EE 160: Principles of Communication Systems
Experiment 5: Wireless transmission and spectral density

I. INTRODUCTION

a. Objectives

i. Study the spectral characteristics of various binary modulation schemes used in wireless radio transceivers.
ii. Understand the effects that the digital modulation format and bit rate have on the spectrum of the transmitted radio signal.

b. Required reading

i. Proakis and Salehi, sections 8.2, 8.3 and 10.4
ii. ADF7020-XDBX Evaluation Note (in web page)
iii. ADF7020 Datasheet (in web page)

c. List of parts

i. ADF7020 RF transceiver: Motherboard, RF module and antenna
ii. RF cable and adaptors
iii. Two SMA connection cable and two wires for data and clock pins
iv. ADALM-PLUTO software radio
v. Desktop personal computer running software to control the transceiver

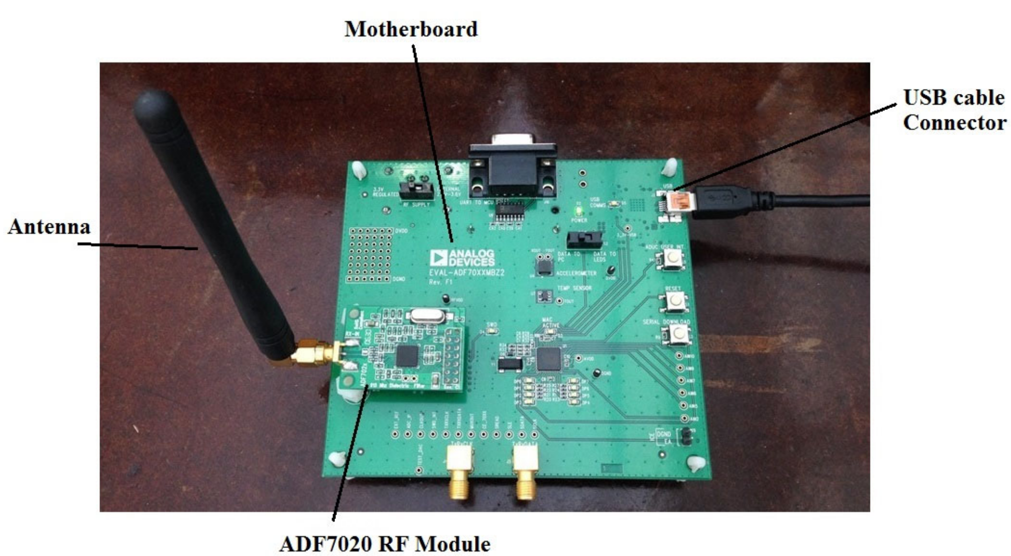

Figure 5.1: The ADF7020 RF transceiver

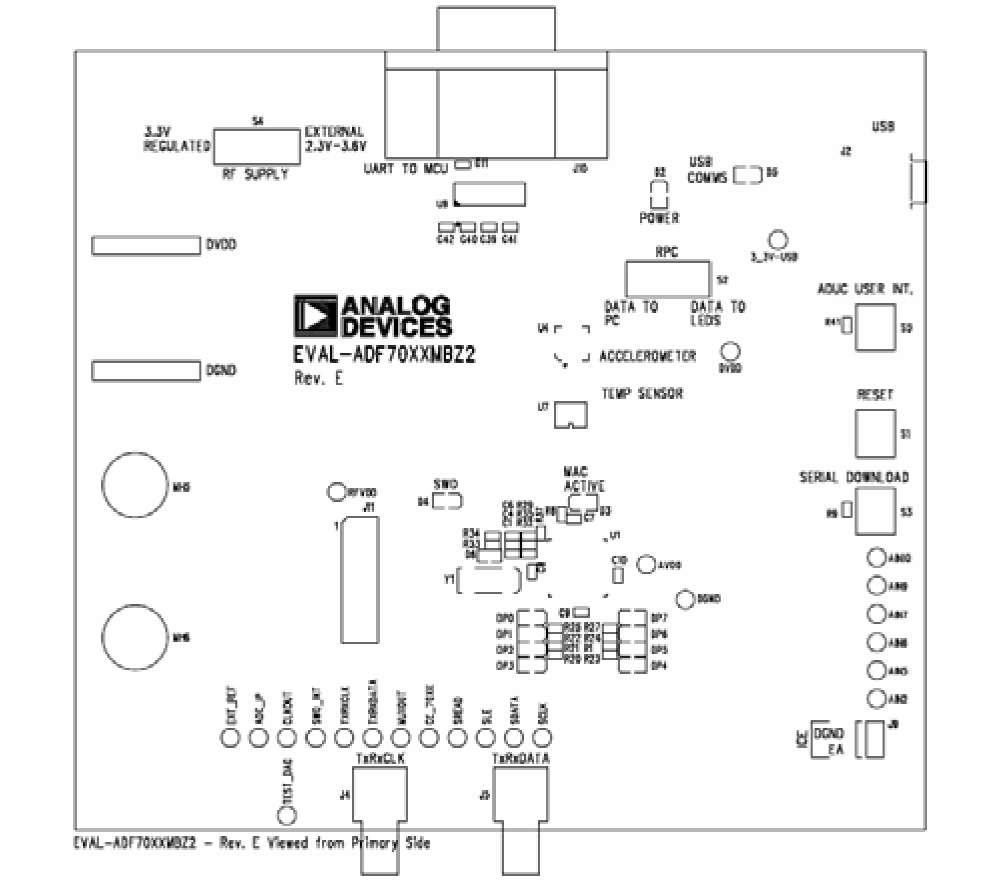

Figure 5.2: Schematic of the ADF7020 motherboard

II. THEORY

In binary modulation schemes, bit sequences are transformed into pulse sequences in a process known as modulation that consists of two basic elements: Mapping and pulse shaping. Examples of bit mapping schemes are polar (mapping 0,1 to +a, -a), unipolar (0,+a) and alternate mark inversion or AMI (0,+/-a). Examples of baseband pulse shapes are rectangular non return-to-zero (NRZ), return-to-zero (RZ) and Manchester. These pulses (with energy normalized to unity) are shown in Fig. 5.3, where T_b denotes the bit duration. The bit rate is $R_b=1/T_b$ bits per second (bps).

Various combinations of mappings and pulse shapes result in popular, widely used, binary modulation schemes, such as polar NRZ, unipolar RZ and Machester code. A Manchester code refers to the combination of polar mapping and a Manchester pulse. This code has historical significance, as it was used in the first standard (IEEE 802.3) of a physical layer for computer networks, due to its unique characteristic of absence of a DC component in the power spectral density of the pulse sequence. In the case of wireless communication systems, sinusoidal pulses are used. A unit-energy sinusoidal pulse of duration T_b seconds is given by

$$\psi(t) = \sqrt{\frac{1}{T_b}} \cos(2\pi f_c t), \quad 0 < t \le T_b$$

The value of the fundamental frequency of the sinusoidal pulse will depend on the wireless channel over which digital transmission will take place. The ADF7020 transceiver operates in the ISM (industrial, scientific and medical) band of 900 MHz, spanning from 902 MHz to 928 MHz.

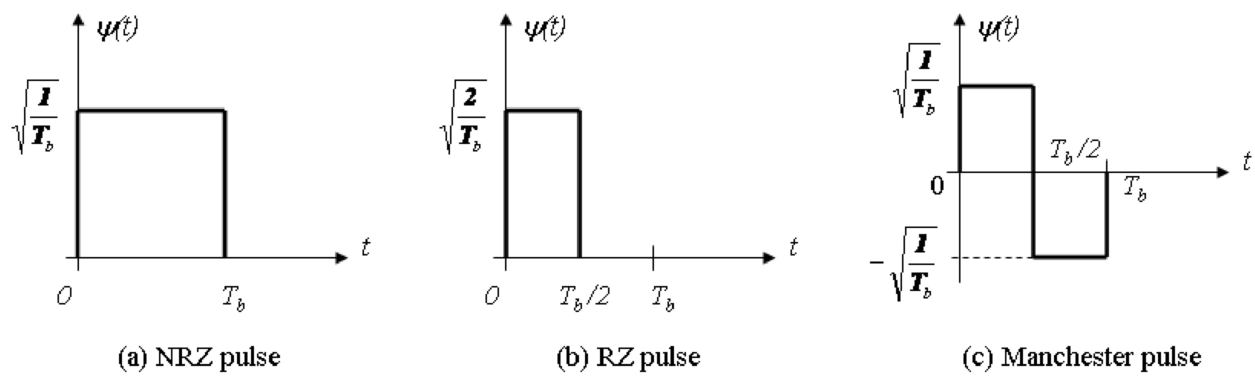

Figure 5.3: Some examples of basic baseband pulses used in digital communications

The combination of mapping and pulse shape determines the spectral characteristics of the transmitted signal as well as the error performance of the communication system.

II.1 ASK modulation

An amplitude shift-keying (ASK) signal is produced by the combination of polar mapping and a sinusoidal pulse. This form of binary modulation is also known as binary phase-shift keying or BPSK. An ASK modulator outputs one of two possible signals. Each signal is associated with a bit value, as shown in the table below:

Bit value	Transmitted signal
B=0	$s_1(t) = A_c \cos(2\pi f_c t)$
B=1	$s_2(t) = -A_c \cos(2\pi f_c t)$

An ASK signal can be interpreted as an AM signal in which the message signal is polar NRZ. This particular combination of polar mapping and sinusoidal pulse shaping has a power spectral density (PSD) given by

$$S_{ASK}(f) = \frac{1}{4}\left[S_x(f + f_c) + S_x(f - f_c)\right],$$

where

$$S_x(f) = A_c^2 T_b \,\boldsymbol{sinc^2}\left(T_b f\right) \tag{1}$$

is the PSD of polar NRZ.

II.2 OOK modulation

An on-off keying (OOK) signal is produced if an ASK modulator has the mapping changed form polar to unipolar. Here the association of bits to signals is:

Bit value	**Transmitted signal**
B=0	$s_1(t) = 0$
B=1	$s_2(t) = A_c \cos(2\pi f_c t)$

Similar to the case of ASK modulation, and OOK signal can be interpreted as an AM signal in which the message signal is *unipolar* NRZ. For this combination of unipolar mapping and sinusoidal pulse shaping, the PSD is given by

$$S_{ASK}(f) = \frac{1}{4}\left[S_x(f + f_c) + S_x(f - f_c)\right],$$

where

$$S_x(f) = \frac{A_c^2 T_b}{4}\,\mathrm{sinc}^2\left(T_b f\right) + \frac{1}{4}A_c^2\delta(f) \tag{2}$$

is the PSD of unipolar NRZ. Notice the presence of an impulse in the PSD, just as in the case of conventional AM modulation. Here, the modulation index is 100% (why?) The error performance of OOK modulation is inferior to that of ASK modulation: To attain the same value of bit error rate requires 3 dB (twice) more SNR.

II.3 FSK modulation

This is a special case of binary orthogonal modulation, which includes binary pulse-position modulation (PPM). In frequency-shift keying (FSK), signals are selected as two sinusoidal pulses of different frequencies:

Bit value	Transmitted signal
B=0	$s_1(t) = A_c \cos(2\pi f_1 t)$
B=1	$s_2(t) = A_c \cos(2\pi f_2 t)$

Signals $s_1(t)$ and $s_2(t)$ or, equivalently, the values of f_1 and f_2, are selected in such a way that they are orthogonal:

$$\int_0^{T_b} s_1(t) s_2(t) dt = 0. \tag{3}$$

The values of the two fundamental frequencies such that equation (3) is satisfied need to be each equal to a multiple of $R_b/4$ and their difference $f_1 - f_2$ equal to a multiple of $R_b/2$. In the case $\Delta f = f_1 - f_2 = R_b = 1/T_b$, $f_1 = f_c - \Delta f/2$ and $f_2 = f_c + \Delta f/2$, the resulting FSK signal does not have discontinuities. This scheme is known as Sunde's FSK modulation. Its PSD is given by

$$S_{ASK}(f) = \frac{1}{4}\left[S_x(f+f_c) + S_x(f-f_c)\right],$$

where

$$S_x(f) = \frac{A_c^2}{4}\left[\delta(f+\frac{1}{2T_b}) + \delta(f-\frac{1}{2T_b}) + T_b\left(\frac{2A_c\cos(\pi T_b f)}{\pi\left[1-(2T_b f)^2\right]}\right)^2\right] \tag{4}$$

The error performance of FSK modulation, with coherent detection, is the same as that of OOK modulation. Both FSK and OOK are inferior to ASK modulation by 3 dB in SNR value required to achieve the same bit error rate.

III. INSTRUMENTS AND MATERIAL

In this experiment, a radio frequency (RF) transceiver will be employed. The circuits that you built in experiments 1 through 4 are no longer required. You will be using the desktop PC located in the workbench to run a graphical user interface (GUI) that controls the ADF7020 RF transceiver. Figure 5.4 shows a screenshot of the interface.

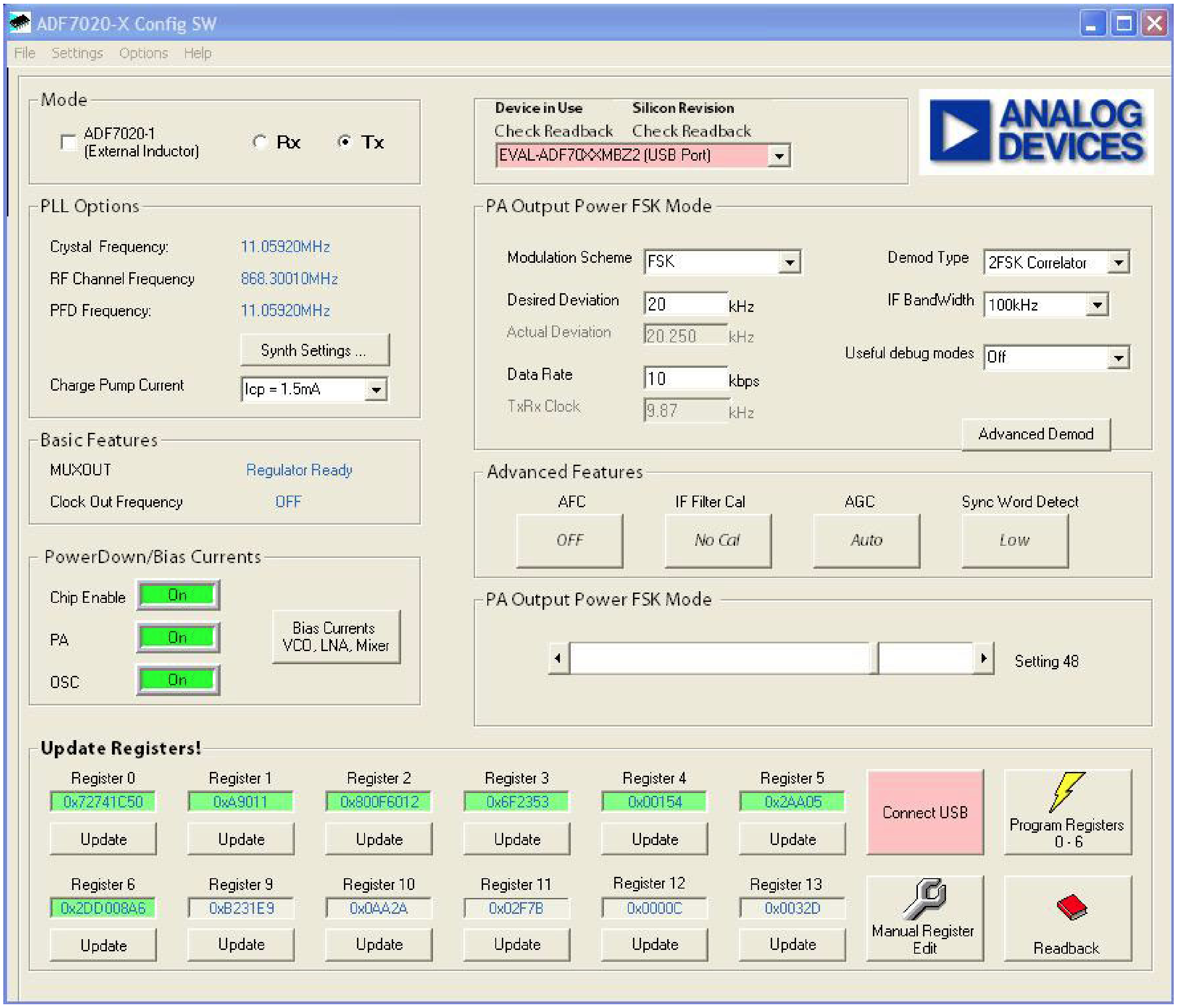

Figure 5.4: Screenshot of the ADF7020's GUI (Showing modulation scheme selection)

IV. PRE-LAB WORK

Create a Matlab script to plot the baseband equivalent power spectral densities $S_x(f)$ of ASK, OOK and FSK modulations, given in equations (1), (2) and (4), respectively. For the purpose of the plot, you may use a normalized frequency such that $T_b=1$ and $A_c=1$. Make sure to append this script to your report.

Download and run the three Matlab Simulink models of ASK, OOK and FSK modulations, which are available in the Web page of the course. All these models use as default a random bit sequence as input to the modulator. Double click on the switch to select a square waveform, just as in the lab experiment. Run each model and sketch or print the spectral density.

V. MEASUREMENTS

The following are the initial steps required to get started with the ADF7020 and also to become familiar with it. There are two processes involved: Hardware and Software. **These have to be done carefully or transceiver might be damaged.** Please make sure to follow these steps correctly and carefully because it is almost impossible to replace the ADF7020 due to its cost and availability.

V.1 Hardware setup

The first process is called “bring up”. The directions below put the ADF7020 to its initialization stage. After initialization, the transceiver can be controlled for the experiment. Fig. 5.1 shows the motherboard with the RF module mounted onto it, Fig. 5.2 shows the Mother Board with key component. Fig. 5.4 shows the GUI that will be used to set the different modulation schemes and signals characteristics. Further explanations on how to use the GUI will be elaborated upon in the following sections. Fig. 5.5 below is a functional block diagram of the transceiver IC.

The USB cable provides 5V from the host pc to power the device. The jumper S4 regulates the input voltage coming from the external power supply.

1. Set up the RF module onto the motherboard.
2. Use the USB cable to connect the motherboard to the computer.
3. Confirm that the regulator jump switch S4 is connected to position 3.3V.
4. Confirm that the RPC switch S2 is connected to position “DATA TO PC”.

V.2 Instruments setup

Once the hardware setup procedure is completed, the oscilloscope, function generator and spectrum analyzer need to be connected to the transceiver to observe its performance.

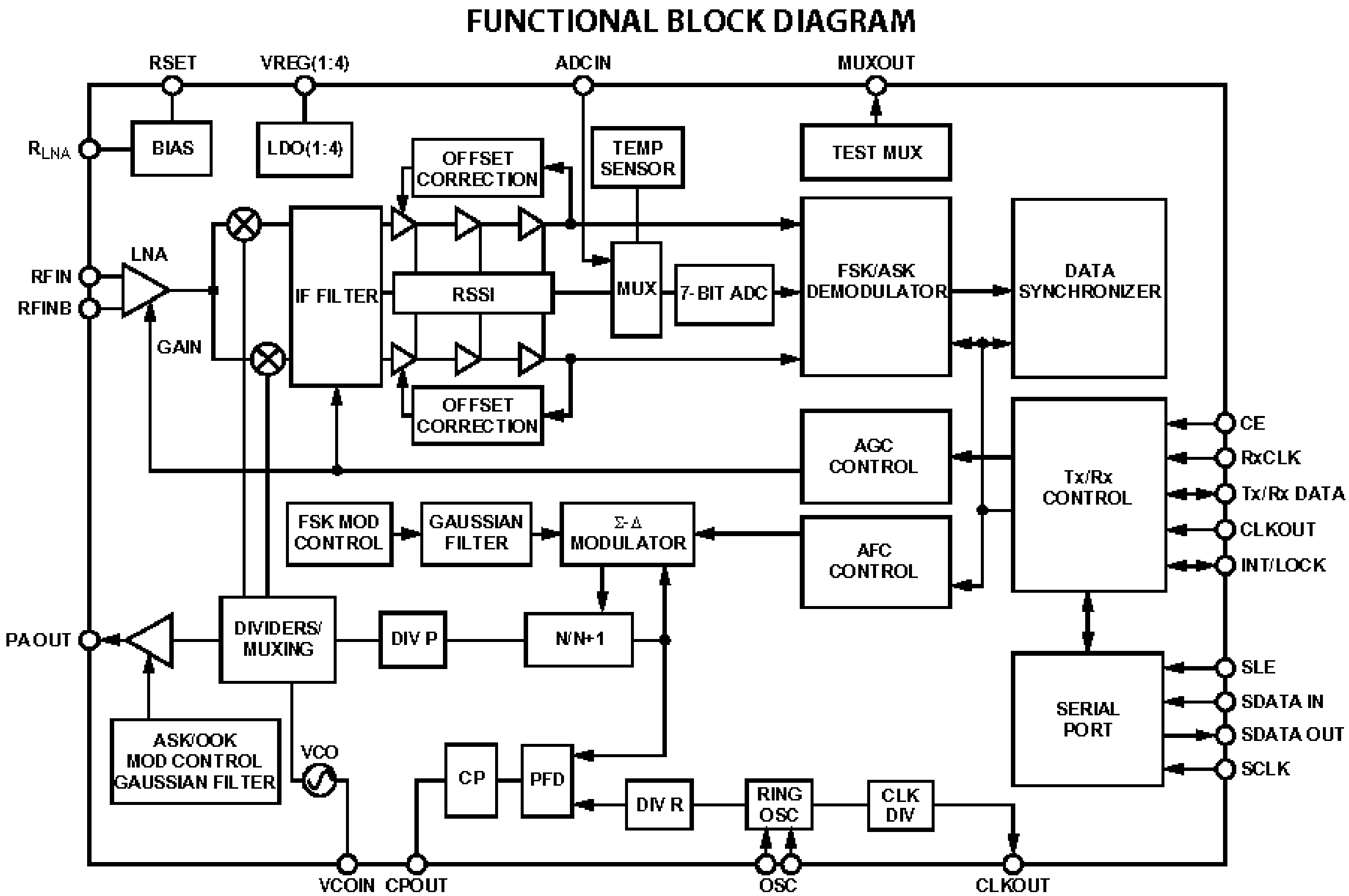

Figure 5.5: Functional block diagram of the ADF7020 transceiver IC

Follow the steps below:

1. Connect the *TxRxDATA* SMA connector to the output of the function generator.
2. Connect the *RFout* (antenna) SMA connector of the RF Module to the input of the spectrum analyzer.
3. Connect the *CLOCKOUT* pin of the I/O pins to the input of the oscilloscope.

V.3 Software setup

Upon finishing the hardware process and verifying that the transceiver is powered on, the next step is to bring up the ADF7020's graphical user interface (GUI). Select "Start" and then go to your program files directory to locate and use the ADF7020.exe application. In this section, you will learn how to manipulate the ADF7020 GUI and perform different tasks.

V.4 Transmission mode setup

The setup for evaluating the ADF7020 transceiver in transmission (Tx) mode is depicted in Fig. 5.6. Upon successful setting of hardware and software, the next step is initializing the ADF7020 to transmission mode (Tx).

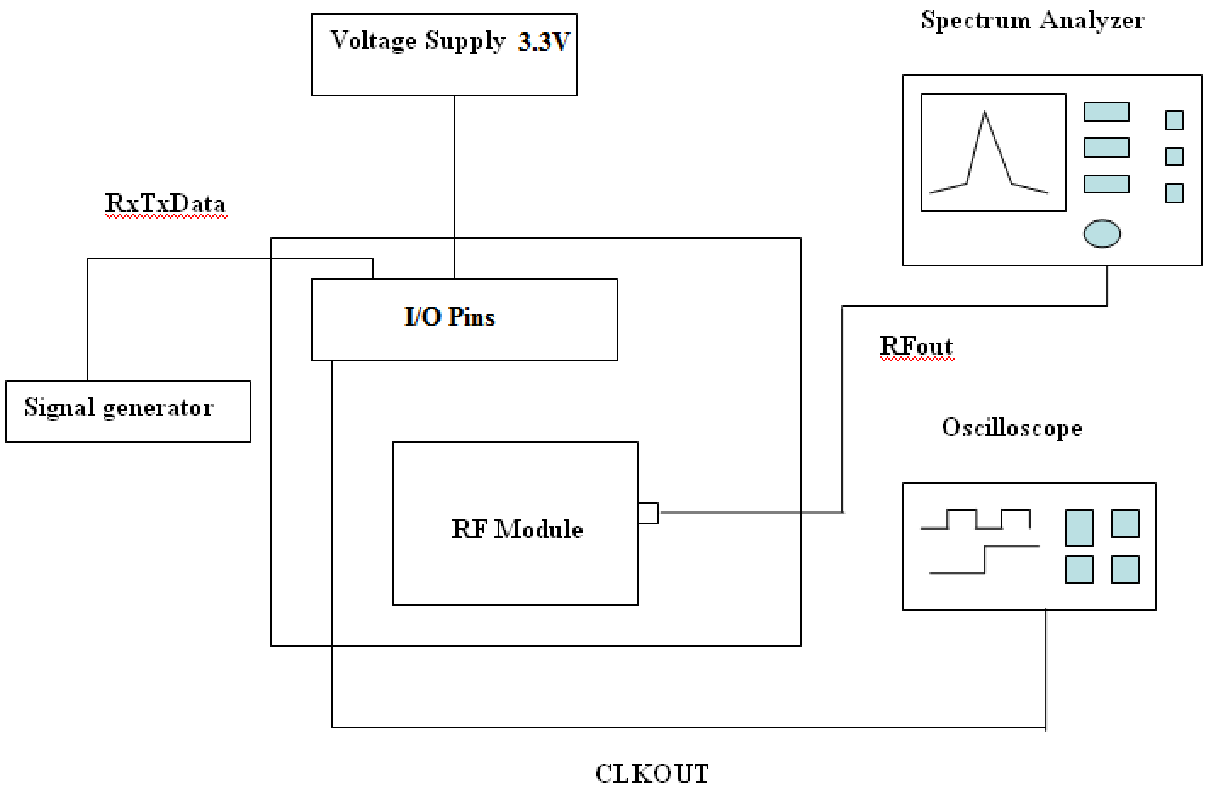

Figure 5.6: Evaluation of the ADF7020 in transmission mode

Use the GUI to set the transmission parameters as follows:

1. Click on the "Connect USB button" which is in pink color.
2. Select T_x mode
3. Verify PLL is On
4. Verify PA is On
5. Click on the "Off" text in "ClockOut Frequency" and set the dial to 8 div. This sets the clock frequency of the ADF7020 daughter board to 1.38 MHz. Hit the "Return to Front Panel" button.

6. Click on the text of the RF channel frequency and set it to 868.3 MHz. This will be the frequency of the carrier signal. Verify that the Crystal Frequency is equal to11.0592 MHz and that the PLL (phase-locked loop) has a phase frequency detector (PFD) frequency equal to 11.0592 MHz. Hit the “Calculate” and “Return to front panel” buttons.
7. Modulation Scheme (drop-down menu)

    Select OOK modulation

    Change the PA output power (a sliding bar) to 43
8. Click the “Program Registers 0-6” button to load the settings.
9. Click the “Updated” button of the other registers when needed (the box will turn green) to load the settings.

Verify that the CLOCKOUT pin of the I/O pins outputs a square wave of amplitude 0-4.6V DC and fundamental frequency 1.38 MHz. (Note: Some boards will not show this signal.)

V.5 Test signal

After setting up the parameters on the GUI, use the waveform generator to apply a square waveform of fundamental frequency equal to 4.8 kHz and amplitude 0-3 V DC (LoLevel=0 V and HiLevel=3 V) to the TxRxData. This waveform serves to emulate a regular bit pattern of alternating “ones” and “zeros” at 9.6 kbps. Then use the GUI to change the data rate to 9.6 kbps.

(1) Record the spectrum of the signal at the antenna port (This is labeled “RX-in” in the ADF7020 RF module). If you cannot save a photograph of the spectrum analyzer display, then please sketch carefully the spectral density in your lab notebook and include it in your report.

(2) To confirm that the correct signal is obtained, click on the text of the RF channel frequency value to change it (the new value can be either in the 431 MHz to 478 MHz range or in the 862 MHZ to 956 MHz range) and hit “Program Registers”. This causes the signal spectrum of the RFout signal to shift depending on the value of RF channel frequency. Verify with the spectrum analyzer that indeed the spectrum is now centered at the new selected frequency. Change the RF Channel Frequency back to 868.3 MHz and hit “Program Registers”.

(3) Increase the PA output power by using the sliding bar and then clicking "Program Registers". This changes the transmitted power of the ADF7020. Monitor changes in the OOK spectrum. Set at least three different values of PA output power level, including 1 (or –16 dBm) and 63 (or +13 dBm).

V.6 Measurement of power spectral densities of different digital modulation schemes

In this part of the experiment, the modulation scheme of the transmitted signal will be changed from OOK to other formats, such as GOOK, ASK, FSK, and GFSK, as described below.

(1) Change the Data Rate to 12 kbps. **NOTE: Changing the Data Rate involves two steps: (i) Using the GUI to change the data rate; and (ii) Changing the frequency of the external test signal (square waveform of amplitude 0-3 V DC) to a value equal to one half of the Data Rate. For a Data Rate equal to 12 kbps, you need to set the frequency value of the external test signal to 6 kHz.** Record the spectra for different PA output power levels.

(2) Change to **Gaussian OOK** modulation, selecting **GOOK** in the drop-down menu in Modulation Scheme. In the popup window, the value of "Mod counter" is irrelevant (it applies to FSK modulation). To obtain a Data Rate of 9.6 kbps, set the other parameter values as follows: Index counter = 32 and Divide number = 36. Click on "Calculate" and "Update and Return to Front Panel". (NOTE: You can also obtain 9.6 kbps with the values 16 and 72 respectively. Refer to the ADF7020 datasheet for details.) To set the Data Rate to 12 kbps, these values are 32 and 29 respectively. Record carefully the spectra for different PA output power levels. You can change the PA output power level by clicking on the "Bias Current" box and then changing the value PA bias.

(3) Change to **ASK** modulation, by selecting ASK in the drop-down menu in Modulation Scheme and clicking on the "Program Registers" button. Set the PA power levels "low" and "high" both equal to 32. Observe the spectrum. Change the PA output powers (respectively low and high) to (52,12) and (62,1). For each setting, record the effects on the spectrum displayed in the spectrum analyzer. With PA powers set to (62,1), increase Data Rate to 20 kbps and observe the effects that this has on the spectrum. NOTE: Remember that the square waveform needs to be modified in order to match the increased data rate by increasing its frequency to 10 kHz.

(4) Return the frequency of the square waveform to 4.8 kHz and select **FSK** modulation. Set "Desired Deviation" to 2.4 kHz and Data Rate to 9.6 kbps. Remember to click on the "Program Registers" button to load these new settings**.** Experiment with values of frequency deviation $\Delta f/2$ equal to 4.8 kHz, 9.6 kHz, 20 kHz, 50 kHz and 100 kHz. For each value, observe and record carefully the signal spectrum. Note its behavior with respect to Δf. (NOTE: You may want to change the amplitude scale of the spectrum analyzer to linear to obtain a cleaner spectrum.)

(5) Change the modulation scheme to Gaussian-pulse shaped FSK or **GFSK** by selecting from the drop-down menu of Modulation Scheme GFSK. In the Gaussian OOK/FSK popup window select Mod Control equal to 2, Index Counter equal to 16, and Divider Number equal to 72 (this will match the 9.6 kbps data rate). Click on "Calculate" and "Update and Return to Front Panel". To observe the spectral density with the spectrum analyzer, change the amplitude scale back to logarithmic if needed. Repeat with Mod Control set to 3,4 and 5.

Record carefully the different spectral shapes displayed by the spectrum analyzer and compare them. Take note on the differences between ASK and FSK modulation. If photographs of the PSD shapes displayed in the spectrum analyzer are not available, then sketch them clearly and neatly and include them in your report. Fig. 5.7 shows a photograph of the spectrum analyzer for FSK modulation with a Center Frequency of 868.3 MHz, a Data Rate of 9.6 kbps and a Frequency Deviation of 40 kHz.

V.7 Software-defined radio receiver

In the last part of the experiment, we use the software defined radio (SDR) ADALM-PLUTO, connected to the PC via a USB port, to observe the spectrum of the over-the-air signal sent with transmit antenna of the ADF7020 RF transceiver.

Download model *ee160lab_APR_receiver_ISM_915MHz_2021a.slx* from Canvas and run it. The instructor will help you set up the center frequency and other parameters.

Now disconnect the cable between *RFout* and the spectrum analyzer and connect the antenna to the transceiver. Capture the spectrum of the received FSK signal with Rb=9.6 kbps and Δf=40 kHz generated in step (4) above. Attach the spectrum to your report.

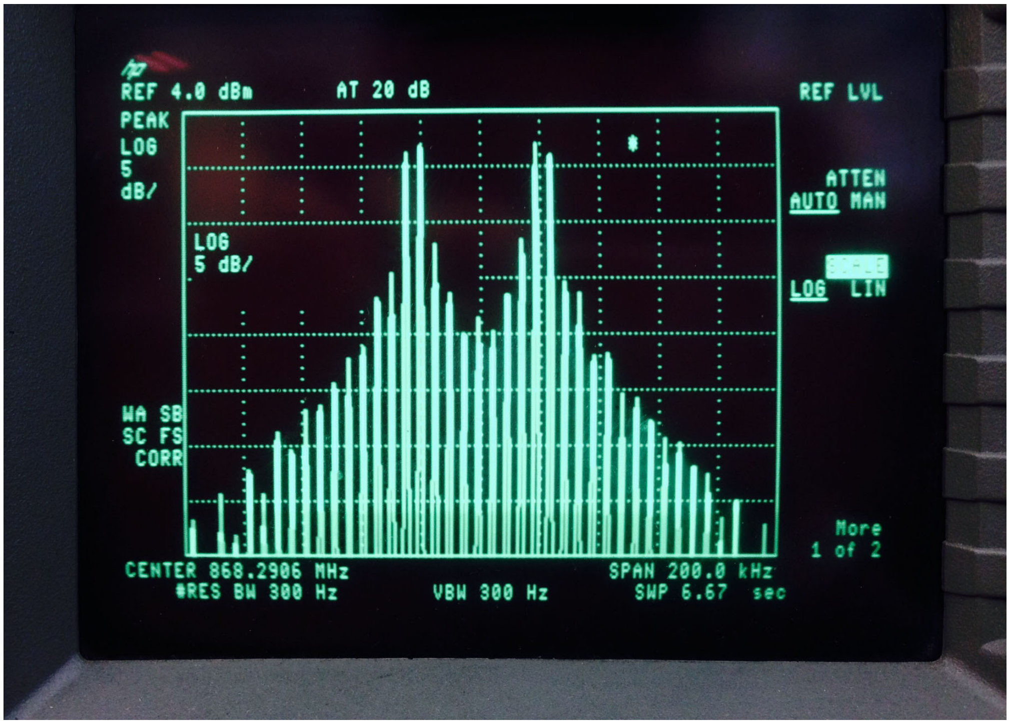

Figure 5.7: Spectral density of FSK modulation with Rb=9.6 kbps and Δf=40 kHz.

VI. ANALYSIS OF RESULTS

(1) Compare the theoretical power spectral densities of OOK, ASK and FSK for different modulation parameters, such as bit rate and signal amplitude. Include in your report the plots from the Matlab script written in the pre-lab work. The plots from Matlab shall be in logarithmic scale (dBm) over the frequency range $[f_c\text{-}4R_b, f_c+4R_b]$, with f_c=925 MHz, R_b=4800 bps and A_c=1 V. For FSK modulation, use Δf=4.8 kHz.

(2) Compare the spectra from the Matlab Simulink models of ASK, OOK and FSK modulations with your measurements, being careful to use appropriate parameter values in the Matlab models. How well do the measurements agree with the computer models results?