Low-power radio design for the IoT
Exercise 6 (31.03.2022)

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Problem 1 Receiver Front-End

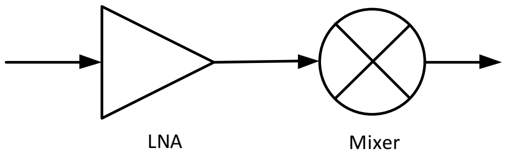

Figure 1: Block diagram of a receiver front-end

The system shown in Fig. 1 consists of a cascade of an LNA followed by a mixer. The system has the following specifications:

- Total Gain, $G_{tot} \geq 20\,\text{dB}$
- Total Noise Figure, $NF_{tot} = 4\,\text{dB}$
- Total $IIP3$, $IIP3_{tot} = 5\,\text{dBm}$

1.1 LNA Design

- Design the LNA (calculate the gain) such that its noise figure $NF_{LNA} < 1\,\text{dB}$. Calculate its $IIP3$ if $IIP3_{mixer} = 20\,\text{dBm}$. Assume the noise figure of the mixer $NF_{mixer} = 10\,\text{dB}$.
- Design the LNA such that its noise figure $NF_{LNA} = 3\,\text{dB}$. Calculate the $IIP3$ assuming $IIP3_{mixer} = 20\,\text{dBm}$. Assume the noise figure of the mixer $NF_{mixer} = 10\,\text{dB}$.
- Comment on the results.

1.2 Mixer Design

- Assuming that the mixer stage contributes half of the total gain, compute the Noise Figure of the mixer such that the Noise Figure of the LNA is less than 1 dB.
- Assuming that the mixer stage contributes one-fourth of the total gain, compute the Noise Figure of the mixer such that the Noise Figure of the LNA is less than 1 dB.
- Comment on the results.

Solutions to Exercise 6 (31.03.2022)

Problem 1 Receiver Front-End

1.1 LNA Design

1.1.1 Case 1: $NF_{LNA} = 1\,\mathrm{dB}$

Friis equation helps to calculate the gain required for a stage depending on the noise figure (NF) constraints. In this problem, as the individual and overall NF's are given, it is straightforward to find G_{LNA} by substituting the values into Friis equation as given below.

$$\begin{aligned} F_{tot} &= F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 \cdot G_2} + ... \\ F_{tot} &= F_{LNA} + \frac{F_{mixer} - 1}{G_{LNA}} \end{aligned} \tag{1}$$

where $F_1, F_2, ...$ are the noise factors and $G_1, G_2, ...$ are the power gains expressed as a magnitude and not in dB. Similar to the Friis equation, cascaded $IIP3$ equation is used to express overall $IIP3$ in terms of individual $IIP3$'s and individual gains as,

$$\begin{aligned} \frac{1}{P_{IP3tot}} &= \frac{1}{P_{IP3_1}} + \frac{G_1}{P_{IP3_2}} + \frac{G_1 \cdot G_2}{P_{IP3_3}} + ... \\ \frac{1}{P_{IP3tot}} &= \frac{1}{P_{IP3_{LNA}}} + \frac{G_{LNA}}{P_{IP3mixer}} \end{aligned} \tag{2}$$

where P_{IP3} is expressed in mW.

In order to use (1), the quantities expressed as dB need to be converted in linear.

$$NF \triangleq 10 \log (F) \Rightarrow F = 10^{(NF/10)} \tag{3}$$

By applying (3) to NF_{LNA}, NF_{tot} and NF_{mixer}, we obtain $F_{LNA} = 1.26$, $F_{tot} = 2.51$ and $F_{mixer} = 10$.

By manipulating (1), we obtain the LNA gain G_{LNA}:

$$G_{LNA} = \frac{F_{mixer} - 1}{F_{tot} - F_{LNA}} = \frac{10 - 1}{2.51 - 1.26} = 7.18 \tag{4}$$

which, expressed in dB as power gain becomes $G_{LNA}|_{\mathrm{dB}} = 10\ \log(G_{LNA}) = 8.56\,\mathrm{dB}$

In order to use (2), the quantities expressed as dB or dbm need to be converted in linear.

$$IIP3 \triangleq 10 \log (P_{IP3}) \Rightarrow P_{IP3} = 10^{(IIP3/10)} \tag{5}$$

By applying (5) to $IIP3_{\mathrm{tot}}$ and $IIP3_{\mathrm{mixer}}$, we obtain $P_{IP3tot} = 3.16\,\mathrm{mW}$ and $P_{IP3mixer} = 100\,\mathrm{mW}$.

By manipulating (2), we obtain P_{IP3LNA}:

$$P_{IP3LNA} = \left(\frac{1}{P_{IP3tot}} - \frac{G_{LNA}}{P_{IP3mixer}} \right)^{-1} = \left(\frac{1}{3.16\,\mathrm{mW}} - \frac{7.18}{100\,\mathrm{mW}} \right)^{-1} = 4.09\,\mathrm{mW} \tag{6}$$

Finally, by applying (5), be obtain $IIP3 = 6.12\,\mathrm{dBm}$

1.1.2 Case 2: $NF_{LNA} = \mathbf{3\,dB}$

When NF_{LNA}=3 dB, G_{LNA} and $IIP3_{LNA}$ calculated using eq. (1) and (2) are 12.41 dB and 8.48 dBm.

1.1.3 Comments

Comment on LNA Gain:

1. For a given overall NF, the gain of the LNA (or the first stage) is directly proportional to the NF of the LNA which means that if the NF of LNA increases, it demands a higher gain from the LNA stage (as evident from case 2 where a higher gain is required). This is necessary to minimize the noise contribution from the succeeding stages in the receiver.

2. Since the gain achievable practically from an LNA stage is limited from 15 dB to 20 dB, it is necessary to make sure that the NF of LNA does not exceed beyond a certain value. If it is not possible to limit the NF of LNA, then the overall NF constraints cannot be achieved.

Comment on LNA $IIP3$:

1. For a given overall $IIP3$, $IIP3$ of the LNA is directly proportional to the gain of the LNA (as evident from case 2 where the $IIP3_{lna}$ increases compared to case 1). The disadvantage of higher gain is that it demands a good linearity performance which means that the effective voltage (V_{GS}-V_{T0}) of the LNA input needs to be increased resulting in an increase in the power consumption of the LNA.

1.2 Mixer Design

1.2.1 Case1: $G_{mixer} = G_{tot}/2$ and Case2: $G_{mixer} = G_{tot}/4$

Assuming $G_{mixer} = G_{tot}/2$ gives $G_{LNA} = 3\,\mathrm{dB}$ and assuming $G_{mixer} = G_{tot}/4$ gives $G_{LNA} = 6\,\mathrm{dB}$. Since $F_{mixer} = (F_{tot} - F_{LNA}) \cdot G_{LNA} + 1$, noise figure of the mixer is found to be 5.45 dB for case 1 and $NF_{mixer} = 7.8\,\mathrm{dB}$ for case 2.

1.2.2 Comments

This problem gives the conclusion that for a given overall NF, NF_{mixer} can be relaxed whenever the gain of the LNA increases because a higher gain in the LNA stage minimizes the noise contribution of the mixer.