How tough are the front-end requirements for 4G-and-beyond handsets?

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How Tough are the Front-End Requirements for 4G-and-Beyond Handsets?

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***Abstract*—Due to the interrelation of different stages within the handset receiver, it is often desired to have clear requirements for the RF receiver front-end. However, the LTE standard specifies only the system-level performance, and extracting the receiver's front-end requirements is not straightforward given the complexity of current standards. These front-end requirements are important to make the right technology choice. In this paper a clear overview of the required calculations and their results is given, treating the noise figure, selectivity/blocking and cross- and intermodulation requirements. This avoids the need to perform system-level simulations in the early design stage and provides the designer with insight on the impact of the RF receiver front-end on the system-level performance. The results are related to the technology choice, where it is shown that SiGe and GaAs can achieve both the required sensitivity and linearity. To the best of the authors' knowledge this is the first time that such an overview is given and applied to determine a suitable technology. The requirements for 5G systems are expected to be more stringent, making the already tough requirements for 4G even tougher for future systems.**

I. INTRODUCTION

Like most wireless standards, the LTE (4G) requirements for a handset (UE in the standard) receiver are defined by conditions under which the handset must achieve a minimum throughput in a reference channel [1]. This makes sense from the standards and testing points of view, since it defines the handset as a system and leaves the internal design parameters open to the system architect's choice. However, it also means that the RF requirements are not separated from the decoding/digital domain requirements, posing a problem when defining the design targets at the analog/digital boundary. Therefore the system architect has to extract the relevant receiver front-end parameters from the requirements in the standard. Moreover, once the receiver's front-end requirements are clear, an IC process choice has to be made. This often concerns the break down voltage ($\mathrm{BV}_{\mathrm{CEO}}$ or $\mathrm{BV}_{\mathrm{CBO}}$) and current gain cutoff frequency (F_{t}) or maximum oscillation frequency ($\mathrm{F}_{\mathrm{max}}$). $\mathrm{BV}_{\mathrm{CEO}}$ and $\mathrm{BV}_{\mathrm{CBO}}$ determine whether a power amplifier's (PA) 1-dB compression point (P1dB) will fit in the break down voltage. Likewise, F_{t} sets the minimum noise figure (NF) for a transistor, and therefore the lowest achievable NF of an LNA. In addition, the save operation area (SOA) of a transistor is also a point of concern.

The most accurate approach to tackle this problem would be to perform system-level simulations. A drawback of this method is that it can be very time consuming at a critical stage in the design. In addition it requires an estimation of the achievable specifications of each component in the architecture. Therefore it is very useful to make an initial estimate of the requirements on the receiver's RF front-end (RFFE) such as the noise figure (NF), blocking, intermodulation (IM) and cross-modulation (XMOD) requirements. In this paper these system requirements are addressed using easily adaptable modeling approaches, which can also be used for 5G systems. The derived system requirements are then mapped to individual blocks and reflected upon with respect to process choice. Margin in these requirements has to be taken into account for process, voltage and temperature spread (PVT), which depends on the chosen technology. The results are given for all channels and bandwidths present in the most recent LTE release at the time of writing and presented in clear figures and summarized in Table I. To the best of the authors' knowledge this is the first time that such an overview is given and applied to determine a suitable technology.

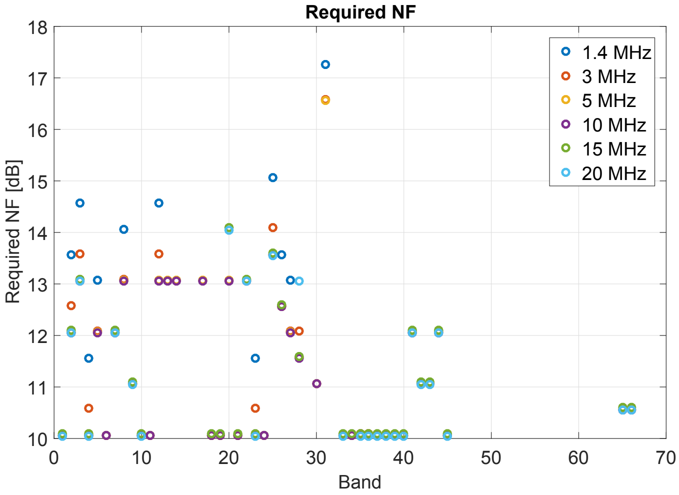


Fig. 1. The overall receiver NF's for LTE Rel. 13's defined bands and channels.

All data, unless specified otherwise, are taken from [1], in which the handset requirements are defined at the antenna connector. Additional specs for carrier aggregation, uplink-MIMO, proximity services (ProSE) and CAT 0 (IoT applications) are neglected to keep the calculations clear and compact. First, the required NF is determined, and brought down from a system level to the LNA, which is illustrated by a real-world example. Next, an overview of the selectivity and blocking tests is presented in Section III. The linearity requirements due to intermodulation and cross-modulation are calculated and transferred to an LNA requirement in Section IV. Finally a conclusion is given in Section V.

II. SENSITIVITY

In the LTE standard, the sensitivity is defined as a power level at which a minimum throughput has to be achieved. This measure is directly related to the receiver's required maximum NF. The reference sensitivity as defined in the standard, P_{REFSENS}, can be calculated by (similar to [2]–[4]):

$$\begin{aligned} P_{\text{REFSENS}}\text{ [dBm]} = \; & - \; 174\text{ [dBm/Hz]} \\ & + \; 10\log_{10}\left(N_{\text{RB}}\cdot 180000\text{ [Hz]}\right) \\ & + \; \text{NF [dB]} + \text{SNR [dB]} - 3\text{ [dB]}, \end{aligned} \tag{1}$$

where the first two terms represent the noise floor in the currently allocated receive band, N_{RB} is the number of allocated resource blocks (defined in the standard), SNR is the signal-to-noise ratio in dB required for 95% throughput and the -3 dB corrects for the second antenna port that is defined in the standard. Note that P_{REFSENS} depends on both the band and the channel bandwidth. In the past, some simulations have been performed within 3GPP to determine the required SNR for 95% throughput [5], [6]. The worst-case (highest SNR) value in [5], [6] is 0.4 dB. Using this value the required NF over all channels and bandwidths of the entire receiver can be calculated, as shown in Fig. 1. Overall the lowest NF is NF = 10 dB. Including an implementation margin of 1 dB, NF = 9 dB is taken in Table I for the overall receiver.

Accounting for 3 dB baseband noise (including quantization noise), 4 dB transceiver noise (downconversion, assuming 12 dB to 15 dB LNA power gain), a band select switch with a 0.4 dB insertion loss and a filter/duplexer with a 1 dB insertion loss, this means that the LNA's NF has to be 0.6 dB or lower, as indicated in Table I. This sets quite a demanding NF requirement for the LNA stage. For instance, a 130 nm CMOS LNA has a NF = 0.78 dB as shown in Table II, not meeting the required LNA NF. This requires an external LNA in either GaAs or SiGe. Both technologies are capable of delivering a sufficiently low NF. For example, the NXP BGU8052 has a NF = 0.5 dB at its terminals at a 3.3 V supply voltage, as shown in Table II, and the two GaAs examples that are shown are also able to fulfill this requirement, although at a higher power consumption.

III. SELECTIVITY

Four different interference/blocker requirements are defined in the LTE UE standard: to test the adjacent channel selectivity (ACS), narrowband blocking, out-of-band blocking and in-band blocking. Adding selectivity to the receiver (e.g. using a(n) acoustic filter(s)) relieves the electronics' requirements, making them achievable at low power-consumption levels.

TABLE I
UE RECEIVER AND LNA REQUIREMENTS

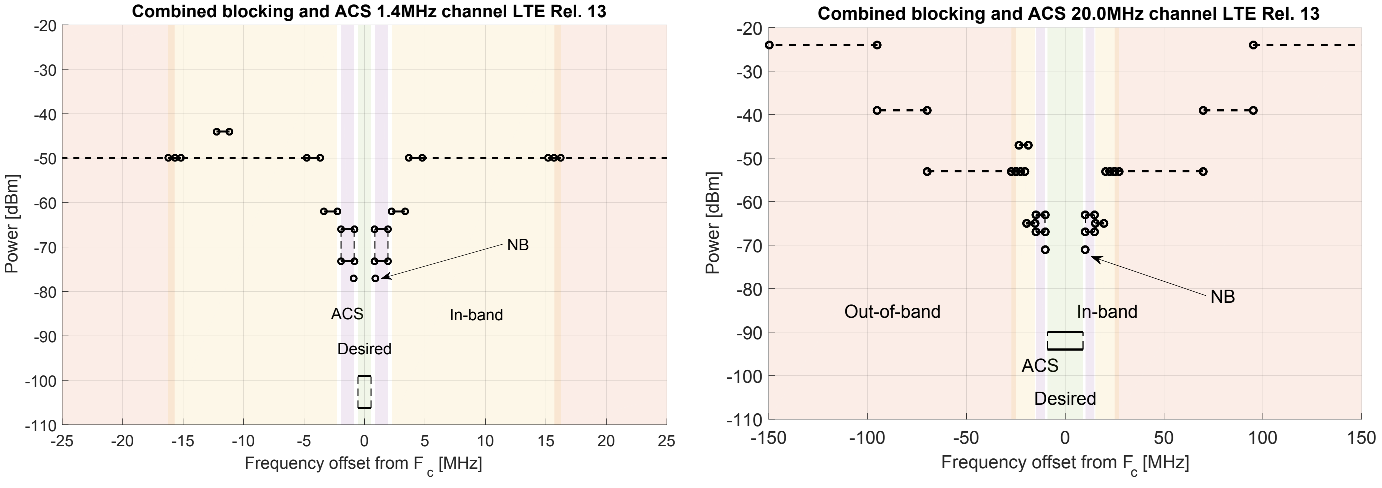
Parameter	**Minimum**	**Typical**	**Maximum**
Frequency [GHz]	0.45		3.8 5.9 (B46)
Channel BW [MHz]	5	20	90 (FDD)
Channel FBW [-]	0.4%	2%	6% (FDD)
Receiver NF [dB]	≤ 9	≤ 9	
LNA NF [dB]	≤ 0.6	≤ 0.6	
Min. input power [dBm]	-106.2	-97	-90.5
Max. input power [dBm]	-27		-25
Receiver IIP3 [dBm]			$\geq$ +0.9
LNA IIP3 [dBm]			$\geq$ 5.4
ACS [dBc]	27	33	33
ACS+1 [dBc]	46.5	53	62.2

In order to combine all the ACS and blocking requirements, they are normalized to the desired signal power. Thus, a spectral mask can be constructed that indicates the overall required interferer resilience, assuming that the received signal can always be properly scaled and the NF is sufficiently low (as determined in Section II) to receive the smallest signal. This provides an estimate of the required overall selectivity, though the required SINR ratio at the demodulator is not visible, i.e. using this spectral mask directly will result in a signal to interference plus noise (SINR) = 0 dB during the test. As an example, the spectral masks constructed this way are shown in Fig. 2 for the 1.4 Mhz (smallest) and 20 MHz (largest) channel bandwidths, where the frequency offset from the center of the desired channel of each requirement is indicated. The required ACS and the required selectivity for the channel next to the adjacent channel (ACS+1, estimated using out-of-band blocking range 1) are given in Table I. From the Figure and the Table it can be observed that the requirements are quite stringent, i.e. a required attenuation of approximately 30 dB over only slightly more than 1 MHz frequency shift for the 20 MHz channel. Therefore these requirements cannot be fully fulfilled by selectivity, resulting in an increased linearity requirement, which is determined in the next section.

IV. LINEARITY

For a receiver the required linearity is mainly set by the interference/blocking requirements, since they are large w.r.t. the maximum desired signal. While the addition of selectivity helps in most cases (since it attenuates the blocker power if the blocker is in the rejection band), determining the required linearity without selectivity sets a worst-case requirement.

For the calculation of the required linearity, two modulation requirements are calculated: one from the intermodulation test, and one based on cross-modulation. In the intermodulation test, one continuous wave (with power P_1) and one modulated signal (with power P_2) are defined, with a frequency offset such that their mixing product falsl into the desired



(a)

(b)

Fig. 2. Spectral-masks combining ACS and blocking requirements, including the desired signal, for 1.4 MHz (a) and 20 MHz (b) channels.

signal band. While there is no explicit definition for cross-modulation in the LTE standard, the single-tone tests (Narrow-band blocking and ACS) can be used to calculate an estimate required IIP3. The calculations are performed assuming there is no selectivity, SNR = 0.4 dB (Section II) and the minimum sensitivity (worst-case).

The required third-order intersection point (IIP3) can be calculated by [3], [7]–[9]:

$$\text{IIP3 [dBm]} = P_1 \text{ [dBm]} + \frac{P_2 \text{ [dBm]} - P_{\text{MOD}} \text{ [dBm]}}{2}, \quad (2)$$

in which P_{MOD} represents the maximum acceptable power due to inter- or cross-modulation falling into the desired signal's band.

For the intermodulation test, P_{MOD} is due to the 3rd-order intermodulation product [3], [7], the maxmimum allowed power of which can be calculated (along the lines of [9]) by:

$$\begin{aligned} P_{\text{MOD}} \text{ [dBm]} = \; & P_{\text{REFSENS}} \text{ [dBm]} - \text{SNR [dB]} \quad (3) \\ + \; & X_{\text{REFDEG}} \text{ [dB]} + 10\log_{10}(B_{\text{signal}} \text{ [Hz]}) \\ - \; & 10\log_{10}(B_{\text{interferer}} \text{ [Hz]}), \end{aligned}$$

in which all quantities are the same as in Section II, X_{REFDEG} is the allowed sensitivity degradation defined for this test, B_{signal} is the desired signal's bandwidth and $B_{\text{interferer}}$ is the bandwidth of the modulated interferer. It is necessary to compensate for the (potential) bandwidth difference of interferer and desired signal (using the last two terms in (3)) since the overall SINR in the desired signal band is of interest. This results in slightly relaxed requirements for larger signal bandwidths, since the maximum interferer bandwidth in LTE is 5 MHz. The worst-case result based on (3) substituted in (2) is -21.7 dBm, as indicated in Table I.

The cross-modulation depends, among other things, on the modulation that is used and the frequency spacing. Therefore formulations to estimate the required IIP3 contain empirically determined correction factors, C_{XMD}. Out-of-band blocking is not addressed since in that case the blocker is far away from the desired signal. In the case of the cross-modulation, P_{MOD} can be calculated in a similar manner as for the intermodulation, corrected by C_{XMD}. Assuming that the cross-modulation is uniform in the desired receive band, this results in:

$$\begin{aligned} P_{\text{MOD}} \text{ [dBm]} = \; & P_{\text{REFSENS}} \text{ [dBm]} - \text{SNR [dB]} \quad (4) \\ + \; & X_{\text{REFDEG}} \text{ [dB]} - C_{\text{XMD}} \text{ [dB]}. \end{aligned}$$

For the ACS, $C_{\text{XMD}} = 1.6 \cdot \text{PAPR} - 20.75$ (PAPR $= 12$ dB is taken) is used [4], [8], while for the NB blocking $C_{\text{XMD}} = -2.4$ dB [4] is taken and a Tx leakage signal of -15 dBm is assumed to be present at the Rx input. Now, substituting (4) in (2) (P_1 represents the power of the distant blocker, P_2 the power of the close blocker), the required IIP3 due to cross-modulation is calculated. The worst-case result due to cross-modulation is +0.9 dB, as indicated in Table I. Note that any selectivity presented to the interfering signal relieves this requirement.

As indicated in Table I, the cross-modulation sets the linearity target of the total receiver. The indicated +0.9 dBm is the system requirement, but can be broken down over the receiver blocks. Assuming that all passive elements (such as the antenna, interconnects and acoustic filters) do not contribute significantly to nonlinearity, only two nonlinear blocks have to be accounted for: LNA and downconversion. In addition, assuming that the downconversion (mixer) and LNA contribute equally to the IIP3 of +0.9 dBm, the IIP3 of the downconversion IC and of the LNA are each required to be approximately 2.4 dBm. Since this is an approximation, a 3 dB implementation margin is taken, resulting in a required minimum LNA IIP3 of around +5.4 dBm. As shown in Table II, the SiGe and GaAs technologies are able to fulfill this requirement, while the CMOS technology falls short. This clearly shows the demanding targets for LNA performance,

TABLE II

Comparison of LNA's in various technologies. F, I_{CC}, V_{CC} and S_{21} denote operating frequency, supply current, supply voltage and gain, respectively.

Parameter	**SiGe** [10]	**GaAs I** [11]	**GaAs II** [12]	**CMOS** [13]
F [GHz]	1.9	1.9	1.95	2.1
I_{cc} [mA]	48	48	70	3.5
V_{cc} [V]	3.3	5	5	1.2
S_{21} [dB]	18.4	17.4	20.4	12
OIP3 [dBm]	32.5	36	35.7	9.5[1]
IIP3 [dBm]	14.1[2]	18.6[2]	15.3[2]	-2.5
NF [dB]	0.49	0.44	0.41	0.78

which can be achieved by using an external LNA in a suitable technology.

For illustration, assume a downconverter IIP3 of 10 dBm, and a total gain of 40 dB. In this case a SiGe LNA with a 14 dBm IIP3 and 18 dB gain (NXP BGU8052 [10]) results in a cascaded IIP3 of 5.3 dBm.

V. Conclusion

In this paper a clear overview of the requirements in the latest LTE standard for a receiver front-end is presented using approximate calculations. The required noise figure per band is given and broken down to the LNA spec. In addition, the required LNA linearity is determined, and it is shown that SiGe and GaAs can achieve both required NF and IIP3. The key LTE handset receiver front-end requirements are summarized. The presented calculations can be easily modified to other situations and applications, such as WiFi of 5G applications. As it is expected that 5G will integrate LTE-A and WiFi and add a new air interface [14], [15], the requirements are bound to get more stringent. Especially considering the expected flexibility requirement, it is safe to say that the front-end requirements for 5G handsets will be very tough indeed.

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