ZJU-UIUC INSTITUTE

ECE-210 Analog Signal Processing Spring 2023 **Laboratory Exercise #4**

Student ID	3210111519	**Pre-lab**	**/20**
Student Name	Shao Xihe	**Lab**	**/50**
Semester/Section		**Total**	**/70**

Lab 4: Fourier transform and AM radio

In Lab 4, you will finally connect all of your receiver components and tune an AM radio broadcast. You will follow the radio signal through the entire system, from antenna to loudspeaker, in the time domain and the frequency domain.

1 Prelab

You should prepare for this lab by reviewing Sections 8.3 and 8.4 in the textbook on AM detection and superheterodyne receivers, familiarizing yourself with your own receiver design shown in Figure 3 in this booklet, and answering the prelab questions.

Suppose you want to tune your AM receiver in the lab to an AM station broadcasting close to Champaign-Urbana with a carrier frequency of $f_c = \frac{\omega_c}{2\pi}$ kHz, but your receiver is prepared to decode an AM signal with carrier frequency of 14 kHz. Therefore, a previous step is needed to bring down the broadcasted signal from f_c to the intermediate frequency $f_{\text{IF}} = \frac{\omega_{\text{IF}}}{2\pi} = 14\,\text{kHz}$. That step is achieved by multiplying (mixing) the signal at f_c with a co-sinusoidal signal generated by a LO (local oscillator) with frequency $f_{\text{LO}} = \frac{\omega_{\text{LO}}}{2\pi}$. In our superheterodyne AM receiver, the LO will be the function generator. There are two possible LO frequencies that will bring the signal from it's broadcasted carrier frequency f_c to the intermediate frequency f_{IF}. One is the case depicted in Figure 1, where $f_{\text{LO1}} = f_C - f_{\text{IF}}$, and the other one is the case depicted in Figure 2, where $f_{\text{LO2}} = f_C + f_{\text{IF}}$.

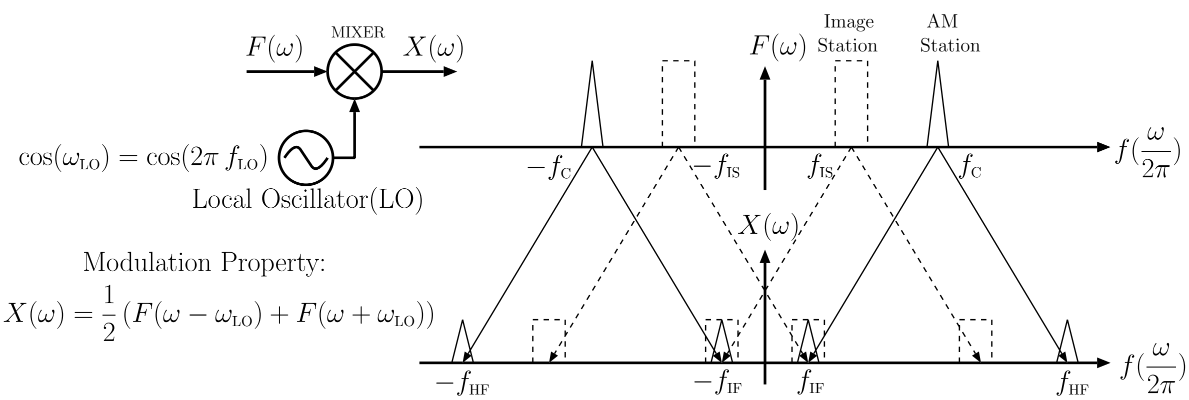


Figure 1 − Diagram showing the modulation property in a graphical way for one of the two possible L.O frequencies (f_{LO1}). In this case $f_{\text{LO1}} = f_C - f_{\text{IF}}$. The "image station" problem is also shown, where another AM station located at f_{IS} can interfere at f_{IF} after being shifted in frequency by f_{LO1} .

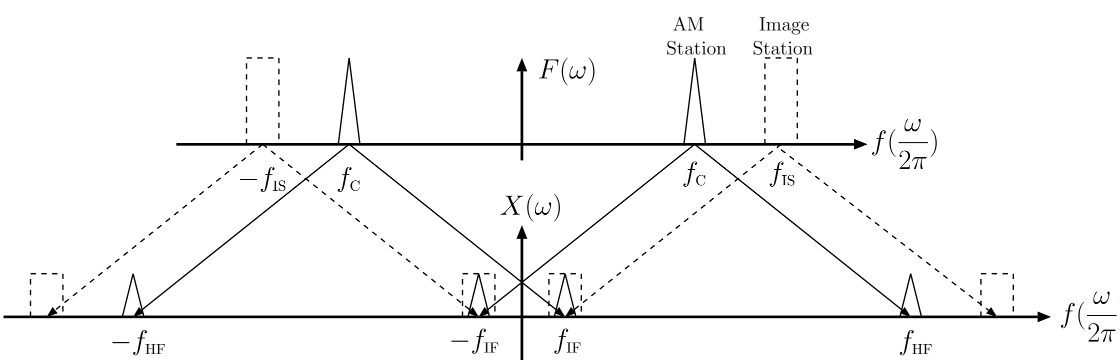


Figure 2 − Diagram showing the modulation property in a graphical way for one of the two possible L.O frequencies (f_{LO2}). In this case $f_{\text{LO2}} = f_C + f_{\text{IF}}$. The "image station" problem is also shown, where another AM station located at f_{IS} can interfere at f_{IF} after being shifted in frequency by f_{LO2} .

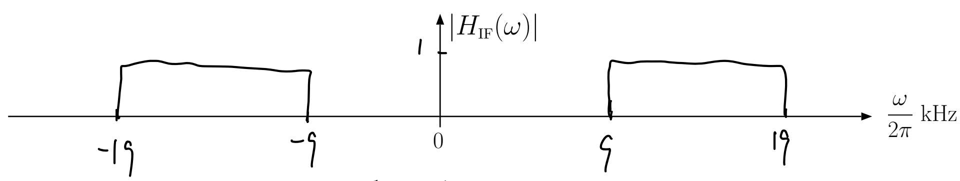
1. Find the L.O. frequency (f_{LO1}) needed to have the following AM stations shifted in frequency from their carrier frequencies to the intermediate frequency $f_{\mathrm{IF}} = 14\,\mathrm{kHz}$ using the case shown in Figure 1, where $f_{\mathrm{LO1}} = f_C - f_{\mathrm{IF}}$. Also find the "image station" frequency (f_{IS}) and the high frequency (f_{HF}) where the AM station is also shifted in frequency. (____/4)

AM Station:	WDWS AM, $f_C = 1400\,\mathrm{kHz}$	WILL AM, $f_C = 580\,\mathrm{kHz}$
$f_{\mathrm{LO1}} =$	1386 kHz	566 kHz
$f_{\mathrm{IS}} =$	1372 kHz	552 kHz
$f_{\mathrm{HF}} =$	2786 kHz	1146 kHz

2. Find the L.O. frequency needed to have the following AM stations shifted in frequency from their carrier frequencies to the intermediate frequency $f_{\mathrm{IF}} = 14\,\mathrm{kHz}$ using the case shown in Figure 2, where $f_{\mathrm{LO2}} = f_{\mathrm{C}} + f_{\mathrm{IF}}$. Also find the "image station" frequency and the high frequency (f_{HF}) where the AM station is also shifted. (____/4)

AM Station:	WDWS AM, $f_C = 1400\,\mathrm{kHz}$	WILL AM, $f_C = 580\,\mathrm{kHz}$
$f_{\mathrm{LO2}} =$	1414 kHz	594 kHz
$f_{\mathrm{IS}} =$	1418 kHz	408 kHz
$f_{\mathrm{HF}} =$	2804 kHz	1174 kHz

3. Sketch the amplitude response curve $|H_{\mathrm{IF}}(\omega)|$ of an *ideal* IF filter designed for an IF of $f_{\mathrm{IF}} = \frac{\omega_{\mathrm{IF}}}{2\pi}$ =14 kHz if the filter bandwidth must be 10 kHz. Label the axes of your plot carefully using appropriate tick marks. Indicate on your graph the upper and lower cut-off frequencies in kHz. Don't forget the negative frequencies axis.



(____/3)

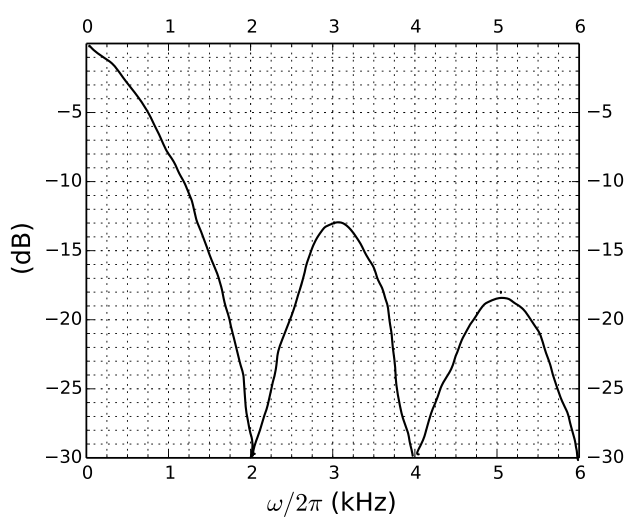
4. Write down the Fourier transform of $f(t) = \frac{1}{\tau}\mathrm{rect}(\frac{t}{\tau})$ (use tables). Then, assuming $\tau = 500\,\mu\mathrm{s}$, sketch $|F(\omega)|$ in dB scale, (i.e. sketch $20\,\log_{10}|F(\omega)|$, where $\log_{10}$ is the base 10 logarithm). Find all the local extrema (min. or max.) of $|F(\omega)|_{\mathrm{dB}}$ in the region shown below [0 - 6 kHz], fill in the table and plot. (Useful information: $|\mathrm{sinc}(x)| = 0$, for $|x| = n\pi$, where $n \geq 1$ is an integer. $|\mathrm{sinc}(x)|$ has local maxima, computed numerically, at $|x| \approx 0$, 4.493, 7.725, 10.904, 14.0662...)

$F(\omega) = \mathrm{sinc}\left(\frac{\omega\tau}{2}\right)$ (____/2)

f(kHz)	$\lvert F(f)\rvert_{\mathrm{dB}} = 20\log_{10}(\lvert F(f)\rvert)$
0.00 kHz	$20\log_{10}(1) = 0\,\mathrm{dB}$
2	$20\log_{10}(0) = -\infty$
2.84	-13.24 dB
4	$-\infty$
4.92	-17.83 dB
6	$-\infty$

(____/4)

$|F(\omega)|_{\mathrm{dB}} = 20\log_{10}|F(\omega)|$



(____/3)

Student ID	3210111519	Pre-lab	/20
Student Name	Shao Xihe.	Lab	/50
Semester/Section		Total	/70

2 Laboratory exercise

- Equipment: Function generator, oscilloscope, protoboard, and wires.
- Components: Three-stage circuit from Lab 2, band-pass filter from Lab 3, RF amplifier, and mixer.

2.1 Fourier Transform

Your scope is capable of displaying the Fourier transform of its input signal. We have already used this feature in Lab 3 in "observing" the Fourier coefficients of periodic signal inputs. In this section we will learn how to examine non-periodic inputs in the frequency domain.

1. No circuit is used for this part of the laboratory. Connect the function generator's output to Channel 1 of the oscilloscope.

2. Set the function generator to create a 1 kHz square wave with amplitude 4 V peak-to-peak (remember: HIGH Z mode). Turn on burst mode by pressing "Shift" then "Burst". In this mode the generator outputs a single rectangular pulse, (i.e., rect(t/τ)), which is repeated at a 100 Hz rate. Confirm that pulses are generated at a 100 Hz rate (that is, 100 pulses per second, or a pulse every 10 ms).

   Next, measure the rectangle width τ choosing an adequate time scale (zoom in):

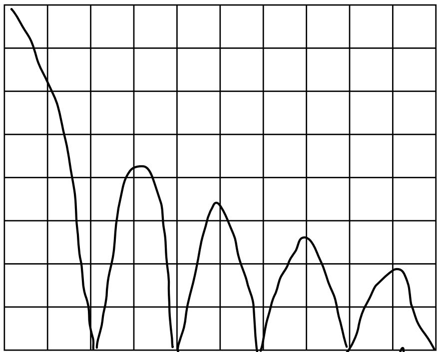
   $\tau =$ 500 μs (____/2)

3. Set the oscilloscope to display the magnitude of the Fourier transform of a segment of the input signal, taking the following steps :

   - Press "Auto Scale" button, acquire in "High Resolution" mode. Set the time/div to 1 ms, and the V/div to 1 V. The trigger should be applied to source 1.
   - Your time domain signal should be contained completely inside the scope, since any calculation performed by the oscilloscope uses only what fits inside the display.
   - Press "FFT" button in the oscilloscope.
   - Set the FFT Source 1 (The channel that is receiving the signal).
   - Press the "Auto Setup" button (under the "More FFT" options).
   - The default "Window" setting "Hanning"[1] should be used.
   - Press the "Back" button and set the frequency span to 10.0 kHz and the center frequency to 5.0 kHz.
   - Using the knobs to the right of the FFT button, select the FFT scale to be 5 dB/div and the "FFT Offset" so that the maximum value of the FFT reaches the top of the display.
   - The oscilloscope now displays $|F(\omega)|$ in dB units, defined as $20\log_{10}|F(\omega)|$, where $F(\omega)$ is the Fourier transform of a windowed (see the footnote regarding Hanning window) segment of the oscilloscope input $f(t)$. Since $20\log_{10}|F(\omega)| = 10\log_{10}|F(\omega)|^2$, the scope display is also related to the *energy spectrum* $|F(\omega)|^2$ of the segment of $f(t)$. We will refer to the display as the *frequency spectrum* of the input. Note that the spectrum is shown only over positive frequencies $f = \frac{\omega}{2\pi}$ within the frequency band specified in a previous step above.

[1] As a result of this choice, the incoming signal $f(t)$ is effectively multiplied with $w_H(t) \equiv \mathrm{rect}(\frac{t}{T})\cos^2(\frac{\pi t}{T})$ prior to Fourier transformation. This procedure limits the length of the Fourier transform segment to duration T of the window function $w_H(t)$. Alternative window functions such as $w_B(t) = \mathrm{rect}(\frac{t}{T})$ give rise to frequency spectra $|F(\omega)|$with slightly different resolution and side lobe details.

4. Sketch only the frequency spectrum $|F(\omega)|$ (in dB) of the oscilloscope input and compare with theory (Hint: look back to Problem 4 in the Prelab).



Span : 10kHz Center : 5kHz Scale : 5dB (____/3)

Write down the pertinent Fourier transform pair:

$\mathrm{rect}(\frac{t}{\tau}) \leftrightarrow \tau\,\mathrm{sinc}(\frac{w\tau}{2})$ (____/1)

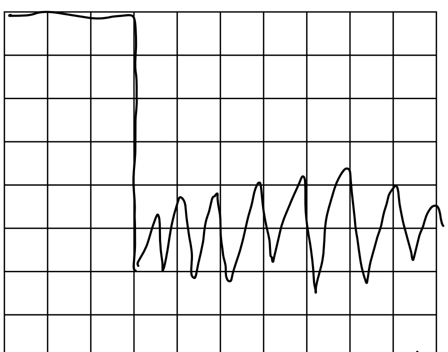
Compare the obtained spectrum with the theoretical expectation:

it's the same. (____/2)

5. With the function generator still in Burst mode, change the input to a sinc pulse (press "Shift", "Arb List", select "sinc", and press "enter"). Set the frequency to 1 kHz, and the amplitude to 1 V peak-to-peak (remember HIGH Z mode). In the scope, press the "Auto Scale" button, acquire with "High Resolution" mode, set the time/div to 20 μs, and the volts/div to 200 mV. The trigger should be applied to Channel 1. The sinc function shown in the scope is proportional to $\propto \mathrm{sinc}\,(Wt)$. Measure the time difference (ΔT) between the immediate zero-crossings surrounding the main lobe of the sinc function and calculate the corresponding value of W.

$\Delta T =$ 50μs	(____/2)	$W = \frac{\pi}{50E-6}$ $\frac{\text{rad}}{\text{s}}$	(____/1)	$W = 2\times 10^4$ Hz	(____/1)

6. In the scope, set the scales to 1 ms/div, and 200 mV/div. Press the "FFT" button. In the More FFT section press "Auto Setup". The frequency span should be 80 kHz, the center frequency 40 kHz. Using the knobs to the right of the FFT button, adjust the FFT scale to 10 dB/div and the FFT offset so that the maximum reaches the top of the display. Sketch only the frequency spectrum. Then compare with theory.



Span : 50kHz Center : 40kHz Scale : 100dB (____/3)

Write down the pertinent Fourier transform pair:

$\sin(W\tau) \longleftrightarrow \frac{\pi}{W}\,\mathrm{rect}(\frac{w}{2})$ (____/1)

Compare the obtained spectrum with the theoretical expectation:

it's the same. (____/2)

2.2 AM Signal in Frequency Domain

Amplitude Modulation (AM) is a communications scheme that allows many different message signals to be transmitted in adjacent band-pass channels. Before the message signal is multiplied by the high-frequency sinusoidal carrier, a DC component is added so that the voltage of the message signal is always positive. This makes it easy to recover the message signal from the envelope of the carrier. In Lab 1, you synthesized an AM signal with the function generator and then displayed it on the oscilloscope in the time domain. Let's see how the same AM signal looks in the frequency domain (Hint: Use the modulation property to interpret what you will see on scope display!):

1. No circuit is used for this part of the laboratory. Connect the function generator's output to Channel 1 on the oscilloscope.

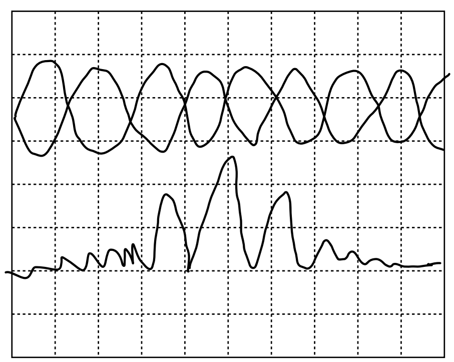
2. Set the function generator following the instructions below if needed to create an AM signal with $f_c = 14$ kHz and 1 V peak-to-peak amplitude, no DC offset, modulated by an 880 Hz sine-wave with 80% modulation depth.

   - First turn off the burst mode if it was on. Get rid of the arbitrary function if it was on by selecting a sine-wave. Set the frequency to 14 kHz and the amplitude to 1 V peak-to-peak(High Z mode).

- Press “Shift” then “AM” to enable amplitude modulation. Press “Shift” then “<” then ”∨” to select the shape of the message signal. You can select a sine, square, triangle, or arbitrary waveform by pressing “>”. For this part of the lab, select a sine waveform. Press “Enter” to save the change and turn off the menu. Later on, you will come back to this point to select a rectangular wave as the message.
- Press “Shift”, then “Freq” to set the message signal frequency to 880 Hz. Press “Shift”, then “Level” to set the modulation depth to 80%. This adjusts the DC component added to the message signal before modulation.

3. Set your oscilloscope to display the frequency spectrum of the input:
   - Press the “Auto-Scale” button and acquire in “High Resolution” mode.
   - Set the time/div to 1 ms, the Volt/div to 500 mV, and adjust the Offset, so that the time domain signal stays in the top part of the display. Remember that the time domain signal has to be completely inside the scope display before performing the FFT. To synchronize the scope with the AM signal you can rise the threshold level of the trigger to about 450 mV.
   - Press “FFT” button. Inside “More FFT” press the Auto-Setup button.
   - Set the center frequency to 14 kHz and the frequency span to 20 kHz.
   - Set the Scale to 15 dB/div (You need to turn on the “Fine” scaling by pressing once the “Scale” knob) and adjust the Offset so that the frequency spectrum stays in the bottom of the display, without interfering with the time domain..

4. Sketch both, the time domain AM signal and its frequency spectrum and explain what you see in terms of the modulation property of the Fourier transform. (Hint: How is the frequency spectrum of the message signal (co-sinusoid of 880 Hz) plus a DC component in base band, i.e. before modulation?)



Span : 1.25kHz Center : 14kHz Scale : 20db

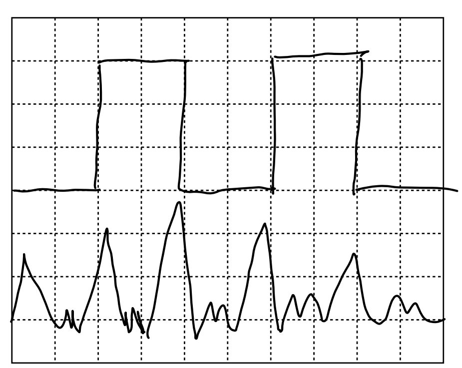
V/div : 500mV t/div : 1ms (____/4)

Explain the shape of the frequency spectrum. (____/4)

There is a wave (14 kHz) for high freqnency

And the frequency difference of peak is 880 kHz

5. Change the shape of the message signal in the modulation menu from `SINE` to `SQUARE` (In the function generator press “Shift” then “<” then ”∨” to select the shape of the message signal. You can select the waveform by pressing “>”.). **You are not changing the carrier signal, only the message.** In the scope the center frequency should remain at 14 kHz, the frequency span at 20 kHz and the dB/div at 15 dB. Sketch the AM signal in time domain and its frequency spectrum and explain what you see. (Hint: Remember the Fourier analysis of the square wave performed in Lab #3.)



Span : 1.25kHz Center : 14kHz Scale : 20db

V/div : 500mV t/div : 1ms (____/4)

Explain the shape of the frequency spectrum. (____/4)

A large period of 14 kHz at high frequency

It consists on add hermonics of 880 Hz

2.3 AM Radio Receiver

The most popular AM communications receiver is the superheterodyne receiver, which was developed for greater sensitivity and selectivity. A block diagram for the superheterodyne receiver is shown in Figure 3.

The antenna, RF amplifier, and frequency mixer all rely on electrical components *not covered* in this textbook, but their effects on the incoming signal should be familiar. You built the remaining components of the circuit in Labs 1 through 3. In this section, you will combine all of the components to tune in an AM radio broadcast and follow the signal from the antenna to the loudspeaker.

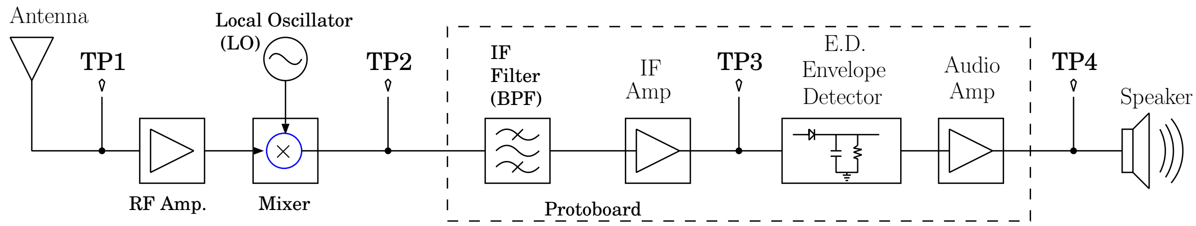


Figure 3 – Superheterodyne AM receiver.

Perform the following steps:

1. Connect the RF amplifier and frequency mixer modules provided. Make sure the labels on the boxes are right side up and facing you. Connect a Y-cable with banana connector terminals to the input stage of the RF amplifier — this will serve as a crude AM antenna. You might need to add some banana-banana cables to the signal terminal of the Y-cable (colored red) to increase the size of the antenna and have a better reception. Connect the ground banana connector of the Y-cable to a power outlet ground.

2. Use the DC source to power the modules by connecting +15 V to the blue terminals, -15 V to the purple terminals, and the ground ("Com") to the black terminals. Also, using a banana-banana cable, connect the ground ("Com") together power outlet ground .

3. Using a Y-cable, connect the output of the frequency mixer to the input of your band-pass filter from Lab 3. Connect the +15V, -15V, and ground ("Com") to your circuit.

4. Connect the output of the band-pass filter to the input of your three-stage circuit from Lab 2.

5. Connect the function generator to the local-oscillator input on the frequency mixer. Tune either WILL 580 (580 kHz) or AM 1400 (1400 kHz) by selecting an appropriate mixing frequency with 100 mV peak-to-peak (remember high Z mode) as the local oscillator so that the intermediate frequency $f_{IF} = 14\,\text{kHz}$. (Hint: look back to Problem 1 in the Prelab).

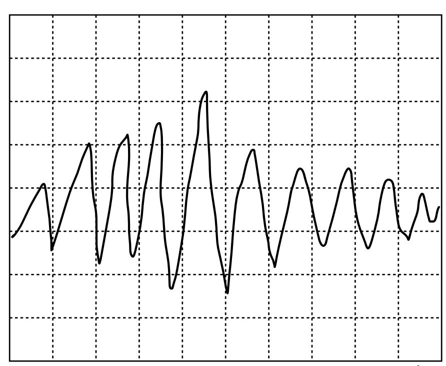
6. Now you will follow the processing of the received RF signal into an audible signal by displaying the time and frequency domain of the four test-point signals on the oscilloscope. The test points are described below.

When displaying the signals from each of the test points, it will be your task to select an appropriate time scale for the time-domain waveform and center frequency and frequency span for its Fourier spectrum. If you select inappropriate numbers, all you will see on the oscilloscope is noise. You may ask the TA for hints, but give your choice some thought and discuss it with your partner before displaying the signal.

2.3.1 Test Point 1: RF Amplifier

(____/4)

Connect the Antenna (described in step 1 above) to the oscilloscope (TP1). Use high resolution mode, and set the time/div to 500 μs. Press the FFT button and set the span to 100kHz and the central frequency to put the signal of either WILL 580 (580 kHz) or AM 1400 (1400 kHz) at the center of the frequency span (It might be easier to push the knob and type the value directly). **Sketch the waveform in both the time and frequency domains and label the peak corresponding to the radio station signal**. Place the time domain signal in the upper part of the display, scaling it appropriately, so that it does not interfere with the freq. domain graph, and it is not cut-off by the display. You might need to reposition your antenna or increase its size in order to detect the signal.



Span : 6kHz Center : 14kHz Scale : 20dB

V/div : 500mV t/div : 500μS

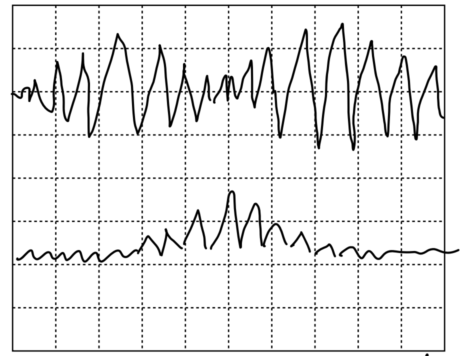
2.3.2 Test Point 2: Frequency Mixer

(____/4)

The mixer multiplies the RF signal with the signal coming from the local oscillator, which is tuned so that all subsequent processing is independent of the radio broadcaster's carrier frequency. In most commercial receivers, the mixer is tuned to produce an Intermediate Frequency (IF) of 455 kHz. We are going to use an IF of 14 kHz since the band-pass filter and envelope detector you built are suited for an IF of 14 kHz.

The function generator will be the local oscillator (LO), To produce an IF of 14 kHz, the LO must be set at a frequency 14 kHz above or below the carrier signal of the station we are trying to tune. **We will be tuning AM 1400 or WILL 580. So, set the LO to the appropriate co-sinusoidal signal with an amplitude of 100 mV peak-to-peak** (remember high Z mode). Make sure that the function generator's AM feature is turned off. Set the time/div to 2ms and V/div to 200mV for the oscilloscope.

Probe TP2 and sketch the output in the **time domain and the frequency domain**. Adjust to a suitable frequency span. (Hint: At which frequency do you expect the signal to be after the mixer?). You might want to adjust the LO frequency to maximize the amplitude in time domain.



Span : 6kHz Center : 14kHz Scale : 20db

V/div : 200mV t/div : 500μs

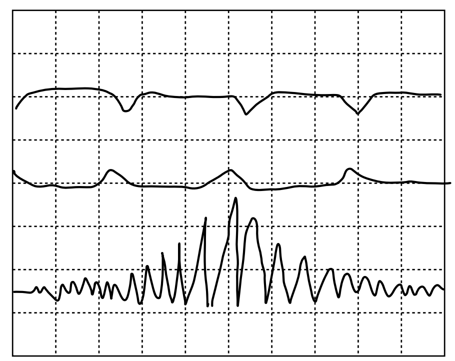
2.3.3 Test Point 3: IF Filter and Amplifier

(____/4)

The IF filter is used to select the signal centered on the IF frequency and to reject all other signals. Receivers employing higher IF's typically include ceramic IF filters that operate on a piezoelectric principle. Although small and inexpensive, ceramic filters can have very sharply tuned responses needed with large IF compared to AM bandwidth. With lower IF such as 14 kHz, a sharply tuned response is not necessary, and thus even the low-Q op-amp-based band-pass filter from Lab 3 that we are using is more than adequate.

Depending on the AM signal strength from the antenna and the noise level, you may find it necessary to add gain to the IF amplifier. Feel free to experiment with different gain values (remember the design equation from Lab 2) to get an output that can be demodulated by the envelope detector. An IF gain of about 30 or 50 is not uncommon.

Probe the signal at TP3. Sketch the time waveform and the frequency spectrum. Result should be similar to test point 2, but amplified, due to the IF amplifier.



Span : 6kHz Center : 14kHz Scale : 20db

V/div : 500mV t/div : 50μs

2.3.4 Test Point 4: Envelope Detector and Audio Amplifier

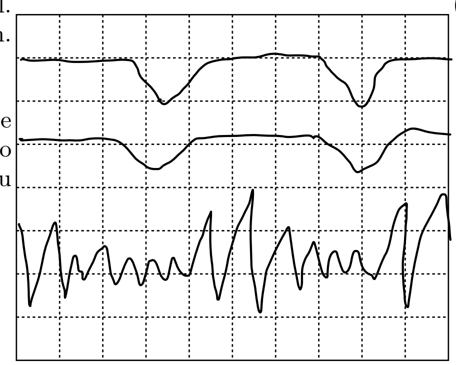
(____/4)

The envelope detector then recovers the message signal from the IF signal. Probe TP4 and sketch the time-domain waveform and frequency spectrum.

At this point, if all stages of the AM radio behave as expected, hook up the output of the audio amplifier to the speaker. Experiment tuning to radio stations : WILL 580 kHz and WDWS 1400 kHz. Do you hear what you expect to hear?

Yes

Up to 20 points bonus will be given by letting your TA hear the radio station.



Span : 8kHz Center : 14kHz Scale : 20db

V/div : 500mV t/div : 500μs

The Next Step

Now that your AM radio receiver is complete, you will turn your attention to a "software radio" implementation of the same design using digital signal processing in the next lab.