Low-power radio design for the IoT
Exercise 6 (29.04.2021)

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Problem 1 Link budget

In this example we will look into a simplified link budget estimation for a Bluetooth transceiver. According to the Bluetooth specifications the maximum transmit power must not exceed $P_{Tx,max} = 20\,\text{dBm}$. The system operates in the $f_c = 2.4\,\text{Ghz}$ ISM band, where $B = 1\,\text{Mhz}$ bandwidth is available for each Bluetooth channel. This particular transceiver is using GMSK modulation that requires $SNR = 10\,\text{dB}$ to achieve the desired BER performance. Assume that we want to keep a margin of 10 dB in order to make sure that we have a reliable link (received power must remain 10 dB above the sensitivity level), and that antenna gain on the transmitter and the receiver side is $G_{Tx} = G_{Rx} = 0\,\text{dB}$. Consider a source of thermal noise at the input of the receiver with maximum availabe power $P_{n,i} = kTB$. The power attenuation (in dB) when transmitting a signal with wavelenght λ over a distance d is given by:

$$A_{dB} = 10log\left(\frac{(4\pi)^2 d^2}{\lambda^2}\right) \tag{1}$$

In all the calculations you can use $10log(kT) = -174\,\text{dBm}$.

- Find the receiver sensitivity if the transceiver needs to operate at a range of 1 km. Find the maximum Noise Figure (NF) of the receiver front-end in order to achieve the desired sensitivity.
- Recalculate the maximum noise figure if the range is now limited to 100 m.
- Now imagine that the receiver you use has the noise figure $NF = 10\,\text{dB}$. What is the available range in this case?
- Assume that you want to extend the range of the transceiver but you are not allowed to transmit above 20 dBm and that no additional antenna gain is available. The only remaining system parameter is channel bandwidth. Calculate the available bandwidth if the desired range is 10 km.

Problem 2 Indirect conversion architecture

The sliding-IF architecture shown in Fig. 1 is designed for the 11a band (Fig. 2).

- Determine the required LO frequency range.
- Determine the image frequency range.
- Determine the interferer frequencies that can appear in the output baseband as a result of mixing with the third harmonic of the

  first LO or the third harmonic of the second LO.

Problem 3 Direct conversion architecture

The simplified Hartley architecture shown in Fig.3 incorporates mixers having a voltage conversion gain of A_{mix} and an infinite input impedance.

- Taking into account only the noise of the two resistors, compute the noise gure of the receiver with respect to a source resistance of R_S at an IF of $1/(R_1C_1)$.

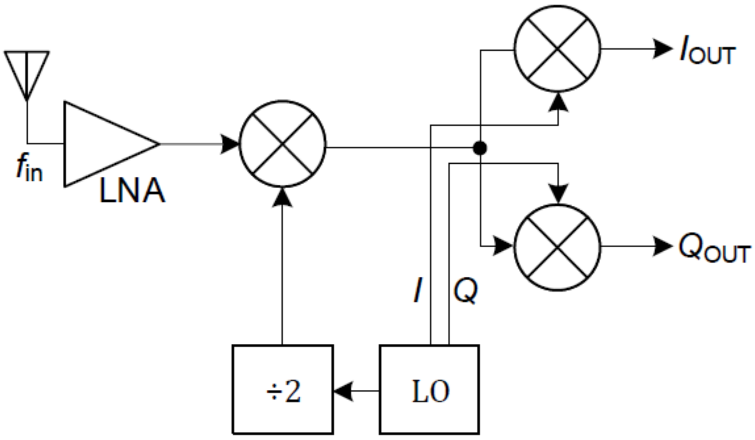

Figure 1: Sliding-IF RX for 11a.

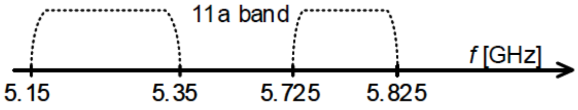

Figure 2: 11a band.

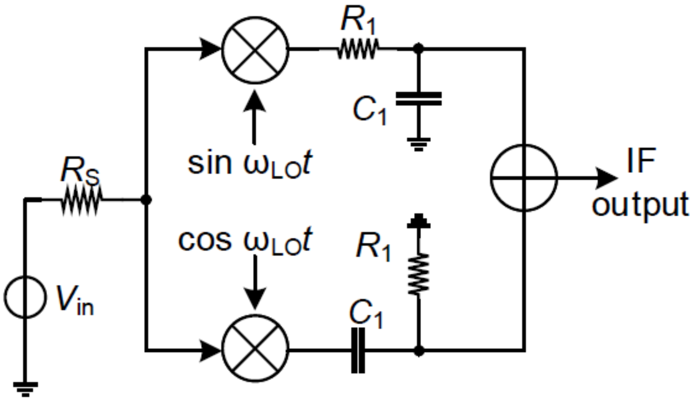

Figure 3: Simplified Hartley RX.

Solutions to Exercise 6 (29.04.2021)

Problem 1 Link budget

- Find the receiver sensitivity if the transceiver needs to operate at a range of 1 km. Find the maximum Noise Figure (NF) of the receiver front-end in order to achieve the desired sensitivity.

For the given parameters, the power available at the receiver will be:

$$P_{Rx} = P_{Tx} + G_{Tx} - 10log\left(\frac{(4\pi)^2 d^2}{\lambda^2}\right) + G_{Rx} = -80\,\text{dBm} \tag{1}$$

where λ is the carrier wavelength.

Accounting for the 10 dB margin the sensitivity of the receiver needs to be better than −90 dBm . Receivers typically consist of an RF/analog front-end and a digital baseband. To achieve this sensitivity we must make sure that the SNR at the output of the analog front-end remains above the given level for an input signal of −90 dBm. The noise figure of the analog front-end is expressed as:

$$NF = SNR_{in} - SNR_{out} = P_{Rx} - 10log(kTB) - SNR_{out} \tag{2}$$

And the maximum allowed noise figure is then:

$$NF = P_{Rx,min} - 10log(kTB) - SNR_{out} = 13.95\,\text{dBm} \tag{3}$$

- Recalculate the maximum noise figure if the range is now limited to 100 m.

Repeating the calculation for a distance $d = 100\,\text{m}$ yields a maximum noise figure of 33.94 dBm. In general, power consumption of receivers is related to the noise figure. If we can afford a higher noise figure we can save power of the receiver and extend the autonomy of the device. However we can see that the available range is now decreased.

- Now imagine that the receiver you use has the noise figure $NF = 10\,\text{dB}$. What is the available range in this case?
- Assume that you want to extend the range of the transceiver but you are not allowed to transmit above 20 dBm and that no additional antenna gain is available. The only remaining system parameter is channel bandwidth. Calculate the available bandwidth if the desired range is 10 km.

Solving Eq. 2 for d with $B = 1\,\text{MHz}$ gives an available range $d = 1575\,\text{m}$ for $NF = 10\,\text{dB}$.

- Assume that you want to extend the range of the transceiver but you are not allowed to transmit above 20 dBm and that no additional antenna gain is available. The only remaining system parameter is channel bandwidth. Calculate the available bandwidth if the desired range is 10 km.

Since the maximum power is limited by regulation and the noise figure of the receiver is fixed, the only parameter that is left is bandwidth. As you can see, the input noise of the receiver depends on the bandwidth as in kTB. Decreasing the bandwidth therefore decreases the input noise power and can extend the range of the radio. For the desired 10 km distance the bandwidth must be reduced to 25 kHz. As a consequence the data rate will now drastically reduce (it is proportional to channel bandwidth). As a general rule, there will always be a trade-off between power consumption, range and data rate.

Problem 2 Indirect conversion architecture

- Determine the required LO frequency range.

Sliding-IF Receivers employ only one oscillator and the LO frequency is therefore derived from the first by "frequency division." In our case, the divider factor is $N = 2$. We know that:

$$f_{in} = f_{LO1} + \frac{1}{N} f_{LO1} \Rightarrow f_{LO1} = \frac{2}{3} f_{in} \tag{4}$$

Then, considering the RF range to be $FR_{RF} = [5.15, 5.825\,\text{GHz}]$, the LO frequency range is $FR_{LO} = 2/3\,FR_{RF} = [3.433, 3.833\,\text{GHz}]$.

- Determine the image frequency range.

$f_{image} = 2f_{LO1} - f_{in} = \frac{1}{3} f_{in} \Rightarrow FR_{image} = 1/3 FR_{RF} = [1.727,\ 1.942\,\text{GHz}]$

- Determine the interferer frequencies that can appear in the output baseband as a result of mixing with the third harmonic of the

  rst LO or the third harmonic of the second LO.

We can write the interferer frequencies $f_{int,1}$ of the first LO as:

$$f : int, 1 = 3f_{LO1} + m\frac{1}{2} f_{LO1} = \left(3 + \frac{m}{2}\right) f_{LO1} \tag{5}$$

and the interferer frequencies $f_{int,2}$ of the second LO as:

$$f : int, 2 = nf_{LO1} + \frac{3}{2} f_{LO1} = \left(n + \frac{3}{2}\right) f_{LO1} \tag{6}$$

Problem 3 Direct conversion architecture

In order to compute the noise factor, one needs to evaluate the noise contribution due to the resistances R_1 and the noise from the source resistance R_S.

The output noise due to the R_1 in both branches results form filtering of the resistance thermal noise by the corresponding RC network. For each branch i, one has:

$$\overline{v_{n,i}^2} = \overline{v_{n,R_1}^2} \left\| \frac{1}{1 + j\,\omega R_1 C_1} \right\|^2 \tag{7}$$

Which at $\omega_{IF} = 1/(R_1 C_1)$ results in its contribution to the output noise:

$$\overline{v_{n,i}^2} = \overline{v_{n,R_1}^2}/2 \tag{8}$$

The total output noise due to the R_1 resistances is then simply given by

$$\overline{v_n^2} = \overline{v_{n,R_1}^2} = 4kTR_1B \tag{9}$$

One now has to compute the output noise due to the source resistance R_S. For any of the branches, we have:

$$\overline{v_{n,i}^2} = \overline{v_{n,R_S}^2}.A_{mix}^2. \left\| \frac{1}{1 + j\,\omega R_1 C_1} \right\|^2 \tag{10}$$

Which summing for both branches and evaluating at the IF as previously yields:

$$\overline{v_n^2} = \overline{v_{n,R_S}^2}.A_{mix}^2 \tag{11}$$

Therefore, one can now compute the noise figure as

$$F = \frac{\overline{v_{n,R_S}^2}A_{mix}^2 + \overline{v_{n,R_1}^2}}{\overline{v_{n,R_S}^2}A_{mix}^2} = 1 + \frac{R_1}{A_{mix}^2 R_S} \tag{12}$$