Radio Frequency Receiver Dimensioning Methodology for IEEE 802.16e Standard

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Abstract — this paper describes a radio frequency receiver dimensioning methodology targeting the IEEE 802.16e standard, mobile WiMAX. Based on direct conversion receiver architecture, the distribution of the standard specifications to the individual receiver blocks is discussed. Design techniques and theoretical calculations are developed while considering ADC (Analog to Digital Converter) full scale constraint. Simulation results are introduced for noise figure (NF), gain and linearity (IIP3: Input-Third Order Intercept Point and ICP1: Input-1dB-Compression Point). The studied receiver performs two gain modes to fulfill linearity and noise constraints. It achieves a total gain of 45dB and a CP1 of -17.9dBm for low gain mode. It provides up to 106dB gain, 7.6dB noise figure and -25.9dBm CP1 for high gain mode.

Index terms — dimensioning methodology, IEEE 802.16e, receiver blocks, linearity, noise, gain.

I. Introduction

Wireless communication and electronic fields have known a vast progress during the last few years. Increasing the data rate, expanding the coverage area and accommodating more components on the same chip are the essential motivations behind designers to develop materials for these wireless communication systems [1-2]. Moreover wireless receivers have to offer different services while satisfying minimum power consumption; this in order to make them suitable for mobile application. Mobile WiMAX (World Wide Interoperability for Microwave Access) is one of the new standards developed in recent times. It can cover an enormous distance and allows an important data rate [3-5].

Designing an RF (Radio Frequency) receiver for mobile WiMAX application became a delicate task if we consider the stringent challenges of this standard. Any design project start with a preliminary task known as receiver dimensioning or system level design. This step is very important in ensuring the verification of the required performances at transistors level as well as in shortening the time-to-market. The realization of an efficient frequency plan and receiver budget is one of the most compelling problems. Many tradeoffs have to be made when fixing the characteristics of each of the blocks [6-7].

The remainder of this paper is planned as follows. Section 1 describes RF parameters, receiver architectures and WiMAX standard Specifications. Section 2 explains receiver specifications computation. Section 3 discusses simulated results. At last, section 4 highlights the main finding and conclusion of the proposed work.

II. Basic Receiver design

A. Receiver Parameters

Many design parameters have to be considered when dimensioning an RF receiver. The most common parameters are sensitivity, noise figure (NF) and IIP3. Sensitivity S is the key parameter of any receiver. By definition, it is the minimum input signal level expressed in dBm that can be detected and correctly demodulated by the receiver. It can be expressed as [8-9]:

$$P_{in\_\min} = -174dBm/Hz + NF + 10\log B + SNR_{\min} \quad (1)$$

Where -174dBm/Hz is the thermal noise power of 50Ω input resistance, B is the receiver channel bandwidth expressed in Hertz, SNR_{min} is the minimum Signal to Noise Ratio and NF is the noise figure which is defined by the following expression,

$$NF = 10\log nf \quad (2)$$

Where nf is the noise factor. Friis formula [10] defines the noise factor of cascaded stages as:

$$nf = 1 + (nf_1 - 1) + \frac{nf_2 - 1}{G_1} + ... + \frac{nf_m - 1}{G_1...G_{m-1}} \quad (3)$$

Where nf_i is the noise factor and G_i is the power gain of the i-th block.

Receiver can be also characterized by its linearity. Moreover, receiver blocks are nonlinear in general. Due to these nonlinearities, blockers can generate intermodulation products. Second order and third order intermodulation terms are the most dominant products. Thus two parameters define the linearity which are the Input-Third Orders Intercept Point (IIP3) and Input-Second Orders Intercept Point (IIP2) [8-9].

A similar equation to the cascaded noise factor can be obtained for IIP3:

$$\frac{1}{IIP_3^2} = \frac{1}{IIP_{3,1}^2} + \frac{G_1}{IIP_{3,2}^2} + ... \frac{G_1 ... G_{m-1}}{IIP_{3,m}^2} \qquad (5)$$

Where G_i is the power gain of the i-th block.

B. Receiver Architectures

Three different receiver architectures are studied, superheterodyne, homodyne and low-IF. The choice is determined by criterion including complexity, power, noise and surface.The most traditional architecture is the superheterodyne receiver. It consists on down converting the RF signal spectrum to at least one intermediate frequency (IF). In fact, the RF signal is first down-converted to the intermediate frequency IF, and then it is down-converted from IF to baseband signal. Baseband is the range of frequencies occupied by the signal before modulation or after demodulation. The major problem of this architecture is the image frequency and complexity (number of blocs)[8]. In Low-IF receiver architecture, RF signals are translated to low-IF frequency which is then down-converted to baseband signal. This type of architecture presents tow problems which are image rejection limitation and high power consumption. The third studied architecture is the homodyne one. It translates received signal directly from RF to baseband. In this case the intermediate frequency is null (ω_{IF}=0). Hence this architecture is called Zero-IF architecture or Direct IF architecture. The homodyne receiver presents many advantages specially the simplicity (less hardware) and image problem rejection [9]. Thus, total integration, high flexibility, integration density and low power consumption can be offered only by the homodyne architecture. We deduced that this type of architecture is the more suitable and, probably, allows attending the required performances of WiMAX standard. Therefore we chose this architecture in our research. Figure 1 shows the bloc diagram of the chosen architecture.

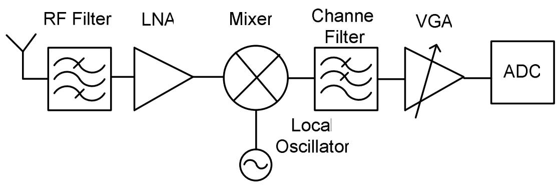

Figure 1. WiMAX receiver schematic

C. WiMAX Standard Specifications

WiMAX stands for World Wide Interoperability for Microwave Access. The main characteristic of this norm is the huge distance which it can cover (up to 50 Km) and the important data rate insured (up to 70 Mb/s). Nowadays, mobile WiMAX represents a very interesting norm since it can offer wireless connection everywhere at any time. WiMAX has two versions: the first one is for fixed network (IEEE 802.16a); in this case the frequency band is between 2-11GHz. The second is for mobile applications (IEEE 802.16e); the frequency band is restricted to 2-6GHz [11]. WiMAX, for fixed applications, adopts orthogonal frequency division multiplexing (OFDM) modulation scheme. Mobile WiMAX uses only Orthogonal Frequency Division Multiple Access (OFDMA). The channel bandwidth is variable from 1.25 MHz to 20 MHz. The subcarrier spacing is set to 10 KHz. Each subcarrier can be modulated with different modulation schemes (QPSK, 16 QAM or 64 QAM). The standard specifies the noise figure to be less than 8dB in addition to a maximum of 5dB from implementation losses. The BER have to be less then 10^{-6}. The WiMAX receiver shall be able of detecting and decoding a maximum input signal of -30dBm, the minimum input signal can be calculated with the following expression [11]:

$$P_{in\_min} = -101 + SNR_{RX} + 10\log[F_s . \frac{N_{used}}{N_{FFT}} .10^{-6}] \; P_{in\_min} = -101 + SNR_{RX} + 10\log[F_s . \frac{N_{used}}{N_{FFT}} .10^{-6}] \qquad (6)$$

Where:

- -101 [noise Floor + 8dB noise figure (NF) + 5dB implementation losses (IL)] expressed in dBm/MHz,

- SNR_{RX} the receiver SNR in dB,
- F_S Sampling frequency in MHz,
- N_{used} Number of used subcarriers,
- N_{FFT} 1024.

According to [12], FFT size and channel bandwidth depend on frequency band. Table I lists some of the mobile WiMAX profiles and their corresponding channel bandwidth and N_{FFT}.

TABLE I. WIMAX PROFILES

Frequency range (GHz)	Channel bandwidth (MHz)	FFT size	Duplexing mode
2.3-2.4	5	512	TDD
	10	1024	
	8.75	1024	
3.3-3.4	5	512	TDD
	7	1024	
	10	1024	
3.4-3.6	5	1024	TDD
	7	1024	
	10	1024	

Assuming that to design a mobile WiMAX receiver operational at the 3.4-3.6GHz frequency band, the channel bandwidth would be 10MHz and the N_{FFT} corresponding value is 1024. The receiver sensitivity is computed by means of equation (6), it is estimated to be around -94.5dBm [7].

III. RECEIVER SPECIFICATIONS COMPUTATION

Dimensioning methodology is based on two steps: receiver parameters computation and blocks specifications. Indeed, the link budget analysis uses several key parameters to determine the receiver line up and the requirements of receiver blocks such as SNR, dynamic range, ICP1 and IIP3. These parameters are not directly given by the standard. This typically involves their calculations.

B. SNR and Dynamic Range

Signal-to-Noise Ratio (SNR or S/N) is a measure used to calculate how much a signal is corrupted by noise. By definition it is the ratio of signal power by the noise power. In RF, the minimal signal to noise ratio at the input of the receiver SNR_{in} can be calculated as [13]:

$$SNR_{in\_min} = P_{in\_min} - N_t \quad (7)$$

Where:

- N_t=10 log KTB/10^{-3} : thermal noise,
- T=288 Kelvin: thermal temperature,
- B=10MHz : channel bandwidth of mobile WiMAX,
- K= boltzman constant = 1.38 10^{-23},
- P_{in_min} is the minimal sensitivity calculated above = -94.5dBm,

In our application SNR_{in_min} is 13dB.

SNR at the input of the ADC can be calculated as [13]:

$$SNR_{out} = SNR_{in\_ADC} = E_b/N_0 - 10log(PG) \quad (8)$$

Where: PG=BW/R= bandwidth/rate and E_b/N_0 is the energy per bit to noise power spectral density ratio.

It can also be calculated as [13]:

$$NF = SNR_{in} - SNR_{out} = SNR_{in} - SNR_{in\_ADC} \quad (9)$$

$$SNR_{in\_ADC} = SNR_{in} - NF$$

Knowing NF and SNR_{in} values, SNR_{in_ADC} is computed and it is equal to 5dB.

The dynamic range (DR_{in}) is generally the parameter that defines the receiver and the received signals. DR_{in} can be calculated as the difference between the maximal and minimal received signal. The maximal signal power S_{max} is –30dBm and the minimal signal is the reference sensibility S=-91dBm. Thus dynamic range would be [15]:

$$DR_{in} = P_{in\_max} - P_{in\_min} = 61dB \quad (10)$$

DR_r, or dynamic range of the analog part of receiver can be measured as [15]:

$$DR_r = DR_{in} + SNR_{out} = 66dB \quad (11)$$

The received signal at the antenna can be quite low level, thus the receiver must provide a maximum gain. On the other hand, it is limited by the ADC full scale level. Considering that the full scale Sf_s is equal to 13 dBm, we can compute the total gain, provided for the weakest signal (G_{min}) and for the strongest signal (G_{max}) [15]:

$$G_{min} = Sf_s - P_{in\_max} = 43dB \quad (12)$$

$$G_{max} = Sf_s - P_{in\_min} = 104dB \quad [13]$$

C. CP1 and IIP3 Computation

As mentioned in the precedent section, IEEE 802.16 fixes the minimum input signal at $P_{in,\ min}$=−94.5dBm and the maximum input signal at $P_{in,\ max}$=−30dBm. One can notice that received signal will have a huge variation (~60dB of variation) which is depending on signal path and distance between emitter and receiver. For low signal, LNA and VGA have to furnish the maximum of their gain to preserve constant signal strength at the input of the ADC. For a powerful signal, LNA and VGA gain will be reduced [16-17-18]. Thus receiver requires two switched gain modes to carry out the desirable amplification for strong or weak input signal [7].

- *Strong Signal: Low Gain Mode*

When the input signal is strong, it does not require an important amplification. So receiver is working at the low gain mode. The required ICP1 for this mode would be:

$$ICP1 = P_{in\_max} + 12 = -18dBm \quad (14)$$

Were 12dB is the PAPR (Peak to Average Power Ratio) value in WiMAX standard [19].

According to the rule of Thumb, the IIP3 is normally larger than ICP1 by 9~10 dB [20]. Consequently, the required IIP3 for WiMAX receiver would be around -8 dBm:

$$IIP_3 = ICP1 + 10 = -8dBm \quad (15)$$

- *Weak Signal: High Gain Mode*

If signal is weak with low power, the receiver is working at high gain mode and provides the maximum of gain.

Assuming that the desired signal is generally accompanied by a CW (continuous waveform) interferer with a maximum power of -30dBm, then the required back-off from the ICP1 is around 4dB approximately. Consequently the input-1dB-compression point is measured as:

$$ICP1 = P_{in\_max} + 4 = -26dBm \quad (16)$$

The third order intercept point can be calculated as:

$$IIP3 = ICP1 + 10 = -16dBm \quad (17)$$

Table III and IV summarizes the WiMAX standard specifications and receiver parameters respectively. All these parameters are dispatched through the receiver blocks wile using link budget analysis under ADS (Advanced Design System) tool.

TABLE III. WIMAX STANDARD SPECIFICATIONS

Parameters	values
Frequency band	3.4-3.6GHz
Channel bandwidth	10MHz
P_{in_min}	-94.5dBm
P_{in_max}	-30dBm
NF	8dB
Modulation	OFDMA
Duplexing mode	TDD
FFT sizes	1024

TABLE IV. WIMAX RECEIVER PARAMETERS

Parameters	High gain mode	Low gain mode
ICP1	-26 dBm	-18 dBm
Gain	104 dB	43 dB
IIP3	-16 dBm	-8 dBm
Sfs	13 dBm	
SNR_{in_min}	13 dB	
SNR_{in_ADC}	5 dB	
DR_{in}	61 dB	
DR_r	66 dB	

IV. BLOCKS SPECIFICATIONS

In this step, the distribution of WiMAX specifications throw the different components of the RF receiver is completed. Budget simulations are completed while using ADS tool. Each block characteristics, such as gain, ICP1, IIP3, NF, and output power are obtained for both low gain and high gain mode.

A. Receiver Dimensioning for Low Gain Mode

In this mode, receiver chain is simulated while considering the highest signal which can be received (-30dBm). The more challenging constraint here is the linearity; in fact we have to verify an IIP3 around -8dBm for the whole receiver. As the input signal is strong, LNA and VGA gain are low. Figure 3 presents the gain evolution among different WiMAX receiver blocks, where: block 0 is the RF filter, block 1 is the LNA, block 2 is the Mixer, block 3 is the channel filter and the last block is the VGA. Receiver provides 42.9dB of gain dispatched as follows: 10dB for LNA, 14dB for the mixer and 21dB for the VGA. The 2dB difference shown in this figure is due to the losses considered in the filter/duplexer and switch which are supposed around 2dB. Indeed, while simulating the ADS receiver model, we took in consideration 2dB as insertion losses (IL) for the RF filter. Figure 4 shows the output power evolution among receiver blocks. The signal power falling to the ADC is maintained constant (12.9dBm~ADC full scales: 13dBm). Figure 5-6 shows ICP1 and IIP3 evolution among different WiMAX receiver blocks. Simulations illustrate that ICP1 at the receiver input is around -17.8dBm (>-18dBm: theoretical value). The ICP1 value is dispatched as follows: -6dBm for the LNA, 5dBm for the mixer and 15dBm for the VGA.

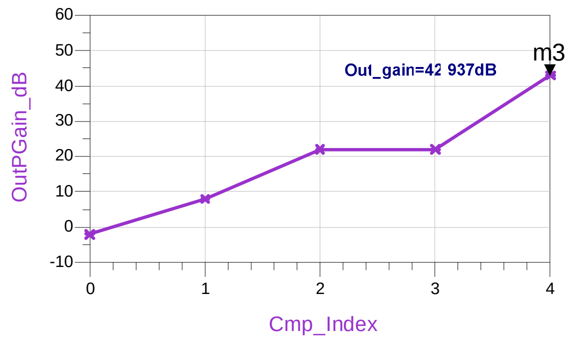

Figure 3. Evolution of gain along WiMAX receiver blocks for low gain mode

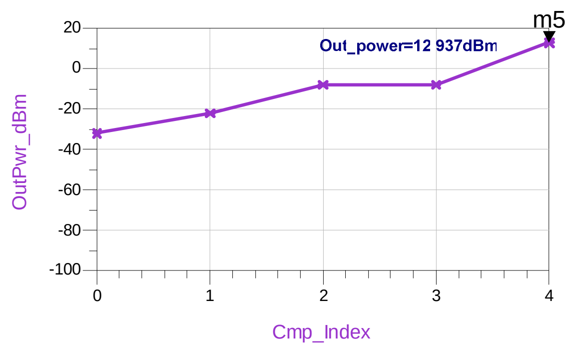

Figure 4. Evolution of output power along WiMAX receiver blocks for low gain mode

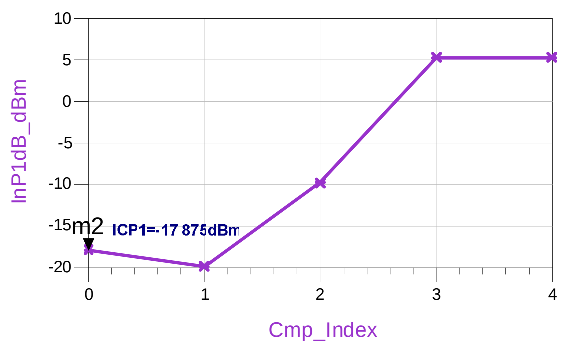

Figure 5. Evolution of ICP1 along WiMAX receiver blocks for low gain mode

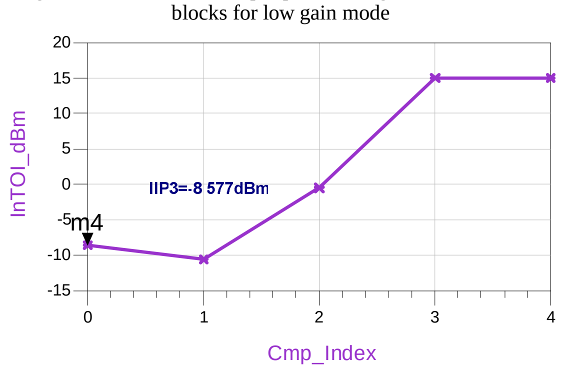

Figure 6. Evolution of IIP3 along WiMAX receiver blocks for low gain mode

B. Receiver Dimensioning for High Gain Mode

The linearity challenges are more suitable in this case since the input signal is weak; however noise can affect and degrade easily the signal quality. In this mode, only the LNA and VGA parameters are modified and this while satisfying noise and linearity conditions. All the others block specifications have the same values as previously, this condition make the distribution of the parameters more delicate. In this mode the receiver chain is simulated wile considering the minimum input signal (-94.5dBm).

Figure 7 shows the NF budget among receiver blocks. The 2dB difference shown in this figure is due to the losses considered in the filter/duplexer and switch. Total noise figure is equal to 7.68dB. Thus standard specifications is verified (<8dB). The total gain provided by the receiver chain is 104dB distributed as follows (figure 8): 20dB for the LNA, 14dB for the mixer and 72dB for the VGA. Figure 9 demonstrates that receiver output remainders constant (13dBm) which enables it to be treated by the ADC. Figure 10 and 11 introduce the evolution of ICP1 and IIP3, respectively, among the receiver blocks. The total ICP1 is around -25.9dBm distributed as follows: -15dBm for the LNA, -5dBm for the mixer and 8dBm for the VGA.

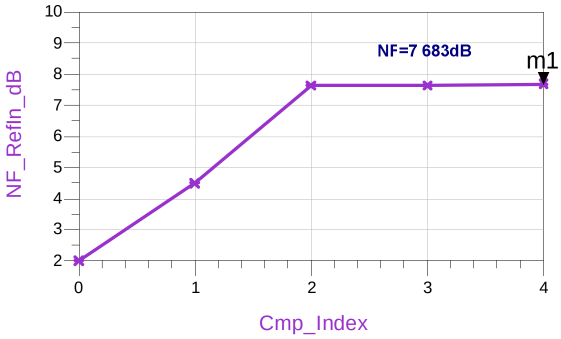

Figure 7. Evolution of noise figure along WiMAX receiver blocks for high gain mode

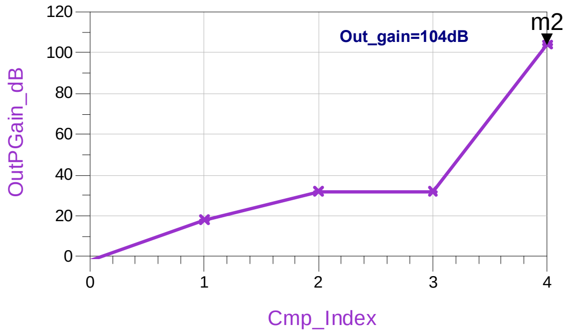

Figure 8. Evolution of gain along WiMAX receiver blocks for high gain mode

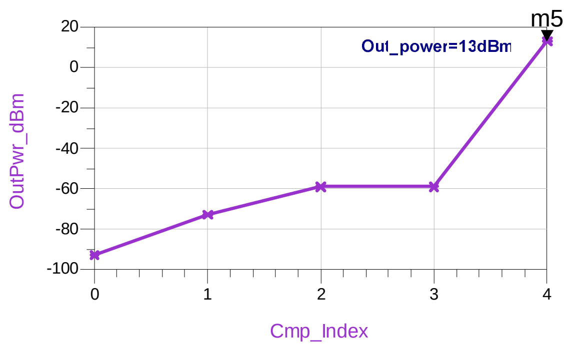

Figure 9. Evolution of output power along WiMAX receiver blocks for high gain mode

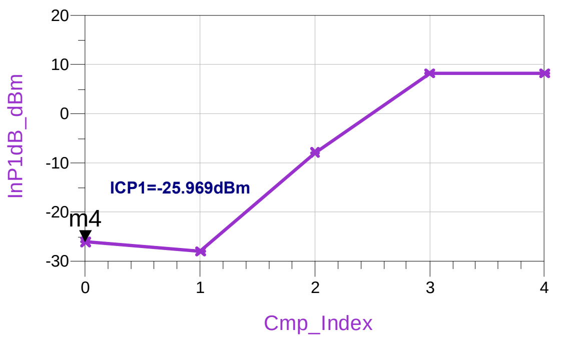

Figure 10. Evolution of CP1 along WiMAX receiver blocks for high gain mode

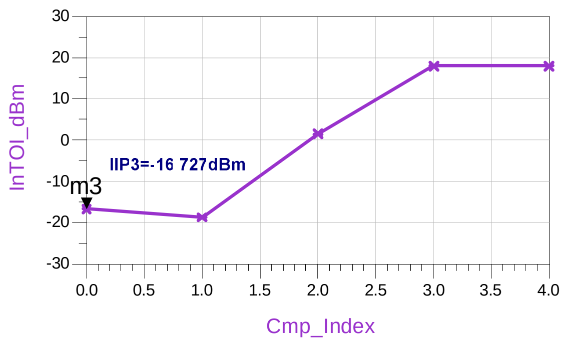

Figure 11. Evolution of IIP3 along WiMAX receiver blocks for high gain mode

The WiMAX receiver characteristics are summarized in table II. The total gain for low gain mode is around 43dB, and 104dB for high gain mode. These results satisfy the WiMAX standard requirements.

TABLE II. BLOCKS SPECIFICATIONS

Parameters	**LNA**		**Mixer**	**VGA**	
	HGM	***LGM***		***HGM***	***LGM***
Gain (dB)	20	10	14	72	21
NF (dB)	2.5	6	8	20	17
ICP1 (dBm)	-15	-5	-5	8	5
IIP3 (dBm)	-5	5	5	18	15

A comparison between theoretical and simulated results is listed in table III. Comparison shows that theoretical calculations are verified for NF, CP1 and the out power of the studied receiver.

TABLE III. RECEIVER SPECIFICATIONS

Gain mode	Parameters	Theoretical calculations	Experimental results	Relative error (%)
High Gain Mode	NF (dB)	8	7.68	4
	CP1 (dBm)	-26	-25.96	0.15
	IIP3 (dBm)	-16	-16.72	-4.5
	Out_power (dBm)	13	13	0
Low Gain Mode	NF (dB)	8	--	--
	CP1 (dBm)	-18	-17.87	0.72
	IIP3 (dBm)	-8	-8.57	7.1
	Out_power (dBm)	13	12.93	0.53

Relative Error = (experimental results – theoretical calculation)/theoretical calculation*100

V. CONCLUSION

In this paper, a system level design methodology was presented. At first, receiver architecture and standard specifications was introduced. Receiver parameters such as SNR, D_r, ICP1 and IIP3 were then computed. WiMAX receiver operated in two gain modes in order to attempt linearity conditions. Simulations that generate specifications for the different receiver components were presented and discussed. For low gain mode the receiver performed a gain of 45dB and an IIP3 of -8.-dBm. For high gain mode, the receiver achieved up to 106dB of gain, 7.6dB NF and -16.7dBm IIP3. All receiver parameters were verified using budget link analysis via ADS tool.

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