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Institut Mines-Telecom

Transceiver Specifications

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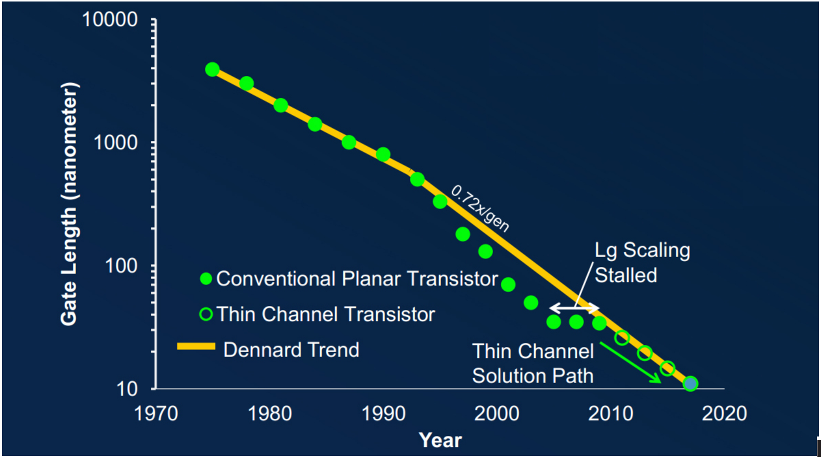
ICS905

Exercise 1-Why transceivers are this complex?

- Transceiver purpose is to receive and transmit signals
- Digital processing becomes less and less complex and power hungry with technology shrinking



Exercise 1-Why transceivers are this complex?

Power consumption of digital circuits

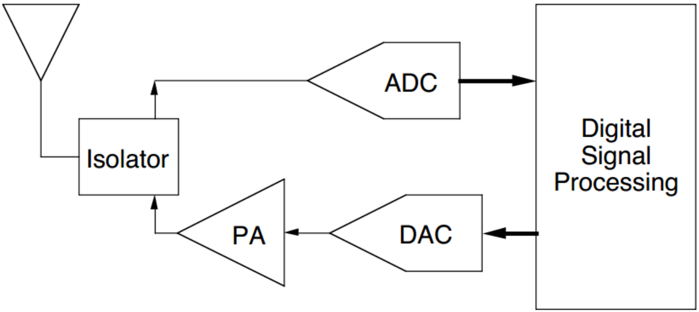
$$P = \underbrace{\frac{1}{2} \cdot \alpha \cdot CL \cdot freq \cdot VDD^2}_{Dynamic\ \ Power} + \underbrace{I_{leak} \cdot VDD}_{Leakage\ \ Power}$$

α is the activity or the probability to have a toggle in the gate
CL is the load, /2 from one technology node to the following
$freq$ is the operation frequency
VDD is the power supply
I_{leak} is the leakage current

Exercise 1-Why transceivers are this complex?

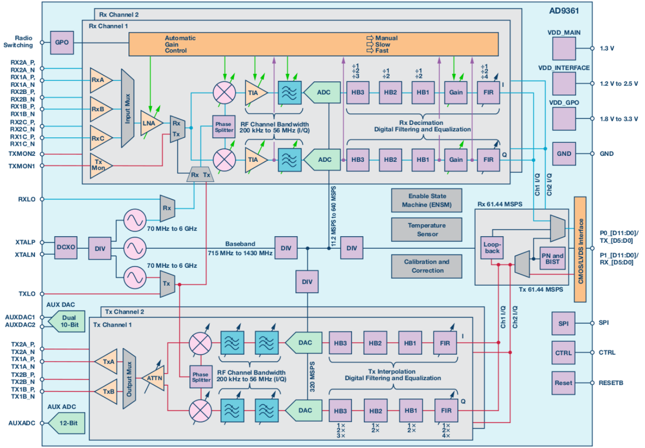
Mitola's Idea: Software Defined Radio proposed in 1991

Let's transfer all the processing to digital domain



BUT!!

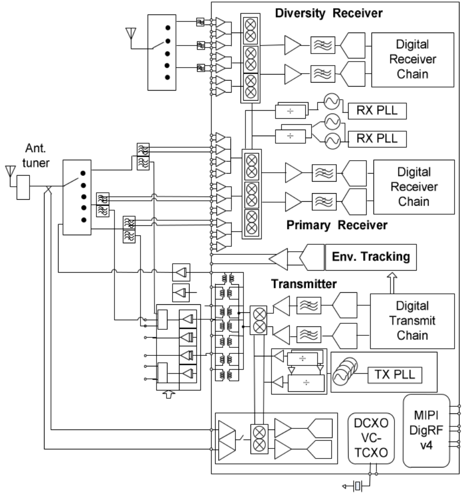
Exercise 1-Why transceivers are this complex?

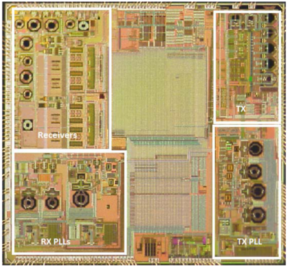


AD9316 Wideband Transceiver of Analog devices

LO 70 MHz-6 GHz, Channel bandwidth up to 56 MHz, CMOS 65nm

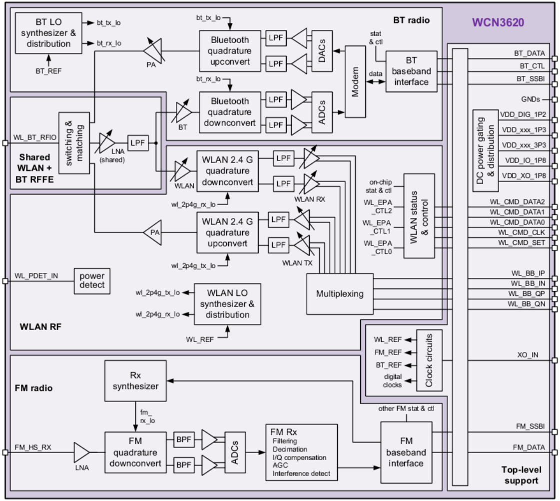
Exercise 1-Why transceivers are this complex?





WCDMA/HSDPA/TDD LTE by Marvell in 55 CMOS

Exercise 1-Why transceivers are this complex?



Connectivity transceiver by Qualcomm (WiFi, Bluetooth, BLE)

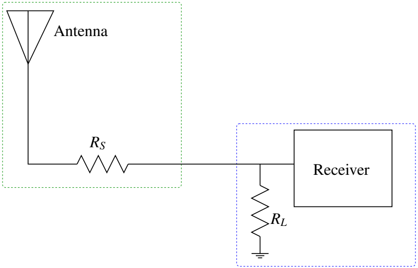
LO 2.4 GHz and 5 GHz , CMOS 65nm

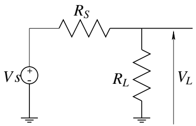
Exercise 1-Why transceivers are this complex?

- Signal Swing too low at the ADC input

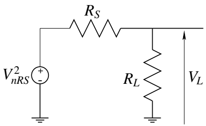
  $\Longrightarrow$ Low Noise Amplifier
- ADC Sampling frequency f_s should be twice higher than the interfere spectrum $>$10 GHz
  $\Longrightarrow$ Mixer
- Signal power can be too low compared to the others signals (blockers/interferers)
  $\Longrightarrow$ Filtering
- Power consumption P ADC would extremely high (For a 10 GHz 20 bit ADC, $P > 100$ W!!!!!)

Exercise 2-Thermal noise, no winning with you!!





Equivalent circuit for the input signal



Equivalent circuit for the R_s thermal noise

$$PSD_{nRs} = V_{nRS\ in\ 1\ Hz}^2 = 4KTR_s$$

Reminders (or not)?

Signal Power in a resistor

$$P_{lin} = \frac{V^2}{R}$$

Power in dBm

$$P_{dBm} = 10 \cdot log_{10}(\text{Power in mW})$$

Relation between Power and Power Spectral Density (PSD)

$$P_{lin} = \int_{Bw} PSD_{lin} \cdot df$$

In case, the signal or noise distribution is uniform in the band

$$P_{lin} = PSD_{lin} \cdot Bw$$

In dBm

$$P_{dbm} = PSD_{dBm/Hz} + 10 \cdot log_{10}(Bw)$$

Exercise 2-Thermal noise, no winning with you!!

1. Calculate the power at the receiver input P_{in} (Voltage V_L) .

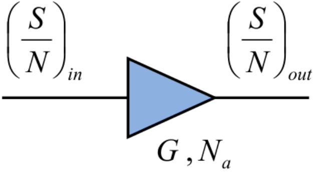
2. Let $\alpha = \frac{R_L}{R_S}$, determine α that allows to maximize P_{in} for a given R_s

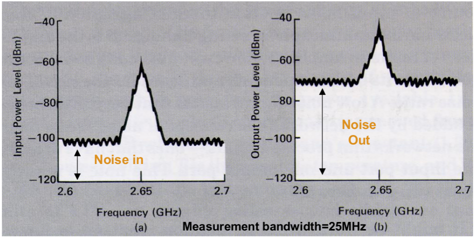
3. Set α to the value obtained in the previous question, determine the thermal noise PSD at the receiver input.

4. Calculate the noise PSD in dBm/Hz for a temperature of 17 ^{o}C. (Blotzmann constant K=1.38e-23 J/K)

5. Chadi claims that he has designed a magnificent receiver: The SNR in a 10 MHz band at his receiver output is 20 dB for an input signal of -90 dBm.
   What do you think about Chadi, are his pants on fire?

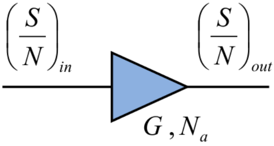
Exercise 3-Noise Figure, what for!!

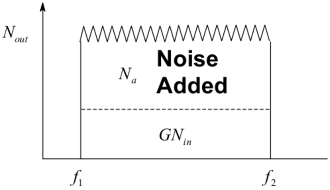




- Noise Factor is a figure of merit that relates the Signal to Noise ratio of the output to the Signal to Noise ratio of the input
- Most basic definition was defined by Friis in the 1940s

$$F_{lin} = \frac{SNR_{in-lin}}{SNR_{out-lin}} \qquad NF_{dB} = SNR_{in-dB} - SNR_{out-dB}$$





$$Gain = G = \frac{S_{out}}{S_{in}} \qquad N_{out} = N_a + GN_{in}$$

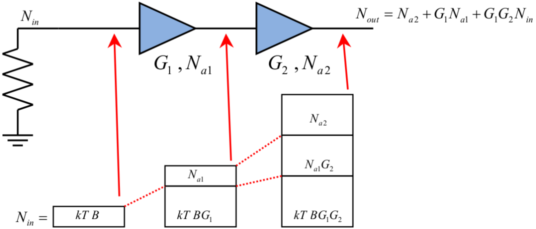
$$F = \frac{\left(\frac{S}{N}\right)_{in}}{\left(\frac{S}{N}\right)_{out}}$$

$$F = \frac{N_{out}}{GN_{in}} = \frac{N_a + GN_{in}}{GN_{in}}$$ **Noise Factor**

$$NF\ (\text{dB}) = 10\log\left(\frac{N_a + GN_{in}}{GN_{in}}\right)$$ **Noise Figure**

Note that G is a power Gain not a voltage gain

Exercise 3-Noise Figure, what for!!



$$F_1 = \frac{SNR_{in}}{SNR_1} = \frac{\frac{P_{in}}{N_{in}}}{\frac{G_1 \cdot P_{in}}{G_1 \cdot N_{in} + N_{a1}}} \implies N_{a1} = G_1(F_1 - 1)N_{in}$$

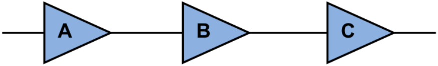
$$F_{12} = \frac{SNR_{in}}{SNR_2} = \frac{\frac{P_{in}}{N_{in}}}{\frac{G_1 \cdot G_2 \cdot P_{in}}{G_1 \cdot G_2 \cdot N_{in} + G_2 \cdot N_{a1} + N_{a2}}} = F_1 + \frac{F_2 - 1}{G_1}$$

Generalization for N stages, Friis formula

$$F_{tot} = F_1 + \frac{F_2 - 1}{G_1} + \ldots + \frac{F_N - 1}{G_1 \cdot G_2 \cdots G_{N-1}}$$

Exercise 3-Noise Figure, what for!!

We have at our disposal 3 amplifiers. We would like to cascade them to obtain a higher gain.



	A	B	C
Gain (dB)	6.0	12.0	20.0
Gain	4.0	16.0	100.0
Noise Figure(dB)	2.3	3.0	6.0
Noise Factor	1.7	2.0	4.0

1. Calculate the noise figure of the chain ABC using Friis equation
2. Compare the calculated result to the one given by the script *AmplifierChain.m*
3. Simulate the configurations BCA and CAB, compare the obtained NFs with ABC.
4. G_a is flexible, it can be set to 0 dB, 6 dB or 12 dB. Try the 3 possibilities and analyze the impact of this change on the NF of the complete chain.

3-Nonlinearity

- Electronic systems have a non-linear behavior due to many reasons:
  - The transistors are not linear
  - Slew Rate
  - Inter symbol interference (ISI)
  - Mismatch

- To model this effect, many models exist:
  - Memory-less models: polynomial,hyperbolic, orthogonal ...
  - Memory aware: Volterra, Hammerstein, Wiener, Narmax...

3-Third order system

Let us consider a third order system:

$$y(t) = \alpha_1 x(t) + \alpha_3 x(t)^3 \qquad \alpha_3 < 0 \text{ in practice}$$

with a two-tone input

$$x = Acos(\omega_1 t) + Acos(\omega_2 t)$$

The system output yields

$$y(t) = \underbrace{(\alpha_1 A + \frac{9}{4}\alpha_3 A^3)\,[cos(\omega_1 t) + cos(\omega_2 t)]}_{\text{Fundamental Terms}} + \underbrace{\frac{1}{4}\alpha_3 A^3\,[cos(3\omega_1 t) + cos(3\omega_2 t)]}_{\text{3rd order harmonics}} +$$
$$\underbrace{\frac{3}{4}\alpha_3 A^3\,[cos((2\omega_1 + \omega_2)t) + cos((\omega_1 + 2\omega_2)t) + cos((2\omega_1 - \omega_2)t) + cos((2\omega_2 - \omega_1)t)]}_{\text{3rd order Inter Modulation Products}}$$

3-Impact of non Linearity

- Gain compression (since $\alpha_3 < 0$).
- Harmonics: New terms arising at 3 times the useful band.
- Inter modulation products: terms arising in the useful RF band

The higher α_3 or/and the higher the input amplitude A, the higher the impact of Nonlinearity

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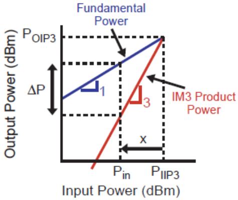
3-Nonlinearity metrics!!

How to characterize non-linearity: 1-dB compression point, Spurious Free Dynamic Range, Second order intercept point IIP2, Third order intercept point IIP3 ...

$$y(t) = \alpha_1 x(t) + \alpha_3 x(t)^3 \text{ with an input } x(t) = Acos(\omega t)$$
$$y(t) = (\alpha_1 A + \frac{3}{4}\alpha_3 A^3)cos(\omega t) + \frac{1}{4}\alpha_3 A^3 cos(3\omega t)$$

The IIP3 is the input amplitude A for which the third harmonic power is equal to the linear power (without compression)

$$\alpha_1 IIP3_{lin} = \frac{1}{4}\alpha_3 IIP3_{lin}^3 \Longrightarrow IIP3_{lin} = 2\sqrt{\frac{\alpha_1}{\alpha_3}}$$



$$IIP3_{dBm} = Pin_{dBm} + \frac{\overbrace{P_{signal-dBm} - P_{harmonic-dBm}}^{IM3 \;\; or \;\; HD3}}{2}$$

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IIP3 formula calculation

The linear curve power (blue curve) can be modeled by

$$y_1(x) = x + a$$

The third order curve (red curve) can be modeled by

$$y_3(x) = 3x + b$$

We perform a measurement at an input power P_1, the difference between the two curves is the third inter-modulation term IM3.

$$IM3(P_1) = y_1(P_1) - y_3(P_1) = P_1 + a - 3P_1 - b \implies a - b = IM3(P1) + 2P_1$$

The third order intercept point is the point for which the linear term becomes equal to the third order term.

$$y_1(IIP3) = y_3(IIP3) \implies IIP3 + a = 3IIP3 + b \implies IIP3 = \frac{a-b}{2}$$

We replace $a - b$ by the expression determined earlier.

$$IIP3 = P_1 + \frac{IM3(P_1)}{2}$$

Exercise 4-Nonlinearity!!

We will use the amplifier A employed in the previous exercise. We will model its non linear behavior using the following equation:

$$y(t) = \alpha_1 x(t) + \alpha_3 x(t)^3$$

1. Explain why and in what conditions it is reasonable to neglect the second order distortions in our model
2. Use the script *Amplifier_NL.m* to plot the SNDR vs Pin curve. Explain the behavior of the curve
3. Observe two plotted spectrums for the two input powers. Compare the IM3 value. Calculate the IIP3 of the amplifier.

Exercise 4-Nonlinearity (con)!!

The gain of amplifier A is not sufficient to receive very low input signals ($P_{in} < -90dBm$). We will use the complete chain ABC.

4. Calculate the IIP3 of the full chain using the script *AmplifierChain_NL.m*.

5. Observe carefully the output spectrums of the second and third stages. What can be noticed?

6. G_a is flexible, it can be set to 0 dB, 6 dB or 12 dB. Try the 3 possibilities and analyze the impact of this change on the IIP3 of the complete chain.

Exercise 5-Dynamic Range

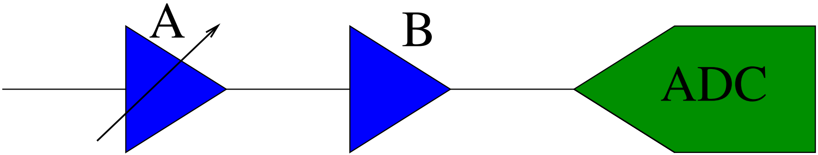
We would like to build a receiver for LTE signals. The signal bandwidth is 10 MHz and we would like to receive signals with power going from -94 dBm (the sensitivity level) to -24 dBm. The system is matched with a 50 Ω resistance. For the sake of simplicity, we will just consider 3 modes.

Mode 1: QPSK (CR 1/2) SNR > 2 dB

Mode 2: QAM16 (CR 4/5) SNR > 13.8 dB

Mode 3: QAM64 (CR 1/2) SNR > 18.6 dB

The chosen architecture for the receiver will be simplified to two amplifiers followed by an Analog to Digital Converter.



Exercise 5-Dynamic Range

We remind that the SNR of an ADC is given by:

$$SNR_{ADC} = 20log_{10}\left(\frac{Ain}{Vref}\right) + 6.02n + 1.76,$$

where *Ain*, *Vref* and *n* are respectively the input amplitude, the reference voltage and the number of bits.

1. Calculate the maximum allowable NF for the receiver at the sensitivity level (-94 dBm) to achieve a SNR of 2 dB.
2. The ADC reference voltage is 1 V. Calculate the gain needed for the overall chain AB.
3. Calculate the minimum number bits needed for the ADC
4. Use the script *Receiver_DR.m* to simulate the LTE receiver.
5. For what input range, the 64 QAM mode can be employed?
6. To avoid the SNR degradation for high power input amplitudes, G_A is made flexible with 3 steps: 0, 6 or 12 dB. Explain why using a variable gain would allow to address this problem.
7. Use the script *Receiver_DR_flex.m* to simulate the LTE receiver with flexible gain.
8. What is the second advantage of making G_A flexible?

Specifications Summary

- Transmitter
  - Power amplifier output power, Power amplifier efficiency, Dynamic range
  - LO frequency range, transmitted bandwidth
  - Non linearity: 1-dB Compression point, Adjacent channel power ratio (ACPR) and Error vector magnitude (EVM)
  - Noise in adjacent channels
  - I/Q mismatch
- Receiver
  - Noise figure, sensitivity, Dynamic range
  - LO frequency range, received bandwidth
  - Non linearity: harmonics, In band linearity IB-IIP3, out of band linearity OOB-IIP3
  - Clock: Reciprocal mixing, jitter, ...
  - TX isolation
  - I/Q mismatch