OPTIMAL DISTRIBUTION OF THE RF FRONT-END SYSTEM SPECIFICATIONS TO THE RF FRONT-END CIRCUIT BLOCKS

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ABSTRACT

Rather delicate, distribution of the system specifications to the individual receiver blocks has not gained any exactness for the last decades. When distributing the system specifications to each of the blocks in the receive chain, it is rather common practice to consider each performance parameter separately. However, as both the noise and the linearity performance depend on the gain of the corresponding circuit blocks, the noise figure (*NF*) and the third order intercept point (*IP3*) optimization procedure are not mutually exclusive. Therefore, a procedure for the optimal allocation of the performance parameters to the individual RF front-end circuit blocks is introduced in this paper. Optimizing the system performance with respect to the ratio $NF/IP3^2$, the maximum dynamic range design point can be found, satisfying both the noise and the linearity requirements.

1. INTRODUCTION

RF system performance is usually satisfied by (over)designing the RF front-end circuits, i.e., chasing for the best possible noise figure, linearity and gain [1]. In such a race, little space (and time) is left for new concepts capable of achieving even better performance.

The lack of an all-encompassing treatment of RF front-ends at a high level is just an example. Having gained no exactness, a distribution of the system requirements to the corresponding RF front-end circuit blocks rather relies on magic in the hands of the experienced designer [2,3]. Therefore, a thorough front-end analysis is introduced in this paper, giving insight into the optimal distribution of the system requirements to the circuit blocks in the receive chain. Accordingly, the optimum *individual distribution* design point and the *mutually dependent* noise/linearity *distribution* design point are determined.

The paper is divided into four sections. A distribution procedure of the individual specifications to the system blocks is described in Section 2. The distribution of the mutually dependent noise and linearity performance parameters to the RF front-end receiver circuits is outlined in Section 3. The conclusions are summarized in Section 4.

2. DISTRIBUTION OF THE INDIVIDUAL NF AND IP3 SPECIFICATIONS

In the analysis to come we will, for the sake of simplicity, refer to the RF receiver as to the system consisting of a LNA, a mixer and a base-band (BB) circuitry, as shown in Fig. 1. If *G*, *NF* and *IP3* are the power gain, the noise figure and the third order intercept point of the corresponding RF blocks, as indicated in Fig. 1, the equivalent noise and the linearity performance can be expressed by the Friis formulae, as given by Eqs. (1) and (2).

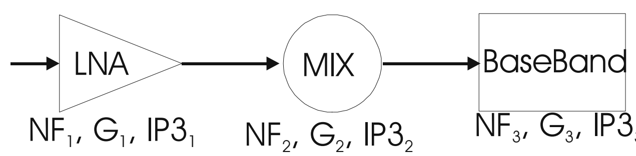

Fig. 1 Simplified RF front-end receiver model.

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

$$\frac{1}{IP3^2} = \frac{1}{IP3_1^{\ 2}} + \frac{G_1}{IP3_2^{\ 2}} + \frac{G_1 G_2}{IP3_3^{\ 2}} + ... \quad (2)$$

As both the analysis and the obtained results, regarding the distribution of the specifications, hold equally for *NF* and *IP3*, we will perform the analysis by referring to *NI* as the noise and/or linearity performance parameter (PP). Accordingly, expressions (1) and (2) can be written as:

$$NI = NI_1 + NI_2 + NI_3 = \alpha \cdot NI_E + \beta \cdot NI_E + \gamma \cdot NI_E \quad (3)$$

Here, NI_1, NI_2 and NI_3 stand for the PP contribution of the each block in the receive chain after being transferred to the input of the RF front-end system. The coefficients α, β and γ, represent the deviation of the PP of the LNA, mixer and base-band circuitry from the equilibrium point NI_E, respectively. $NI_E = NI_D - 10log(k)$ (in dB) is the point of the equal contribution of all the blocks' performance parameters to the overall PP of the receiver, k being the number of the considered front-end blocks (in this case k=3). If NI_D is the required (desired) performance parameter of the complete RF front-end, in order to satisfy the system specification, condition (4) must be satisfied

$$B = 10\,log\left(3 - 10^{A/10} - 10^{C/10}\right) \quad (4)$$

A, B and C being the deviations α, β and γ in dB scale, respectively.

Given condition (4), the PP (in dB) of the each block in the receiver chain, NIB, can now be expressed as:

$$NIB_1 = NI_E + A \quad (5)$$

$$NIB_2 = NI_E + G_1 + B \quad (6)$$

$$NIB_3 = NI_E + G_1 + G_2 + C \quad (7)$$

The relation between the deviations A and B is graphically shown in Fig. 2, C being the parameter. Even though rather simple, Eq. (4) and Fig. 2 determine a design space and a design central/optimal point for the RF front-end blocks. As the PP of the receiver depends equally on α (A) and β (B), also the dependency of the deviation A with respect to the deviation B is the same as the dependency of parameter B to parameter A. Accordingly, the most optimal design point in the design space satisfies the equality

$$\partial A/\partial B = \partial B/\partial A \quad (8)$$

i.e., the slope of both dependencies is the same.

Solving Eq. (8), with the aid of Eq. (4), results in A=B as the optimum design choice. However, as the explicit solution of the equation depends also on the base-band circuitry performance, i.e., parameter C, two cases are distinguished. First, if C=0, PP of the BB is at the equilibrium point, the optimal design point is the one satisfying A=B=0, being the already defined equilibrium point. In case of a negligible contribution of the BB to the equivalent PP of the receiver, C=–∞, A=B=1.76 is the optimal choice. Deviation from the equilibrium point always results in a waste of performance, i.e., the improvement in a single block performance is always smaller than the improvement in the overall receiver performance. For example, improving the *NF(IP3)* of the LNA for A=–3dB (point L) with respect to the equilibrium design point, relaxes the *NF(IP3)* requirements of the mixer for B=1.76dB (if C=0), i.e., a 1.24dB waste of the performance for the same desired (required) receiver noise-figure(linearity) $NF_D(IP3_D)$. On the other hand, relaxing the *NF (IP3)* of the LNA for A=3dB would require an infinite noise-figure(linearity) improvement of the mixer block (if C=0). As shown above, a rather common practice of taking into account only the PP of the LNA and the mixer, when distributing the specifications to the RF circuit blocks, would result in 1.76dB relaxed required *NF(IP3)* performance of the very same blocks (point N). This under-estimation would in the end lead to a design not satisfying given specifications of the complete receive chain, i.e., LNA-mixer-base-band combination.

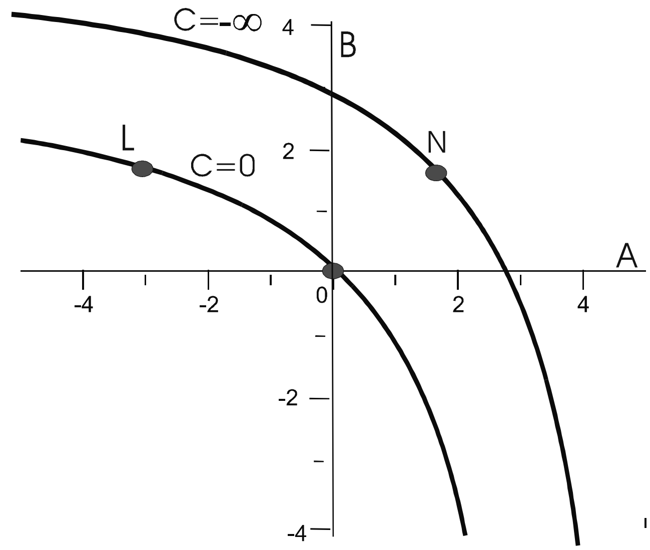

Fig. 2. Condition for the equal contribution of a block performance parameter after being transferred to the input of the receiver.

Finally, it becomes obvious that improving receiver block specifications for more than a few dB from the equilibrium point (Fig. 2), the requirements for the other blocks in the receive chain don't relax drastically. This implies that (over)design, i.e., design for the best noise figure and the best *IP3* of a circuit, can not outperform a rather moderate design with an optimal specification distribution scheme.

2.1. Example

Given the *NF* and *IP3* of both the RF front-end and the LNA, NF_D=10dB, $IP3_D$=-10dBm, NF_1=2dB, $IP3_1$=-1dBm, let us allocate the noise figure and the third order intercept point to the mixer, following the analysis outlined above. With the aid of Eqs. (4)-(8), the equilibrium *NF* and *IP3* points equal NF_E =5dB and $IP3_E$=-5dBm. If G_1=12dB, the PP of the mixer will be, as calculated by Eq. (6), $IP3_2$=2.85dB and NF_2=21dB. These PPs provide the whole system with the required specifications. In order to determine the gain of the mixer, let us assume that the base-band circuitry hardly affects equivalent input noise figure or linearity, i.e., γ<<1 (C=-10dB). Now, from Eq. (7), G_2=8dB for NF_3 to be negligible and G_2=2dB for $IP3_3$ to be dominant, assuming typical values for the base-band PPs, NF_3=15dB and $IP3_3$=15dBm. Choosing for G_2=8dB results in $C(IP3)$=-4 and $C(NF)$=-10, with the required value for $IP3_2$=3.6dBm and NF_2=21dB. For G_2=2dB, $C(NF)$=-4 and $C(IP3)$=-10, with NF_2=20dB and $IP3_2$=2.85dBm. Based on the properties of the BB block, the appropriate set of the mixer performance parameters will finally be chosen.

3. DISTRIBUTION OF THE MUTUALLY DEPENDENT NF/IP3 SPECIFICATIONS

When distributing the system specifications to each of the blocks in the receive chain, it is a rather common practice to consider each performance parameter separately. However, as both the noise and the linearity depend on the gain of the corresponding blocks, the noise figure and the third order intercept point optimization procedure are not mutually exclusive [4]. Because there has not yet been developed any exact optimization procedure, Eqs. (1) and (2) are extensively exercised, for a large number of the *G-NF-IP3* combinations, until all the requirements are satisfied. As there are many combinations that satisfy desired specifications, the "magic" of the experienced designer is what makes the decision.

Not relying on experience and magic, we will develop procedure for the mutual *NF* and *IP3* distribution by optimizing the system performance neither to *NF* nor to *IP3* but to the $NF/IP3^2$ ratio (*NF-IP*3 in dB). This appears to be a natural decision-making optimization parameter, establishing a direct relation with the spurious free dynamic range of the system *SFDR*, proportional to *IP*3-*NF* (in dB). Being inversely proportional to the *SFDR*, we will refer to the $NF/IP3^2$ as to the inverse dynamic range (*IDR*).

3.1. Optimality criterion

For the sake of an easier interpretation of the optimization procedure, in the analysis to come, we will resort to a two-block RF front-end system. Combining Eqs. (1) and (2), the inverse dynamic range can be expressed as:

$$IDR = \frac{NF}{IP3^2} = \left(NF_1 + \frac{NF_2 - 1}{G_1} \right)\left(\frac{1}{{IP3_1}^2} + \frac{G_1}{{IP3_2}^2} \right) \qquad (9)$$

Assuming that for any NF_1, $IP3_1$ and NF_2, $IP3_2$ combination there exist an optimal gain value $G_{1,OPT}$, it can be found by solving

$$\partial IDR / \partial G_1 = 0 \Rightarrow G_1 = G_{1,OPT} \qquad (10)$$

Now, the optimum gain $G_{1,OPT}$ (dB) and the optimum dynamic range IDR_{OPT} (dB) equal:

$$G_{1,OPT} = (NF_2 + IP3_2 - NF_1 - IP3_1) / 2 \qquad (11)$$

$$IDR_{OPT} = 20 log\left(10^{(NF_1 - IP3_1)/20} + 10^{(NF_2 - IP3_2)/20}\right) \qquad (12)$$

The LNA's optimum gain $G_{1,OPT}$ (11) provides the RF front-end with the optimum inverse dynamic range (12), i.e., a maximum dynamic range. The lower the *IDR,* the larger the dynamic range.

Let us now elaborate in more detail on the simultaneous noise and linearity optimization procedure, i.e., *IDR* optimization. The optimum *IDR* design point, even though providing the RF front-end with the maximum dynamic range, is not always the point that satisfies the individual noise and linearity performance. It is however the case if IDR_{OPT} satisfies conditions (13) and (14), that are obtained by combining Eqs. (1), (2), (11) and (12).

$$2NF_{OBT} = NF_1 + IP3_1 + IDR_{OPT} < 2NF_D \qquad (13)$$

$$2IP3_{OBT} = NF_1 + IP3_1 - IDR_{OPT} > 2IP3_D \qquad (14)$$

NF_{OBT} and $IP3_{OBT}$ being the obtained PP.

Suppose that the noise and the linearity performance of the LNA are known, then the above conditions can be transformed into condition (15) that however coincides with Eq. (16).

$$NF_2 - IP3_2 < 20 log\left(10^{\frac{2NF_D - NF_1 - IP3_1}{20}} - 10^{\frac{NF_1 - IP3_1}{20}}\right) \qquad (15a)$$

$$NF_2 - IP3_2 < 20 log\left(10^{\frac{-2IP3_D + NF_1 + IP3_1}{20}} - 10^{\frac{NF_1 - IP3_1}{20}}\right) \qquad (15b)$$

$$NF_1 + IP3_1 = NF_{OBT} + IP3_{OBT} \qquad (16)$$

to be often referred to in the reminder of the paper.

Let us clarify the procedure outlined above with an example. Given NF_D=10dB, $IP3_D$=-10dBm, NF_1=9dB, $IP3_1$=5dBm, the noise figure and third order intercept point of the mixer, from (15), must satisfy the inequality NF_2-$IP3_2$ <-7.7dB, so that the over-all system performance are within the specifications. Pair NF_2=10dB and $IP3_2$=17.7dBm can, for example, be a design point, resulting in an optimum gain $G_{1,OPT}$=6.85dB and IDR_{OPT}=6dB. As will be explained in the next sub-section, for the system with a poor noise or linearity performance, as it is the case in this example, the optimum design point can be rather unrealistic with respect to the requirements that it imposes on the system blocks.

3.2. Equality criterion

Let us now consider the criteria for the equivalent improvement in the noise and linearity performance from the desired/specified RF front-end specifications NF_D and

$IP3_D$. The PP equivalent-contribution gain value $G_{1,EQ}$ can be found from Eq. (17), that however coincides with Eq. (18).

$$NF_D - NF_{OBT} = -\Delta \quad (17a)$$

$$IP3_{OBT} - IP3_D = -\Delta \quad (17b)$$

$$NF_{OBT} + IP3_{OBT} = NF_D + IP3_D \quad (18)$$

Here, $\Delta<0$ stands for the improvement in both the *NF* and the *IP3* of the front-end system, with the obtained specs being always better than the desired ones, i.e. $NF_{OBT}<NF_D$ and $IP3_{OBT}>IP3_D$. The range of Δ is:

$$\Delta \in \left(max\{ IP3_D - IP3_1, NF_1 - NF_D \}, 0 \right) \quad (19)$$

Given, for example, NF_1 and $IP3_1$, the range of $NF_2 - IP3_2$ values is limited to

$$NF_2 - IP3_2 < 10\,log\left(10^{(\Delta + NF_D)/10} - 10^{NF_1/10}\right) + 10\,log\left(10^{(\Delta - IP3_D)/10} - 10^{-IP3_1/10}\right) \quad (20)$$

with the gain $G_{1,EQ}$ as given below by Eq. (21).

$$G_{1,EQ} = NF_2 - 10\,log\left(10^{(\Delta + NF_D)/10} - 10^{NF_1/10}\right) \quad (21a)$$

$$G_{1,EQ} = IP3_2 + 10\,log\left(10^{(\Delta - IP3_D)/10} - 10^{-IP3_1/10}\right) \quad (21b)$$

Considering the same example as in the case of the optimum gain point, the following is obtained: $\Delta \in (-1,0]$, and $NF_2 – IP3_2$ =1.6 for chosen Δ=-0.9dB. One of the solutions NF_2=10dB and $IP3_2$=8.4dBm with the $G_{1,EQ}$=17.3dB, provides the system with the IDR_{EQ}=18.2dB (NF_{OBT}=9.1dB and $IP3_{OBT}$=-9.1dBm), i.e., equal improvement of 0.9dB in both the noise figure and the third order intercept point.

3.3. Optimality vs. equality

With the aid of Eq. (16), being the optimality criterion, and Eq. (18), being the equality criterion, the condition where these criteria meet has a final form:

$$NF_1 + IP3_1 = NF_D + IP3_D \quad (22)$$

The striking property of the *optimality/equality condition is that it coincides with the optimum individual specification-distribution point*, resulting from Eq. (7). Namely, the equilibrium design point (the equal contribution of each block PP to the system PP) encompasses the optimum design point (maximum dynamic range) and the equality point (equal contribution of the noise figure and the third order intercept point to the *IDR*), if condition (22) is satisfied. Complying with Eq. (22), the allocation of all the specifications to each of the blocks in the RF front-end receive chain is rather simple, and fully controlled by means of Eqs. (11), (15), (20) and (21).

For the same required specifications, NF_D=10dB, $IP3_D$= -10dBm, given NF_2=15dB and $IP3_2$=5dBm, the performance parameters allocated to the LNA according to Eq. (22) result in a design point satisfying all the optimality design criteria, i.e., the optimal distribution of both the individual and the mutually dependent specifications. With the aid of Eqs. (5) and (22), the parameters of the optimal design point are NF_1=5dB, $IP3_1$=-5dB, $G_{1,OPT}$=10dB and IDR_{OPT}=16dB with NF_{OBT}=8dB and $IP3_{OBT}$=-8dBm.

4. CONCLUSIONS

The procedure for the optimal allocation of the performance parameters to the individual RF front-end circuit blocks is introduced in this paper. Optimizing the system performance with respect to the ratio $NF/IP3^2$, the maximum dynamic range design point can be found, satisfying both the noise and the linearity requirements. It is shown that there exists a design point for which the contribution of each block performance parameter to the equivalent system performance parameter are equal and that it coincides with both a design point for the maximum dynamic range and a design point for which the improvement in each performance parameter with respect to the requirements is equal.

5. REFERENCES

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