ECE 4880 RF Systems Fall 2016
Homework 6 Solution

Reading before homework:

- Lecture summary on Gain Modules, Noises and Nonlinearity
- Egan's book, Chaps 3 and 4.
- Simulink tutorial

1. (**Three modules in cascade for noise figures**) Given three unilateral and impedance-match gain modules: M1 has g_1 = 10dB and F_1 = 3dB; M2 has g_2 = 20dB and F_2 = 10dB; M3 has g_3 = 20 dB and F_3 = 20 dB. Calculate the noise figure in dB for the following cascade when all of the noises are referred (lumped) to the source side. In comparing the cases of (a) and (c), take a note how small the difference of the cascade noise figures.
   (a) M1-M2-M3 (**5 pts**)
   (b) M2-M1-M3 (**5 pts**)
   (c) M1-M3-M2 (**5 pts**)

   Case (a): $f_{cas} = 10^{0.3} + \frac{10^1 - 1}{10} + \frac{10^2 - 1}{10 \cdot 100} = 3.0$; F_{cas} = 4.7dB

   Case (b): $f_{cas} = 10^1 + \frac{10^{0.3} - 1}{10^2} + \frac{10^2 - 1}{10 \cdot 100} = 10.1$; F_{cas} = 10dB

   Case (c): $f_{cas} = 10^{0.3} + \frac{10^2 - 1}{10} + \frac{10 - 1}{10 \cdot 100} = 11.9$; F_{cas} = 10.7dB

   We should be careful to push the lowest noise to the beginning, and highest noise to the end, or else there can be severe penalty either way.

2. (**Noise sources**) You make noise measurements for a given MOSFET and obtain the following table. What statement(s) are true? (**10 pts**)

Frequency range	1kHz – 2kHz	10kHz – 11kHz	101kHz – 102kHz	1001kHz – 1002kHz
Noise power	–124 dBm	–133 dBm	–145 dBm	–144 dBm

   (a) Only thermal noise is dominant over the entire range.
   (b) Shot noise does not exist here.
   (c) We can use the measurements above 10kHz to estimate the device temperature.
   (d) The flicker noise has a corner frequency f_c around 1kHz.
   (e) The flicker noise can be ignored in 100kHz.

   Answer: (e). (a) is not true as there is clear Flicker noise in the low frequency range. (b) is not true as the channel carrier over the source barrier will present Shot noise (some will debate the source barrier is small, but still it is difficult to eliminate shot noise possibility). Generally from only measurements you cannot distinguish thermal and shot noises as both noise spectra are nearly white. (c) is not true as we need to assume only thermal noise is dominant. (d) is not true, as we can estimate f_c is above 10kHz.

3. (**IIP3 calculation**) For a power amplifier with 20dB gain, IIP3(IM) = 30 dBm and IIP_{H2} = 20dBm,
   (a) Give OIP3(IM), IIP_{H3}, OIP_{H3}, OIP_{H2}, IIP_{IM2}, and OIP_{IM2} (**12 pts**)

   OIP3(IM) = IIP3(IM) + 20dB = 50 dBm. (Notice that for IM3 is often assumed for IIP3).

IIP_{H3} = IIP3(IM) + 4.77dB = 34.77 dBm.
OIP_{H3} = IIP_{H3} + 20dB = 54.77 dBm.
OIP_{H2} = IIP_{H2} + 20dB = 40 dBm.
IIP_{IM2} = IIP_{H2} – 6dB = 14 dBm.
OIP_{IM2} = IIP_{IM2} + 20dB = 34 dBm.

(b) At an input level of p_{in1} = 10dBm, give p_{H2}, p_{H3} and p_{IM3}. (**6 pts**)

p_{out1} = 30 dBm.
$p_{H2} = p_{out1} - (OIP_{H2} - p_{out1})$ = 20dBm (notice that this is relatively large, and cannot be ignored).
$p_{H3} = p_{out1} - 2\times(OIP_{H3} - p_{out1}) = 3\times30 - 2\times54.77 = -19.54$ dBm
$p_{IM3} = p_{out1} - 2\times(OIP3(IM) - p_{out1}) = 3\times30 - 2\times50 = -10$ dBm.

Notice that IM3 seems small as it is 40dB smaller than the fundamental. However, if the circulator has only 60dB isolation, and the path loss between the transmitter and the receiver is around 100dB, then the IM3 term leaking from the circulator will be as large as the main signal!!!!.

(c) At an input level of p_{in1} = –10dBm, give p_{H2}, p_{H3} and p_{IM3}. (**6 pts**)

p_{out1} = 10 dBm.
$p_{H2} = p_{out1} - (OIP_{H2} - p_{out1})$ = –20dBm (notice that this is relatively small now).
$p_{H3} = p_{out1} - 2\times(OIP_{H3} - p_{out1}) = 3\times10 - 2\times54.77 = -79.54$ dBm
$p_{IM3} = p_{out1} - 2\times(OIP3(IM) - p_{out1}) = 3\times10 - 2\times50 = -70$ dBm (notice that now the ratio of p_{out1} to p_{IM3} is 80dB!!! Intermodulation will not matter much. For Wifi transmitter at around 10dBm radiating power, indeed nonlinearity of the power amplifier is seldom a concern).

(d) If we need p_{H2} = 10dBm out of the power amplifier, what is the input level p_{in1} is needed? What would be the minimal power consumption for the power amplifier assuming 50% output efficiency? (**6 pts**) Output efficiency is defined as the ratio of total output power and total power consumption.

$p_{H2} = p_{out1} - (OIP_{H2} - p_{out1})$ = 10dBm, so we get p_{out1} = 25dBm = 0.32W and p_{in1} = 5dBm. There is 15dB difference between the fundamental and the harmonic. The minimal power consumption of the power amplifier will be (0.32W + 10mW)×2 = 0.66W or 28 dBm.

4. (**Simulink**) Follow the Simulink tutorial, build an RFID transmitter as described below. (**45 pts**)

First model a sine wave source with added phase noise, and view the signal spectrum with a spectrum analyzer module. Requirements: (1) signal source frequency: 915MHz; (2) Amplitude of output signal: 0.1V; (3) Phase noise level -60dBc/Hz @ 100Hz offset. (4) Spectrum frequency resolution: < 1MHz between 890MHz and 940MHz.

For the PA, model AM to AM and AM to PM nonlinearity. Configure as following. Method: Cubic Polynomial; Linear Gain: 22dB; IIP3: 50dBm; AM/PM: 10 degrees per dB; Lower Input Power Limit for AM/PM Conversion: 20dBm; Upper Input Power Limit for AM/PM Conversion: 50dBm; Noise Figure: 5dB.

Insert three filters using Digital Filter Design blocks in the library. For the first two filters before PA, use IIR Butterworth filter with the following configurations. Pass Band: 900 to 930 MHz 0dB; Stop band edge 1: 860MHz; Stop band edge 2: 950MHz; Stopband attenuation: 20dB; For the third filter connected to the PA output, use IIR Elliptic filter and the following configurations. Pass Band: 900 to 930 MHz 0dB; Stop band edge 1: 895MHz; Stop band edge 2: 935MHz; Stopband attenuation: 50dB.

Adjust PA output power to be 30dBm for a 50 Ohms resistor and add a power meter in your system to display the power level (use Display block in Simulink library, you may also need to use dB-Conversion block).

In your homework, submit your system block diagram, the spectrum for the signal at the output of PA and at the output of the filter connecting to the output of the PA. You also need to submit the time domain signal at PA output. (Please remember that you need to simulate the transmitter together with the signal source created in your first homework).

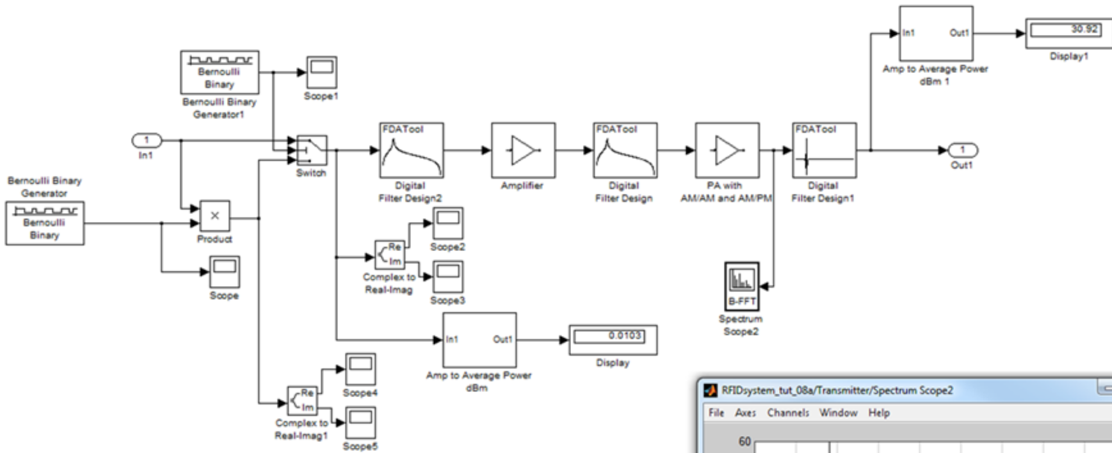
In the signal spectrum at PA output, observe second and third harmonic signal. Reduce IIP3 to 38dBm, compare the third harmonic amplitude with previous simulation results.

Sample Simulink output:

The Simulink transfers between the frequency and time domains for signal analyses. Here, to extract 915MHz waveforms, the sampling limit needs to be smaller than 0.1 ns (at least 10 points to trace out a monotone sine wave). For spectrum resolution of 1MHz, you would need to simulate more than 1µs. This gives a rough estimate of the simulation time.

Frequency resolution is important for your filtering function and channel selection. You will see many other examples in future Simulink assignment. Our final goal is to describe a full transceiver with Simulink.

See the block diagram and simulated spectrum below. Notice the bandwidth and only positive frequencies are plotted.



Transmitter

Output signal spectrum. The third harmonic is due to the nonlinearity of PA at IIP3 of 38dBm.