ECE 4880 RF Systems Fall 2016
Homework 10 Solution

Reading before homework:

- Chaps. 10 and 11 of lecture notes

1. (**Wi-Fi**) Answer the following questions for Wi-Fi radio networks
   (a) Although Wi-Fi can trace its origin to Alohanet and Ethernet, which country has developed its first prototype according to the IEEE standard? Note that there are some controversies about this issue, so we will go with the patent ruling. (**5 pts**)

   Australia. Wi-Fi is credited to Commonwealth Scientific and Industrial Research Organization (CSIRO) with original mission on identifying black holes. Australian radio-astronomer John O'Sullivan and was credited for the critical patents in Wi-Fi for the "signal unsmearing" technique.

   (b) What are the unlicensed bands covered by Wi-Fi as IEEE 802.11b, 802.11a and 802.11g? What interference mitgation (signal unsmearing) techniques were used in each standard? (**5 pts**)

   802.11b: 2.412 – 2.484 GHz: Direct sequence spread sprectrum (DSSS)
   802.11a: 5.15 – 5.35; 5.725 – 5.825GHz: OFDM
   802.11g: 2.412 – 2.484 GHz: OFDM

   (c) What are the modulation schemes used in Wi-Fi? What is the TX/RX duplex technique? (**5 pts**)

   Wi-Fi allows BPSK, QPSK, 16QAM and 64QAM, depending on SNR. The higher the SNR, the highter Mbps.

   Wi-Fi uses time-division duplex (TDD).

   (d) For 2.4GHz, US FCC allows 30dBm while EU ETSI only allows 20dBm. We will assume here the modulation scheme is the same. In the line-of-sight model where the power scales with $1/r^2$ (review Chap. 2, i.e., $\gamma = 2$), what is the reduction ratio of distance in EU? For indoors, if the power scales with $1/r^6$ due to channel fading ($\gamma = 6$), what is the reduction ratio of distance in EU? (**10 pts**)

   For the line-of-sight model where the power scales with $1/r^2$, $20\log(r_{EU}/r_{FCC}) = -10$dB, and we have $r_{EU}/r_{FCC} = 10^{-0.5} = 0.32$.

   For the power scaled with $1/r^6$, $60\log(r_{EU}/r_{FCC}) = -10$dB, and we have $r_{EU}/r_{FCC} = 10^{-1/6} = 0.68$. We can see that the penalty is not very big, but we save 1/10 the power in the Wi-Fi transmitter. Surely when you have less "bars" of Wi-Fi signal, you may complain. You will actually feel a lower data rate, as the modulation scheme depends on SNR.

   (e) To support dual-band Wi-Fi transceivers and to minimize oscillator injection, we have chosen to synthesize the frequency between 3.2 – 3.9 GHz. Describe how we can realize both 2.4GHz and 5GHz LO. (**5 pts**)

   3.2GHz is first ÷2 to become 1.6GHz and mix with itself to become 4.8GHz. This is further ÷2 to give 2.4GHz. This is named as 2/3 and 4/3 schemes.

In the same way, 3.9GHz becomes 5.85GHz and 2.92GHz, which is more than sufficient to cover the entire ISM bands around 2.4GHz and 5 – 5.8GHz.

(f) What are the major extension of IEEE standards to extend Wi-Fi to MIMO and 60GHz? What are the maximum data rate? (**5 pts**)

IEEE 802.11n governs MIMO dual-band Wi-Fi to push the data rate to 0.6Gbps for 4 spatial streams of 40MHz bandwidth with 64-QAM modulation.

IEEE 802.11ad governs 60GHz Alliance to push the data rate to 7Gbps by 64-QAM modulation.

(g) If the Wi-Fi TX has large LO feed through (LOFT), i.e., on top of the desired modulated bandwidth, f_{LO} is an additional component, what will be the homodyne RX concerns for LOFT? (**5 pts**)

LOFT will mix with RX f_{LO} to cause a large DC offset in homodyne RX.

(h) Variable RF gain has been employed to enlarge the dynamic range of the Wi-Fi RX. At the strongest allowable RF_{in}, describe the RF gain and IIP3 need to be at their highest or lowest values? Give one sentence to explain why we need to set a strongest allowable RF_{in}? (**5 pts**)

At the strongest allowable RF_{in}, RF gain needs to be the smallest (not to saturate the RF signals) and IIP3 needs to be the highest (for minimal harmonic and intermodulation generation). If we do not bound RF_{in}, we will not be able to give a specification for RX IIP3.

2. (**Bluetooth**) Bluetooth is a popular "piconet", or wireless personal area network (WPAN)

(a) Which of the following statement is true for the naming of Bluetooth? (There can be more than one answers) (**5 pts**)

i. Bluetooth is named as a proposal to unify the protocols in WPAN.
ii. Bluetooth is the last name of the inventor.
iii. Bluetooth is meant to describe the blue logo with tooth shape.
iv. Bluetooth is derived from a Disney movie character name
v. Bluetooth logo is derived from the combination of Scandinavian alphabet.

Answer: i, v. Harald Bluetooth, the Danish king that the Bluetooth named after, has the bind rune of his initials (HB) to become the Bluetooth logo.

(b) Which one of the following statement is false for the adaptive frequency hopping (AFH) scheme in Bluetooth? (**5 pts**)

i. 40 channels between 2400MHz and 2483.5MHz are used for channel hopping
ii. The frequency hopping scheme can effectively spread out the transmission spectrum over a given period of 0.4s.
iii. Guard bands are inserted between channels to ensure low-cost implementation
iv. A slave device can occupy any given channel for 0.4s
v. AFH in general has lower power consumption than OFDM

Answer: iv. Within 0.4s, Bluetooth is required to hop at least 20 channels.

(c) For a Class 2 (most popular) Bluetooth TX at 0dBm power, an RX 10cm away measures received power at –20dBm. What is the expected power received at 10m if the line-of-sight model can be used with $\gamma = 2$? What is the expected power received at 10m if the indoor fading model is used with $\gamma = 6$? (**10 pts**)

10m/10cm = 100. For $\gamma = 2$, the path loss will be $2\times10\log_{10}100$ = 40dB more, i.e., RX of 10m will be at –60dBm.

For $\gamma = 6$, the path loss will be $6\times10\log_{10}100$ = 120dB more, i.e., RX of 10m will be at –140dBm, which will be very difficult to distinguish due to the low SNR.

(d) You are a Bluetooth engineer considering the two LNA: (actually now most Bluetooth modules have a single-chip integrated solution all except the LO synthesis)

	Maxim	**Microchip**
Gain	20 dB	14 dB
Noise Figure	2.0 dB	2.0 dB
IIP_{IM3}	0.5 dBm	3 dBm
$P_{1dBcomp}$	–13 dBm	–5.5 dBm
Power Consumption	2.45 mW	6.05 mW

When the RX SNR is most important, which LNA will you choose? When RF_{inmax} needs to be as high as –10dBm, which LNA will you choose? Give one-line explanation. (**10 pts**) Calculate the expected IM3 power for RF_{inmax} = –10dBm in both LNA. (**5 pts**)

When the RX SNR is most important, we will choose Maxim, as NF is the same, but the higher gain will reduce the effective NF in the following components. When RF_{inmax} needs to be high, we will choose Microchip for better linearity.

For Maxim LNA, RF_{inmax} = –10dBm, p_{out1} = 10dBm, and p_{outIM3} = 10dBm – 2×(0.5dBm – (–10dBm)) = 10 dBm – 21dB = –11dBm.

For Microchip LNA, RF_{inmax} = –10dBm, p_{out1} = 4dBm, and p_{outIM3} = 4dBm – 2×(3dBm – (–10dBm)) = 4 dBm – 26dB = –22dBm, which is indeed 10 times lower IM3 power. Notice that this nonlinearity can couple with the harmonic and noise of LO to cause many spurs.

(e) Power amplifiers often use EVM (error vector magnitude) at the desirable output power as a measure of linearity. It can be denoted in dB or % by the following definition:

$$EVM\,(dB) = 10\log_{10}\left(\frac{P_{error}}{P_{reference}}\right); \qquad EVM\,(\%) = \sqrt{\frac{P_{error}}{P_{reference}}}\times 100\%$$

For 1dB compression point, the output is 1dB lower than the expected linear output. What is the EVM(%) at 1-dB compression point? (**5 pts**) For a 3% EVM, what is the compression in dB? (**5 pts**)

At 1-dB compression point,

$$\frac{P_{error}}{P_{reference}} = 1 - 10^{-1/10} = 0.20; \quad EVM\,(\%) = \sqrt{\frac{P_{error}}{P_{reference}}}\times 100\% = 45\%$$

For 3% EVM,

$\sqrt{\frac{P_{error}}{P_{reference}}} = 0.03; \quad 1 - 10^{-x/10} = 0.03^2; \quad x = 0.004dB$. We can see that 3% EVM is very close to the output power where distortion can be safely ignored (not even at 1dB).

(f) Bluetooth often uses direct conversion or very low IF to simplify the transceiver structure and avoid the IF generation. Give one-sentence explanation why LNA IIP_{IM2} and LO phase noise become important design considerations. (**10 pts**)

The 2nd order intermodulation of LNA will generate a large DC offset (not from mixing) in direct conversion, which will pollute the DC level from the mixer (RF mixing with LO within very close range). This is especially serious when LOFT is also included.

LO phase noise will also direct mix into the DC level from the mixer.