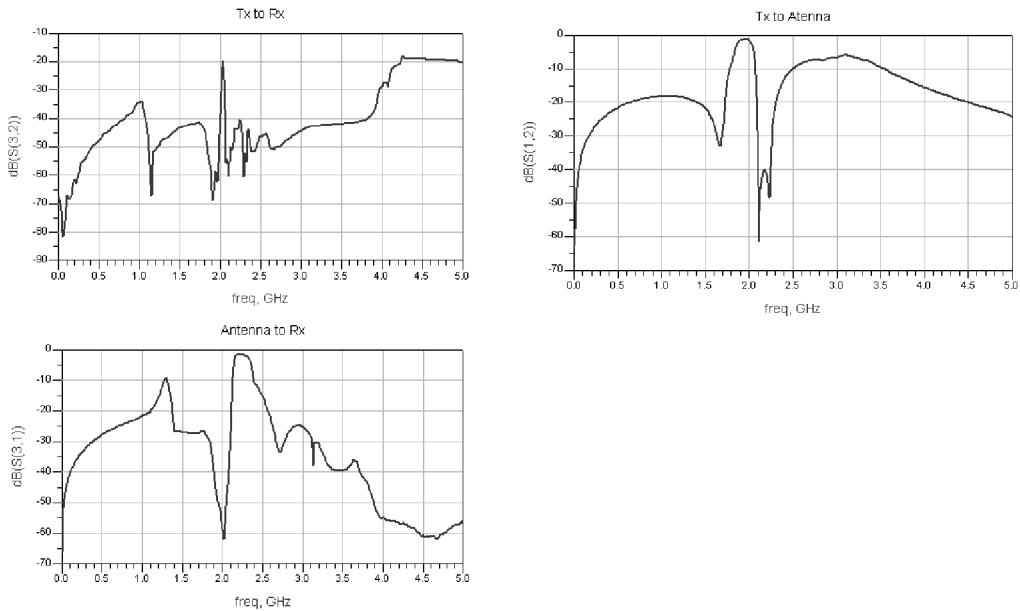


Figure (2): Block Duplexer typical responses

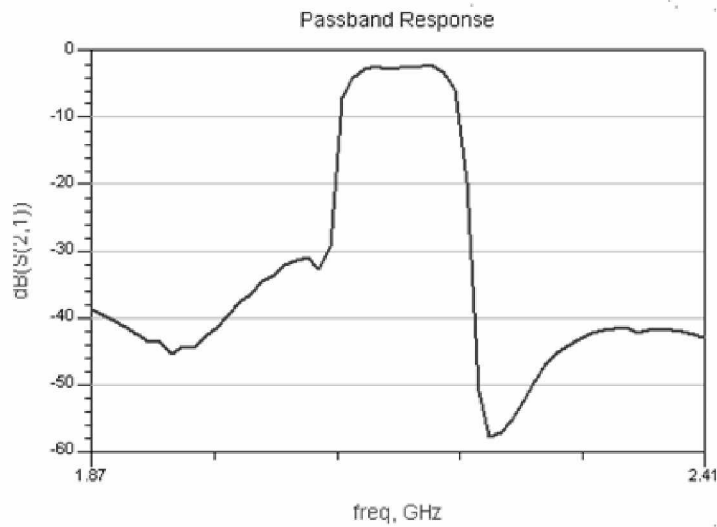


Figure (3): Passband response of the Rx SAW filter

3.3 RF Gain and LNA Selection:

The typical RF gain for a zero-IF receiver is in order of 20 dB since hard design is faced in RF. Also it is difficult to design a narrow-band low-noise amplifier (LNA) in the RF; here one can appreciate the importance of the SAW filter. The LNA in a receiver system is a limiting component for the noise figure (NF) of the system. So, it must provide minimum noise figure in order not to increase the total noise figure of the system.

Two identical LNA RFICs are chosen; each is *HMC548LP3* by *Hittite* that provides the possible minimum NF on the expense of a relatively low IP3 due to its high gain. The typical parameters of each are ($G = 25$ dB, $NF = 1.2$, $IIP3 = -7$ dBm, $OP_{1dB} = 11$ dBm) and the typical response is depicted in Fig. 4.

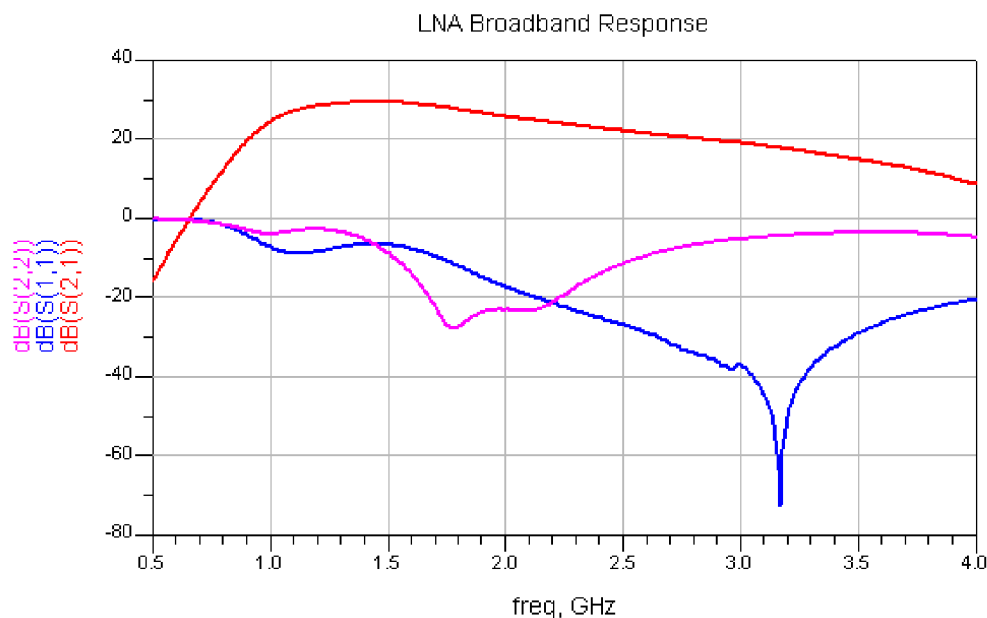


Figure (4): LNA typical frequency response

3.4 System Linearity and Downconverter Selection:

Linearity is the criterion that defines the upper limit for the detectable RF input power level and sets the dynamic range of the receiver. As going far from the antenna in the receiver lineup, the IIP3 of the individual components becomes more effective (since the signal is amplified) which concludes that the downconverter is a limiting element for the linearity. This must be considered in choosing the downconverter RFIC.

A high linearity ($IP_{1dB} = 12$ dBm, $IIP2 = 25$ dBm, $IIP3 = 60$ dBm, $NF = 15$ dB, $G = -3.5$ dB) quadrature down-converter is chosen, namely: *HMC597LP4* by *Hittite*. The high linearity of the downconverter helps in raising the system total linearity to meet the specification and it was chosen quadrature since the W-CDMA uses QPSK modulation technique.

3.5 VCO Selection:

For the homodyne down-conversion, the RF spectrum is simply translated to the baseband in the first down-conversion. So, the local oscillator (LO) frequency and the RF frequency are identical i.e. $f_{VCO} = f_{RF} = 2140$ MHz.

The phase noise of the voltage-controlled oscillator (VCO) (or LO) has effect on both receiver sensitivity and selectivity. So, it must be carefully chosen. A low-phase noise VCO is chosen namely: *HMC384LP4* by *Hittite*, which has a phase noise of -122 dBc/Hz @ 100 kHz. The phase noise effect will be further decreased by the filter action. The power level of the VCO is 3.5 dBm which is suitable to the chosen demodulator that accepts LO power from -6 dBm to 6 dBm. Also this VCO has an embedded buffer to isolate the LO and the mixer.

4. System Integration:

The complete block diagram of the receiver front-end chain with the specifications of the chosen components is shown in Fig. 5. The power levels at each component are shown too for both RF detected signal and the Tx interferer.

Since the passive filters are extremely linear, their $IIP3$ is infinite but they are modeled as 100 dBm and they contribute by their loss in the total noise figure. Using Friis' formula,

$$NF_T = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \dots \quad (1)$$

where G_i is the i^{th} component power gain in ratio and NF_i is the NF of the i^{th} component in ratio, too. One can calculate the over all noise figure of the system to be $3.7 = 5.7$ dB which is below the requirement which is 7.9 dB.

Similarly, the over all IIP3 of the system can be calculated using the formula,

$$\frac{1}{IIP3_T} = \frac{1}{IIP3_1} + \frac{G_1}{IIP3_2} + \frac{G_1 G_2}{IIP3_3} + \dots \quad (2)$$

Substituting the components parameters in the last equations gives a theoretical value for the entire IIP3 of 1.1 mW = 0.43 dBm. This can be considered as an accepted theoretical value, however the requirement on the IIP3 of the over all receiver front-end is to range from -21 ÷ -8 dBm, because the filter will provide some attenuation to the third-order harmonic power giving a more realistic value.

As shown in Fig. 5, the duplexer and Rx SAW BPF strongly attenuates the Tx signal in order not to desensitize the receiver front-end, also this attenuation assures that this signal cannot saturate the LNA of the receiver where the Tx signal level did never exceed the compression points of any stage of the LNA stages at the receiver. The over all gain is in order of 46 dB (gain) – 9 dB (losses) i.e. 35 dB RF gain.

Also the wanted signal at the receiver propagates, within the receiver front-end chain, without reaching neither the compression point of any stage nor the third-order intercept point at any stage. Avoiding reaching the compression point of any stage assures a proper linear operation without saturating any of the active components within the chain, whereas avoiding reaching the value of the third-order intercept point assures minimum intermodulation distortion and better receiver sensitivity.

The entire system does uses a 5 VDC and consumes a DC current of 352 mA, that is, the required DC input power is 1.76W = 32.46 dBm.

5. Simulation Results:

Each component in the system was modeled behaviorally and/ or using the available linear touchstone S-parameter models supported by the manufacturers on the *Agilent* tool *Advanced Design System* (ADS).

The corresponding simulation result for the input-output characteristics of the entire system is depicted in Fig. 6.

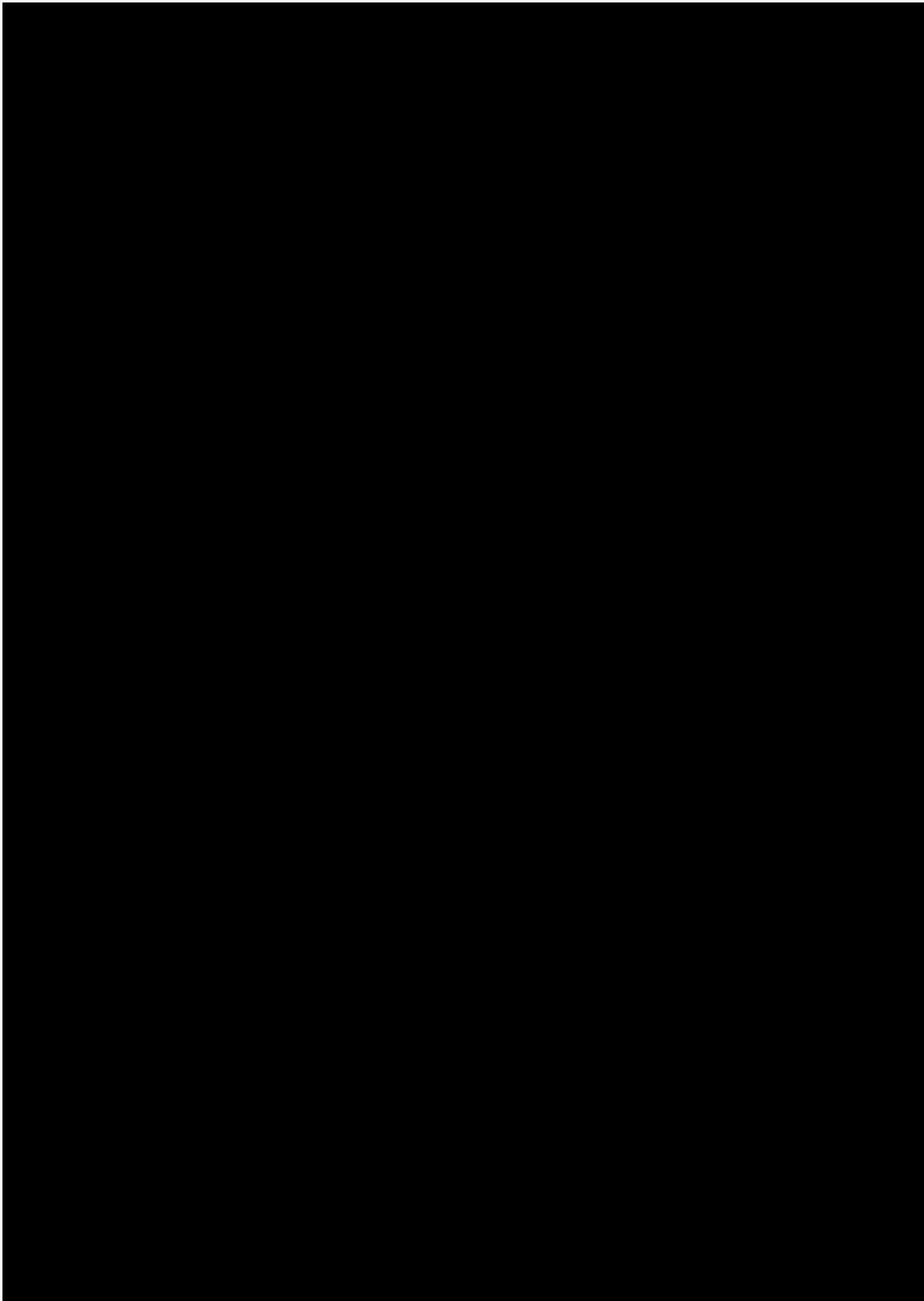


Figure (5): Entire system profile diagram

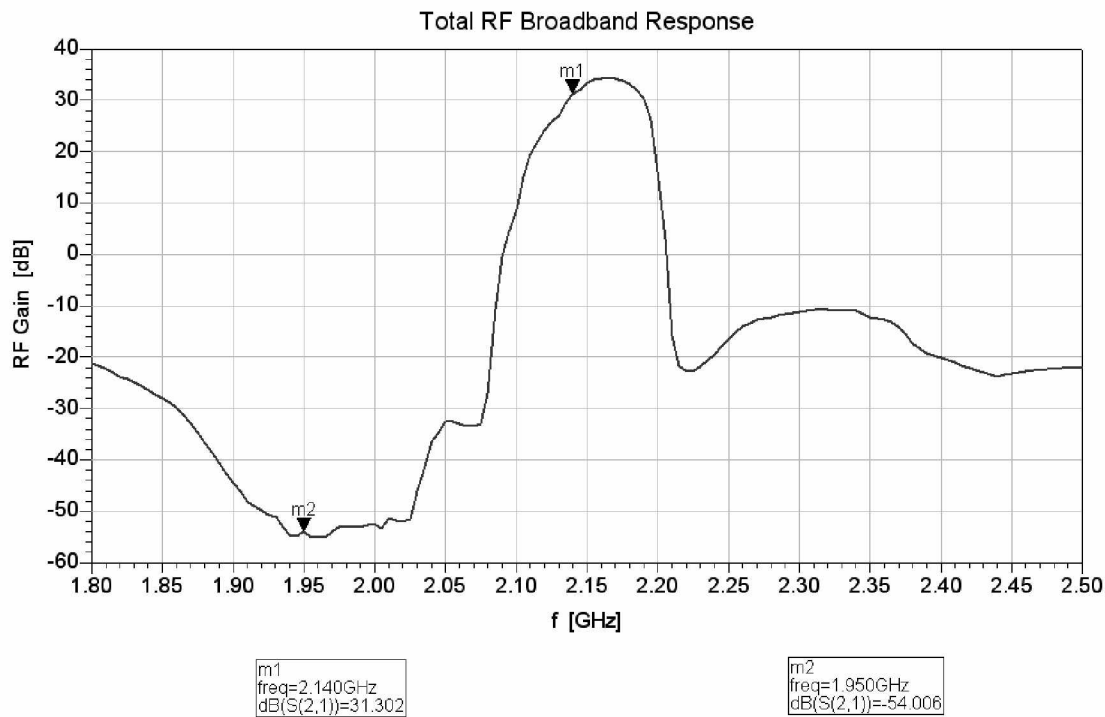


Figure (6): ADS simulation of the entire system response

Fig. 6 shows that the RF gain at the center frequency of the desired band is about 31 dB slightly less than the expected value of 35 dB. Also the corresponding attenuation at the transmitter center frequency due to the RF stages is shown in the figure to be -54 dB while it was expected to be -59 dB, this -59 dB are the contribution of the attenuation of both the duplexer and the SAW filter in addition to the gain of the two stages of the LNA.

6. Conclusions:

The zero-IF receiver architecture was exploited to build a zero-IF receiver frontend for 3G mobile phones. The system uses no more than 6 ICs that occupy a very small area and cost less than approximately 30 USD per system. The entire system uses a 5VDC supply and consumes about 1.76 W. The all components are got from the available RFICs in the international market.

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