Technical Article

LOW-COST INTEGRATED SOLUTION FOR ANALOG CELLULAR RF BLOCKS

Abstract

As the United States analog cellular market continues to enjoy expanding markets in most cities, the need for improved cost performance of analog hand-held units continues to increase. Even though the implementation of digital cellular systems is just around the corner, the analog market is expected to remain significant for years to come. As analog hand-held designs have matured over the years, the design focus has shifted from technology development toward size and cost reductions. A seemingly good solution for the size and cost requirements is to replace discrete or module based RF blocks with surface mount integrated circuits (RFICs), providing that the analog cellular performance requirements (IS-19B) can be satisfied with the IC's particular technology. Until recently, IC solutions were possible that satisfied either the size and performance or the size and cost requirements, but not all three. This paper presents an IC solution to the analog cellular receive LNA/Mixer and transmit Power Amplifier blocks that satisfies the performance and size requirements at a favorable cost, competitive with discrete solutions. System considerations, such as filter requirements, gain levels, noise performance, intermodulation performance, and power control are discussed.

Introduction

The technical specifications for US analog cellular phones are found in Electronic Industries Association Interim Standard 19-B (IS-19B). This paper discusses some of the key RF specifications in that document, but the scope is not intended to be limited to this one system. The issues presented here are directly applicable to other similar analog systems, such as TACS, NMT, and CT1. The concepts and frequencies of operation have much in common between these systems, and the devices summarized in this paper have application to all of them. The receiver LNA(Low Noise Amplifier)/Mixers described here are also relevant to other 900 MHz applications, including digital ones. A generalized, representative block diagram for a US analog cellular phone is shown in **Figure 1**. In response to present day market pressures to minimize cost and size, a logical level of integration for some of the RF blocks is indicated by the dashed lines in the block diagram.

RF Block Descriptions

The duplexer is effectively two ganged filters that accomplish the frequency duplexing (hence the filter's name) of the input Rx frequency band (869-894 MHz) with the output Tx frequency band (824-849 MHz). This allows both bands to share a common antenna. The filter response of the Tx-Ant path serves to limit the amount of Rx-band noise generated in the transmitter that reaches the Rx LNA input. It also attenuates the harmonics of the Tx frequency that reach the antenna and get radiated. The Ant-Rx path filter response protects the Rx LNA from potentially harmful levels of Tx power and attenuates the receiver's response to the first IF image.

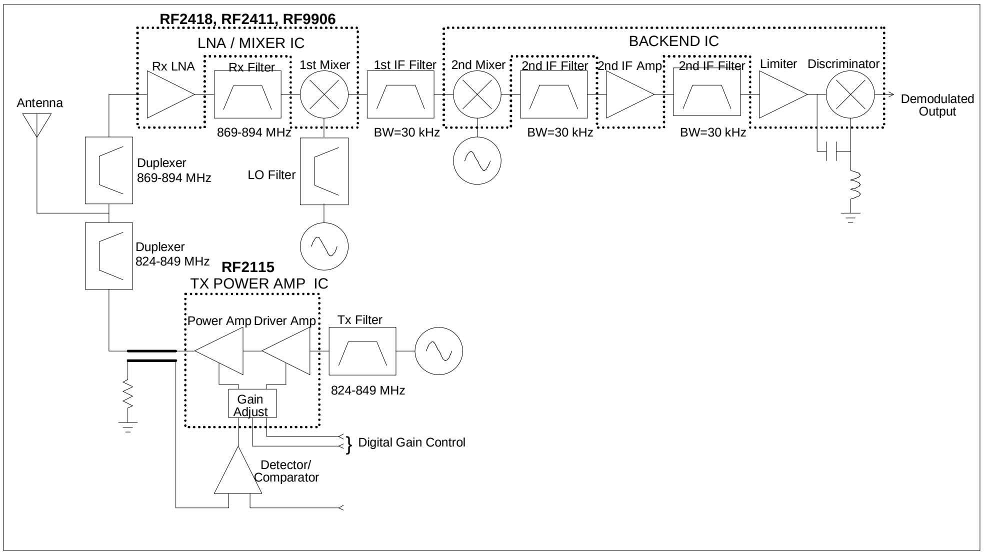

Figure 1: Typical Analog Cellular RF Block Diagram

The LNA's main function is to provide enough gain to overcome the noise figure of subsequent stages, while adding as little of its own noise to the signal as possible. In effect, the Rx LNA sets the receiver's noise figure, and hence its sensitivity level (minimum usable input signal level). In contrast, the LNA's gain tends to work against the over-all linearity of the receiver because the net IP3i (input third order intercept point) will be reduced from the mixer's IP3i by the combined gain of the LNA and filters appearing before the mixer. In other words, the higher the gain of the LNA, the lower the receiver's net IP3i, or linearity, will be. This assumes that the LNA's IP3i is sufficiently high, compared to the mixer's IP3i minus the net gain before it.

In most super-heterodyne receivers, an image filter is inserted between the LNA and the first mixer. This serves two similar functions. It provides attenuation, in addition to that provided by the duplexer, of the first IF image. It also prevents the LNA's output image-band noise from being converted down and degrading the IF signal to noise ratio (S/N).

The primary function of the mixer is to convert the input Rx frequency down to a fixed IF frequency. Which particular channel is converted to the IF is determined by the frequency of the LO source. Since the mixer's IP3i typically sets the receiver's over-all IP3i, the mixer design tends to focus on maximizing IP3i and the associated noise figure is accepted, with the intention of overcoming it with the LNA's gain and low noise figure. The critical balance in the LNA/Mixer design in most multi-channel receivers boils down to trading off the LNA's gain against the mixer's noise figure (balancing overall sensitivity with over-all linearity).

Many receiver designs also incorporate a filter between the Mixer's LO port and the LO source. The purpose of this filter is to prevent the noise at one IF frequency below the Rx from being mixed with the Rx down to the IF.

The IF filter that follows the mixer selects the channel that is to be passed on to the receiver back-end. In addition to initial channel selectivity, this filter prevents off-channel signals from reaching the back-end, where intermodulation distortion would be severe, due to the large levels of gain present. Because the interfering channels do not reach the back-end, the mixer primarily determines the overall IP3i. An additional function of the filter is that it attenuates the 2nd IF image response.

After the IF filter, the back-end of the receiver typically consists of a mixer that converts the IF down to a 2nd IF, limiting amplifiers, highly selective filters, and an FM discriminator. Single ICs that integrate these blocks (not including the filters) are readily available from several manufacturers. The reason for converting to a 2nd IF (commonly 455 kHz) is that tight filtering and high levels of gain (>100 dB) can be accomplished more economically. The demodulated output of the discriminator is passed on to base-band signal processing where voice, supervisory tones, signaling tones, and wide-band data are separated and processed independently.

The Tx Power Amp's (PA's) main function is to supply specified levels of output power at the antenna port. The power amp must be capable of adjusting its output power over a range of at least 20 dB. A key concern for the power amp is that it supply the maximum specified output power as efficiently as possible, since the PA's efficiency is the major factor in determining a hand-held unit's battery life. The PA must also not add so much Rx-band noise that the level that reaches the LNA input degrades receive sensitivity. The PA's noise performance determines the minimum Rx-band attenuation that will be required of the duplexer. Similarly, the harmonic output of the PA and the power detecting circuitry will determine the amount of harmonic attenuation required of the duplexer. The gain designed into a PA must also be carefully considered. There must be enough gain to ensure that the output remains saturated in order to maintain efficiency, but too much gain will degrade the relative attenuation of spurious signals. In many cases there are in-band spurs that cannot be eliminated completely by frequency plan selection and/or shielding. The amount of spur enhancement in the PA, therefore, must be minimized, and this usually correlates to keeping the gain low. Another key consideration for the PA is that it will see a wide range of impedance change from the antenna, as well as a highly reflective impedance outside of the duplexer's pass band. The PA must be able to maintain its performance over a wide range of load VSWR's.

The primary function of the Tx filter preceding the PA is to reduce the amount of Rx-band noise generated in the Tx frequency source. In some cases, by using a high quality (low noise) source, this filter may be eliminated. An additional feature of this filter is that it attenuates Tx harmonics from the source before they reach the PA input.

The coupler between the PA output and duplexer is used to obtain an output power sample that is detected for output power level verification and control.

Specific Analog Cellular Requirements

In describing the receiver performance requirements, it is best to discuss RF Sensitivity first, because this measured level becomes the reference for measuring other receiver criteria. RF Sensitivity is the power level, in dBm, of a carrier FM modulated with a 1 kHz test tone that, when demodulated by the receiver under test, produces a 1 kHz audio signal with a 12 dB SINAD ratio (SIgnal-plus-Noise-plus-Distorton to noise-plus-distortion). 12 dB SINAD is a common reference and is generally regarded as the minimum allowable audio quality. RF Sensitivity is then the minimum useable carrier level that can be received by the subscriber unit. IS-19B specifies this level as -116 dBm, maximum.

Since SINAD is primarily dominated by the S/N of the demodulated audio, assuming that the demodulator and audio circuits have moderate to low distortion, the key issue for achieving adequate sensitivity is to maintain a good S/N throughout the entire receive path. This is synonymous with keeping a low overall noise figure for the entire receiver. In order to keep the overall noise figure acceptably low, certain RF blocks must be carefully designed for low individual noise figures. By referring to the equation for cascaded noise figure (in this equation, NF and G are linear, not dB, expressions),

$$NF_T = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \frac{NF_4 - 1}{G_1 G_2 G_3} + \ldots + \frac{NF_n - 1}{G_1 G_2 G_3 \ldots G_n},$$

we see that the total cascaded noise figure for a given system will be dominated by the noise figure of the first stage or two if the first stages have enough gain, since the noise figure of each stage is divided by the gain that appears before it. Note that in the simple case of two cascaded blocks,

$$NF_T = NF_1 + \frac{NF_2 - 1}{G_1},$$

the noise contribution of the second stage is reduced by the gain of the first stage. From this equation we can see that it is desirable to keep the LNA's gain fairly high, and that the NF of the LNA must be minimized. It is also obvious that every dB of insertion loss before the LNA degrades the NF by approximately 1 dB. For this reason, the insertion loss of the duplexer must be minimized.

Given that the specified level for sensitivity is -116 dBm, that the thermal noise power available in a 30 kHz bandwidth is

$$kTB = -174 + 10\log(30{,}000) = -129.2 \ \ (dBm),$$

and that a Carrier-to-Noise (C/N) of approximately 2 dB at the input of a typical FM demodulator correlates to 12 dB SINAD, the theoretical lowest obtainable sensitivity can be determined as follows:

$$-129.2 + 2 = -127.2 \ \ dBm$$

The maximum allowable noise figure for the receiver to satisfy sensitivity can be found by comparing this limit to the specification:

$$-116 - (-127.2) = 11.2 \ \ dB$$

This indicates that a receiver with an over-all NF of 11.2 dB should barely be sufficient to meet the -116 dBm sensitivity requirement. For every dB of sensitivity margin desired, the receiver's net noise figure must be reduced one dB from 11.2 dB. The spread sheet shown in **Figure 2** calculates, among other things, the total noise figure of a cascaded set of RF blocks, based on the cascaded noise figure equation. The numbers used in this analysis are based on filters and a back-end IC that are commercially available. This spread sheet illustrates how that, given a desired sensitivity of -119 dBm, the gain and noise figure of the LNA and noise figure of the mixer can be set in order to achieve a desired sensitivity.

CALCULATED DATA		ENTERED DATA									
	TOTAL SYSTEM	DUPL.	LNA	RX BPF	MIXER	IF BPF	BK. END 2ND MIXER	BK. END 2ND IF BPF	BK. END IF AMP	BK. END 2ND IF BPF	BK. END LIM.
NF (dB)	**8.2**	3.3	**1.8**	2.5	**9.5**	2.0	6.2	6.0	10.0	6.0	20.0
Gain (dB)	**114.0**	-3.3	**11.0**	-2.5	**3.8**	-2.0	17.0	-6.0	44.0	-6.0	58.0
IP3i (dBm)	**-7.0**	100.0	**-5.0**	100.0	**0.0**	25.0	-9.0	100.0	-30.0	100.0	-40.0
Selecitvity	**N/A**	0.0	0.0	0.0	0.0	20.0	0.0	30.0	0.0	30.0	0.0
Sens. (dBm)	**-119.0**										
IM (dB)	**73.7**		**BW (kHz)**		30.0	**C/N Ratio**		2.0	**C/I Ratio**		6.0

Figure 2: Receiver Performance Spreadsheet Analysis

In order to discuss other receiver specifications, it is first necessary to describe the specified measurement method. In these tests, the RF input is varied until 12 dB SINAD is measured at the output. This sensitivity level is recorded and the input generator's level is increased by 3 dB. Depending on the test being performed, an interfering signal or signals are introduced. The interfering signals' input levels are increased until the measured SINAD falls back to 12 dB. The difference between the interferers and the sensitivity (not the sensitivity plus 3 dB) is what is specified.

In the case of Adjacent and Alternate Channel Desensitization, the specifications are 16 and 60 dB respectively. These specifications dictate the minimum amount of net attenuation required by the IF filters at ± one and two channel spacings away from the input channel. The design tradeoff here is that increasing the selectivity of the 1st and/or 2nd IF filters will improve this measurement, but may have a negative effect on the filters' size, cost, and group delay ripple. Increasing the group delay ripple will increase the demodulated audio's distortion and increase the wide band data Bit Error Rate (BER). For these reasons, it is best not to try for too much margin on the Adj./Alt. specifications.

The IS-19B specification for Intermodulation Spurious Response Desensitization performance (termed here "IM") is 65 dB. IM is the measured difference between the sensitivity level and the level of two interfering sources placed at 60 and 120 kHz above or below the tuned channel. These two interfering sources will produce third order responses due to non linearities in the receiver. One of these responses will land at the same frequency as the tuned frequency, i.e. co-channel interference. **Figure 3**, demonstrates that IM is related to the receiver's IP3i by the following equation:

$$IP3i = S + \frac{C}{2} + \frac{3IM}{2} - \frac{3}{2} \quad (dB).$$

C is the Carrier to Interferer ratio (C/I), in dB, which has the effect of causing the increased input's SINAD to fall back to 12 dB. This ratio is typically 6 dB for FM discriminators. S is the measured sensitivity level.

If we wanted to build a receiver with 70 dB IM and -119 dBm sensitivity, the receiver's net IP3i would then need to be -12.5 dBm. A significant point results from considering this equation. If we rearrange the equation to express IM in terms of IP3i and sensitivity,

$$IM = +\frac{2IP3i}{3} - \frac{2S}{3} - \frac{C}{3} + 1 \quad (dBm),$$

we see that for a fixed IP3i, the IM improves 2/3 dB for every 1 dB of improvement in sensitivity. In other words, for IS-19B applications, noise figure and IP3i are interrelated, and better sensitivity will improve IM without having to increase the IP3i.

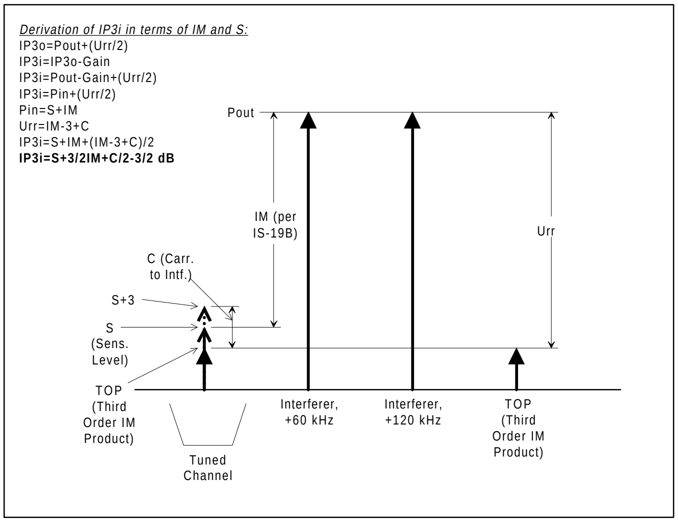

Figure 3: Receiver Output Spectrum

Given that we now have a relationship established between IM and IP3i, we can use the cascaded IP3i equation (in this equation, IP3i and G are linear, not dB expressions),

$$\frac{1}{IP3_{iT}} = \frac{1}{IP3_{i1}} + \frac{G_1}{IP3_{i2}} + \frac{G_1G_2}{IP3_{i3}} + \frac{G_1G_2G_3}{IP3_{i4}} + \ldots + \frac{G_1G_2G_3\ldots G_n}{IP3_{in}},$$

to analyze the effects of individual blocks' IP3is on the receiver's IM. Referring back to the spread sheet of **Figure 2**, we see how the mixer's IP3i and the LNA's gain and noise figure can be traded off and what the expected net IM will be. The mixer and LNA parameters were varied to yield a total sensitivity of -119 dBm and an IM of at least 73 dB.

Another key consideration for the filter selections throughout the receiver is insuring that the receiver does not respond to frequencies outside of its designed input range (869-894 MHz). One of the bands that will most likely have a response is the first image, situated in the band two IF frequencies above the Rx band, assuming the LO is injected at one IF above the Rx-band (high side injection). The response tendency exists here because signals in this band that reach the mixer will also convert down directly to the IF. The combined filtering from the duplexer and Rx filter (or image filter) must attenuate this band enough that signals introduced at 60 dB or more above the measured sensitivity will not cause the SINAD to fall below 12 dB when the receiver is being supplied with an on-channel modulated carrier. Another likely response will occur at what is called a "half-IF spur". This occurs at an input frequency that is one half of the IF frequency above the tuned input channel. The response here is due to 2nd order distortion in the receiver, primarily in the mixer. The mechanism is the

2nd harmonic of the spur frequency mixing with the 2nd harmonic of the LO, and the difference-product lands at the IF. This tends to come into play only when the IF frequency is low and the receiver is tuned to the lower channels. Otherwise, the spur is attenuated by the duplexer and/or the image filter so much that the second order distortion of the mixer does not come into play. Another very likely spur frequency will occur two 2nd IF spacings away from the tuned channel. Both this frequency and the tuned channel will mix down in the 2nd mixer to the second IF frequency. The only filter that can provide any useful attenuation of this relatively close spur is the 1st IF filter. Given that a C/I of ~6 dB will cause the discriminator's output SINAD to fall back to 12 dB, and the specification, relative to the sensitivity level, is 60 dB, then the IF filter should have

$$60-3+6=63\ (dB),$$

minimum, of attenuation at the second IF image.

Another consideration for the filter selection in the receiver is the conducted spurious specification of -47 dBm, maximum. From the receiver, the most likely candidate for leakage out the antenna connector is the LO. The actual amount of LO power conducted out of the antenna port will be determined by the LO drive level, the LO-to-RF leakage in the mixer, the reverse isolation of the LNA, and the net attenuation of the LO band in the image filter and duplexer. This specification has little bearing on most designs, however, because the small amounts of attenuation required of the filters in the LO band tend to fall out naturally by satisfying the image requirements.

Transmitter specifications require the power radiated by the antenna to be controllable over a 20 dB range for hand-held (Class III) units. This range is selectable in 4 dB steps from +28 dBm to +8 dBm. The individual power levels (PL2=+28 through PL7=+8 dBm) are selectable by the cellular system in order to balance system power requirements. These requirements dictate that some sort of power level control circuit be incorporated into the transmit RF power amp. In addition, detector circuitry is normally incorporated after the PA to sample the output power as part of a closed loop control circuit. The key requirement here is that the power amp must be able to vary its output according to an input analog and/or digital control signal. In addition, it must have at least a 20 dB control range for hand-held operation.

The PA must also be as efficient as possible, while meeting the other RF requirements, at PL2 (maximum output). This requirement is not specified by IS-19B. However, it is highly desirable, from the user's point of view, for the current drain under transmit conditions be minimized. This maximizes "talk time", a key consumer consideration.

Another key requirement of the PA is that it maintain stability under a very wide range of load conditions. In-band, the PA may see large impedance changes due to the antenna's proximity to various objects (i.e. users, metal structures, etc...). Out of band, the PA is guaranteed to see severe mismatches, due to the duplexer's out-of-band impedance. The PA will also be required to source a fixed amount of output power, regardless of the load variations, since the power control loop will detect primarily forward power.

Regarding harmonics and spurious Tx frequencies, the maximum relative levels allowed to be conducted to the antenna are related to the output level by the following equation:

$$dBc\,(\min)=43+10\log(Pout, in\ watts).$$

At maximum output (PL2), the output power is 28 dBm, or -2 dBw. Therefore, the minimum attenuation of any spurious or harmonic signal out of the duplexer is

$$43+(-2)=41\ \ (dBc).$$

The difficulty of meeting this requirement is that most FM power amps employ saturating output devices. Saturating amplifiers tend to degrade the input carrier to spurious attenuation due to the fact that the amplifier limits the gain of the carrier due to the output limiting on the larger signal, but the spur's gain is not reduced nearly as much, depending on what the small-signal gain is. Note that this phenomenon is most significant for frequency plans where the spurious signals fall within the Tx band, and the duplexer's selectivity will not help reduce the spurious level. This consideration, along with the power level available from the Tx source, will determine what the gain of the PA is designed for.
Another difficulty with saturating power amps, is that their outputs clip. The obvious by-product of a clipping stage is an output spectrum with appreciable harmonic content. In addition, the diode based detectors used in most power control circuit designs are quite capable of generating harmonically rich spectra. Achieving harmonic suppression at the antenna will be largely the burden of the duplexer.

Another implied requirement of the PA is that it not degrade Rx sensitivity by raising the Rx-band noise floor such that the noise power into the Rx port of the duplexer is higher than kTB. In order to keep the transmitter's noise from affecting the receiver, the noise must be at least a few dB below kTB. Since the Tx source will provide kTB, at minimum, to begin with, the duplexer must filter out at least all of the noise amplified and added by the PA. If the transmitter design includes a Tx filter between the PA and Tx source, then the noise contributions come solely from the PA. This filter is not used in designs where the Tx source has good noise performance and the duplexer provides sufficient attenuation in the Rx-band.

Requirements Satisfied

Three LNA/Mixer ICs have been designed to meet the requirements of IS-19B. **Table 1** summarizes their key performance parameters.

Device	LNA Gain	LNA NF	LNA IP3i	Mxr Gain	Mxr NF	Mxr IP3i	Idd/ Vdd
RF2418	11.0	1.8	-5	3.8	10.5	0	7 / 5.0
RF2411	13.5	1.9	-5	7.2	10.0	5	14 / 4.0
RF9906	16.5	1.5	-6	4.0	9.0	6	20 / 3.6

Table 1: LNA/Mixer Performance

The RF2411 was fabricated in a GaAs MESFET process. It has two output options, one high impedance output suitable for matching to high impedance IF filters, and one ~50 ohm buffered output for devices requiring a low impedance source. The RF2411 is fabricated in a GaAs HBT (Heterojunction Bipolar Transistor) process, and has balanced outputs. The RF9906 is also fabricated in a GaAs HBT process, and features selectable IF amplifiers after the mixer, one balanced output and one single-ended. It's IP3i has also been improved over the other two parts. All three parts operate off of single-ended supplies (no negative supply is required).

CALCULATED DATA		ENTERED DATA									
RF2418	TOTAL SYSTEM	DUPL.	LNA	RX BPF	MIXER	IF BPF	BK. END 2ND MIXER	BK. END 2ND IF BPF	BK. END IF AMP	BK. END 2ND IF BPF	BK. END LIM.
NF (dB)	**8.3**	3.3	**1.8**	2.5	**10.5**	2.0	6.2	6.0	10.0	6.0	20.0
Gain (dB)	**118.7**	-3.3	**11.0**	-2.5	**8.5**	-2.0	17.0	-6.0	44.0	-6.0	58.0
IP3i (dBm)	**-7.3**	100.0	**-5.0**	100.0	**0.0**	25.0	-9.0	100.0	-30.0	100.0	-40.0
Selecitvity	**N/A**	0.0	0.0	0.0	0.0	20.0	0.0	30.0	0.0	30.0	0.0
Sens. (dBm)	**-118.9**										
IM (dB)	**73.4**		**BW (kHz)**		30.0	**C/N Ratio**		2.0	**C/I Ratio**		6.0

CALCULATED DATA		ENTERED DATA									
RF2411	TOTAL SYSTEM	DUPL.	LNA	RX BPF	MIXER	IF BPF	BK. END 2ND MIXER	BK. END 2ND IF BPF	BK. END IF AMP	BK. END 2ND IF BPF	BK. END LIM.
NF (dB)	**7.1**	3.3	**1.9**	2.5	**10.0**	2.0	6.2	6.0	10.0	6.0	20.0
Gain (dB)	**119.9**	-3.3	**13.5**	-2.5	**7.2**	-2.0	17.0	-6.0	44.0	-6.0	58.0
IP3i (dBm)	**-6.2**	100.0	**-5.0**	100.0	**5.0**	25.0	-9.0	100.0	-30.0	100.0	-40.0
Selecitvity	**N/A**	0.0	0.0	0.0	0.0	20.0	0.0	30.0	0.0	30.0	0.0
Sens. (dBm)	**-120.1**										
IM (dB)	**75.0**		**BW (kHz)**		30.0	**C/N Ratio**		2.0	**C/I Ratio**		6.0

CALCULATED DATA		ENTERED DATA									
RF9906	TOTAL SYSTEM	DUPL.	LNA	RX BPF	MIXER	IF BPF	BK. END 2ND MIXER	BK. END 2ND IF BPF	BK. END IF AMP	BK. END 2ND IF BPF	BK. END LIM.
NF (dB)	**5.9**	3.3	**1.5**	2.5	**9.0**	2.0	6.2	6.0	10.0	6.0	20.0
Gain (dB)	**119.7**	-3.3	**16.5**	-2.5	**4.0**	-2.0	17.0	-6.0	44.0	-6.0	58.0
IP3i (dBm)	**-7.5**	100.0	**-6.0**	100.0	**6.0**	25.0	-9.0	100.0	-30.0	100.0	-40.0
Selecitvity	**N/A**	0.0	0.0	0.0	0.0	20.0	0.0	30.0	0.0	30.0	0.0
Sens. (dBm)	**-121.3**										
IM (dB)	**74.9**		**BW (kHz)**		30.0	**C/N Ratio**		2.0	**C/I Ratio**		6.0

Figure 4: Receiver Performance Calculations Based on Three LNA/Mixer ICs

The spread sheet calculations shown in **Figure 4** illustrate IS-19B receiver specification compliance of systems based on all three LNA/Mixer ICs. Here again, the calculations are based on a commercially available back-end IC and filters.

An HBT power amplifier design has been developed, the RF2115, to satisfy IS-19B receiver requirements. Since this PA uses HBT technology, it operates with 50% efficiency on a single supply. No negative supply is required, as is the case with most MESFET PAs. **Table 2** summarizes the major parameters.

Psat, (dBm) Vcc= 5.0	Psat, (dBm) Vcc= 5.8	Psat, (dBm) Vcc= 6.5	Small Sig. Gain (dB)	Eff. (%)
29.3	30.4	31.5	32	50

Table 2: RF2115 Performance

The RF2115 has two types of power control capability. Vcc1 can be used to provide analog power control. Two bits of digital gain control, which vary the output in 10 dB steps over a 30 dB range, are also provided. The analog gain adjustment can be used in conjunction with the digital steps in order to achieve both high resolution and a large range (>30 dB) while maintaining a relatively constant level of compression over the full control range. In addition, the power control loop delay is maintained relatively constant over the full range.

Conclusion

The RF requirements of IS-19B and how they drive individual block requirements were described. In addition, three LNA/Mixer ICs and one power amp that satisfy IS-19B requirements were presented. These devices are available from RF Micro Devices, Greensboro, NC. In addition to these devices, similar designs for digital systems are also available.

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