ECE 145C/218C, Lab Project: Preliminary Description.

Draft March 18, 2024.

Precautions

Precautions to avoid instrument damage

(a) Observe static precautions when working with the network analyzer or spectrum analyzer. Wear the wrist strap.

(b) Never connect a network analyzer or spectrum analyzer directly to a circuit carrying dc. Make sure your circuit is dc blocked, or you will destroy the instruments..

Safety precautions

(a) Safety note: please be very careful with the X-acto razor-blade knives. Use the same level of care you would use with a very sharp kitchen knife ! We want no injuries.

(b) Common solder is tin-lead and is toxic. If ingested, lead accumulates in your body and slowly and progressively causes brain damage as well as damage to other organs. The shop sells non-lead-containing solder. ***Do not bring lead-containing solder into the lab.*** That means, do not purchase solder at Radio-shack or other vendors unless you very carefully check its metal composition. The new non-lead solders have a higher melting point, which makes soldering harder, particularly soldering to ground planes. Use a higher-power (hotter !) iron for soldering to the ground plane.

(c) In case some student fails to follow the solder rules above, ***do not eat or bring food into the lab, wash your hands immediately after leaving the lab***, and sweep up and dispose of any solder debris. ***Do not use solder-suckers for desoldering , as these spray a fine powder of solder all over the room***. Horribly toxic if some fool uses them with lead solder ! Use desoldering wick (braid) instead; it is better anyway.

(d) Basic rules for electrical safety apply. Circuit voltages are low (~5-15 Volts) but avoid bringing in high-voltage DC supplies, use common caution in plugging in 120 V connections, do not stand in or work around water, and do not work with electrical equipment with bare feet.

(e) students who violate these precautions will receive a lab grade of zero.

Project description: Preliminary.

This project is being created for the first time in 2024 and is evolving during the weeks before the quarter starts and will no doubt evolve further in the early weeks of the spring quarter.

Motivation

A number of you have requested a sophisticated project that brings together most of what we've learned over the full year of design. Although a CAD-based project would be one alternative, we would never get back silicon from the foundry in time to test it. And, unless you test your design, you will learn very little. ***It's the business of designing, having something built or making it yourself, testing it, discovering that it doesn't work, figuring out why, and then fixing it, that is the whole business of being an engineer.*** That's what we must practice in the lab.

Besides, it's really fun and rewarding to build something yourself and see it really working. ***There is absolutely no comparison to this experience***.

So we will build a full radio transmitter and receiver in this lab project. This should be exciting and challenging. To make sure it's not overwhelming, you have tremendous discretion in how much of the transmitter and the receiver you actually build, and how much you bypass by using lab instruments instead.

You will have the opportunity to study for the relatively short time, a day or so I understand, to get a basic qualification from the FCC to allow you to operate a radio transmitter, subject to the appropriate regulations, in the 902 MHz to 928 MHz frequency band. I will provide you the information necessary to pursue that option . With that qualification, and obeying all the rules you will have learned, you will be allowed to operate your transmitter and receiver with antennas. If you don't have the time to do this, the transmitter and receiver can instead be connected with a coaxial cable with an appropriate level of attenuation inserted in the link.

The parts supply problem

Building a transmitter and receiver brings up many complications. It would be absolutely overwhelming to design everything design and build everything from a single transistor level up through mixers, amplifiers, VCOs, etc. and all the way to a full radio.

One must use a judicious mix of circuits built up from single transistors, plus other circuit blocks implemented using commercial products. For radios, this would have been easy in 1980 or 1990, but unfortunately to day, it's really hard to get small scale commercial integrated circuits. Commercial products are now highly integrated at the level of a full Wi-Fi radio, with RF baseband and digital signal processing all on a single chip. People building experimental test systems and scientific apparatus face the same problem. There are a few companies, some of whom you will see in the parts list below, who sell blocks like crystal oscillators, voltage controlled oscillators, and mixers, as a single unit. These are units designed for lab prototypes not high volume production, so they are in fact quite expensive. To address these, I'm using some discretionary funds provided to me for the purpose of developing classes and educational programs. So I'll subsidize the parts cost for you, but you need to not treat these parts carefully because they are in fact quite expensive.

Block diagrams and strategic plan

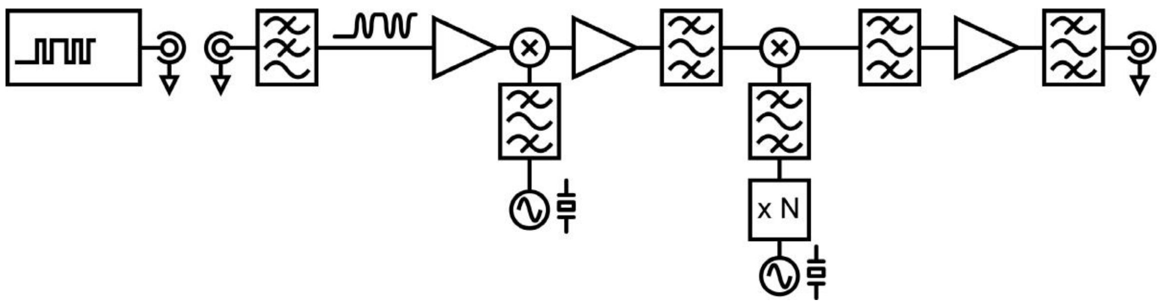


Figure 1: Superheterodyne transmitter architecture with crystal controlled oscillators for both up conversion to the intermediate frequency and up conversion to the radio frequency.

Figure 1 shows a superheterodyne transmitter architecture. On the extreme left is what is called a pseudo random pattern generator; it will generate a sequence of ones and zeros has appears to be random, but does so with deterministic digital logic. We will provide a printed circuit board design and logic diagrams for this, so you can construct this easily.

The signal is then filtered with a root raised cosine channel filter, up converted to an intermediate frequency by mixing against a precision crystal oscillator, amplified, and then up converted again to radio frequencies by multiplying against a second crystal oscillator, perhaps using an internal frequency multiplier chain. A filter after the up conversion mixer removes the image response. A power amplifier increases the signal power to the level appropriate for the desired transmission range. A very sharp and narrow output filter removes out-of-band responses, keeping the transmitter compliant with government out-of-band emission regulations.

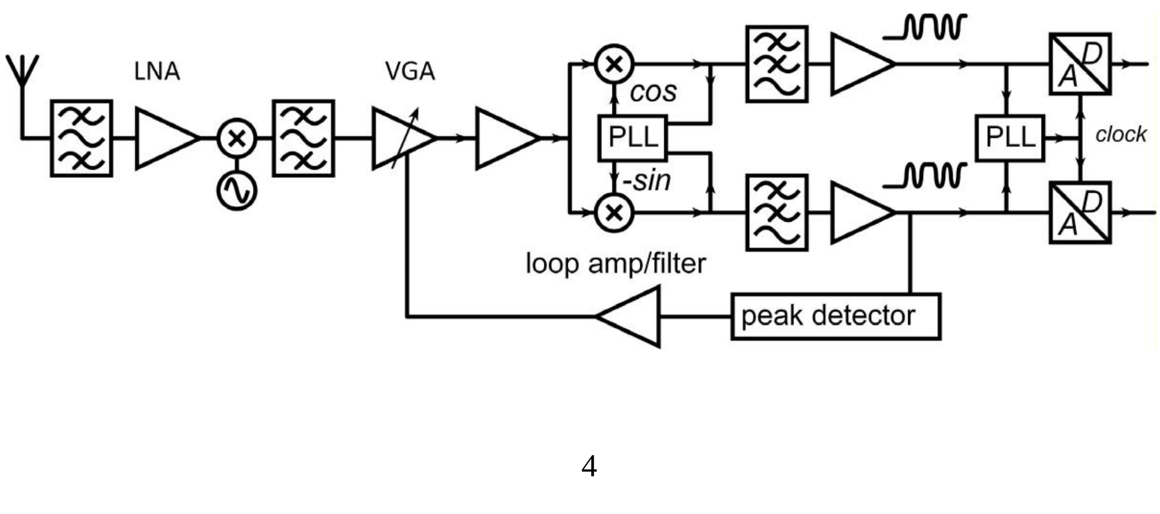


Figure 2: Superheterodyne receiver with PLLs for the 2nd local oscillator and for clock and data recovery.

Figure 2 shows a superheterodyne receiver architecture. The signal is amplified by a low-noise amplifier which serves to suppress the input-referred noise of the mixer. The mixer down-converts the signal to an intermediate frequency (IF). At the IF, very sharp filters remove adjacent-channel and nearby-channel interference, and a great deal of amplification is provided.

The signal is then down converted to (I,Q) baseband using a pair of mixers with a local oscillator (LO) generated by a phase-lock-loop (PLL). As we will learn in lectures, for the PLL to lock on modulated BPSK or QPSK data, it must have quite a complex phase detector. So, this PLL is quite complex.

The baseband (I,Q) outputs are low-pass filtered, not only removing image responses but, more importantly, providing the root-raised-cosine matched filters for optimum receiver sensitivity. The peak-peak output of the baseband signals is measured using a peak detector, which uses this signal to control the gain of an IF (or RF) amplifier, thereby regulating the signal level at the receiver output.

To recover data, data decisions must be made at the center of each symbol period. This requires that the symbol frequency and symbol transition times be determined. This function is also provided by a PLL. As with the carrier recovery PLL, the clock and data recovery PLL, because it must operate with modulated data, is complex.

Simplifications

The transmitter of Figure 1 and the receiver of Figure 2 are far too complex for the ece145C/218C students to complete as a 1-term laboratory project. We must simplify

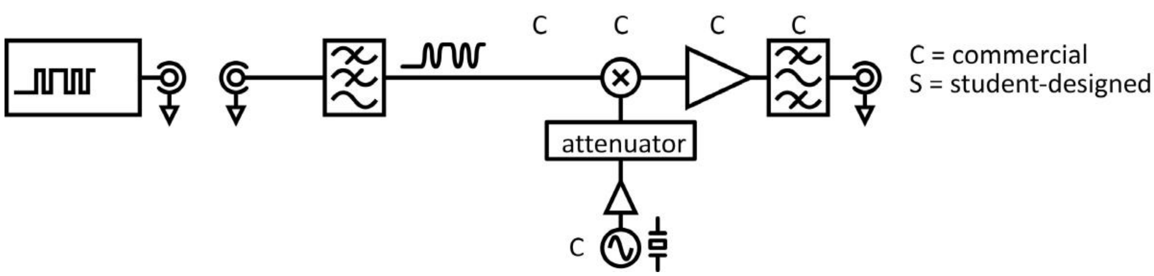


Figure 3: Simplified BPSK transmitter

In the simplified transmitter of Figure 3, data from the PBRS pattern generator is low-pass filtered (root raised cosine filter), and then mixed against a commercially available fixed-frequency oscillator. Adust the bias current in the output buffer of the PRBS pattern generator so as to adjust its output amplitude, giving you about 0dBm output power. This is comfortably below the 1dB gain compression point of the mixer. The oscillator is sold as a "crystal oscillator"; though it in fact has an internal PLL synthesizer or frequency multiplier chain to bring its frequency to that desired from that suitable for a quartz crystal resonator. The frequency of these is fairly precisely controlled, to a precision of perhaps a few parts in 10^5.

The output of the mixer, being BPSK modulated data, is amplified by a power amplifier. It is then passed through a very narrowband filter, with very sharp skirts, to suppress very strongly any out-of-band signals.

The combination of a very precisely controlled oscillator (setting the carrier frequency within the FCC-allocated band) and the very narrow filter (with very high suppression outside the FCC-allocated band) will *help* keep the transmitter FCC-compliant. But, strong IM3 in the power amplifier might produce excessively wide modulation sidebands. Or, the power amplifier might oscillate at some unexpected frequency. In these cases, the output filter might not adequately suppress the out-of--band radiation.

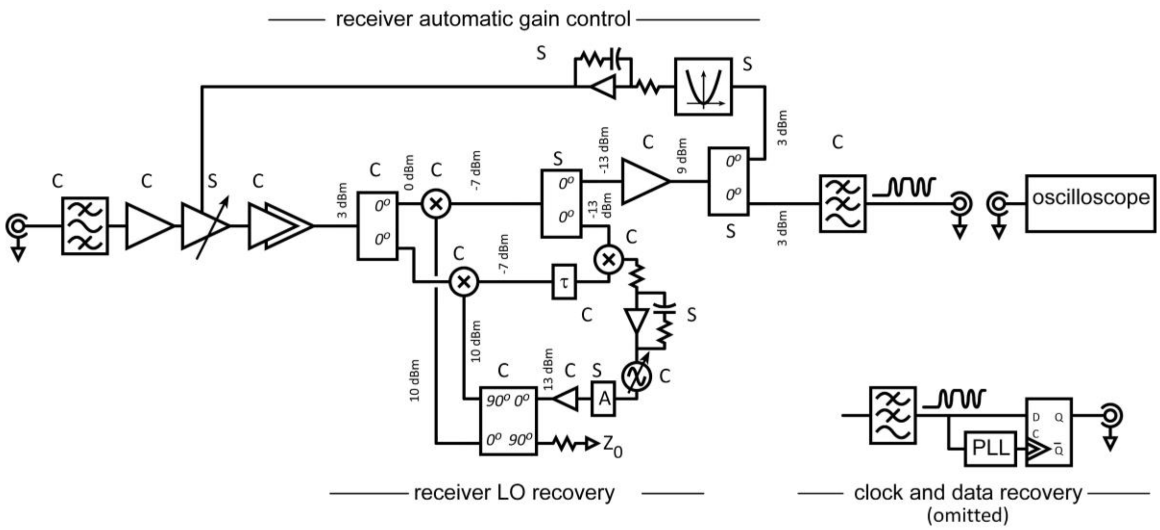


Figure 4: Simplified BPSK receiver. A=attenuator

Figure 4 shows a simplified receiver. We have made two simplifications. First, The clock and data recovery has been entirely omitted. One can simply look at the eye pattern, with the signal and noise at the output of the receiver, and attempt to qualitatively judge whether the signal to noise ratio is sufficient for data recovery.

Secondly, the receiver is direct conversion without any intermediate frequency stages. I offer this option in the spirit of simplifying the design, but it comes with significant complications. In a properly designed BPSK receiver the minimum received power is $P_{\min} = kTFB \cdot \mathrm{SNR}$, where B is the bit rate and ~10 dB SNR is required for 1E-3 bit error rate. At ~5 Mbit/sec and F=5 dB, this is about -92 dBm. If the baseband output of the receiver is at, for example, 0 dBm, then the overall amplification of the receiver, between its RF and baseband stages, must be around 92 dB.   This is a very large gain. Even if were to partition the gain equally between the RF and baseband stages, we would have 46 dB gain in each.   There is then significant chance of oscillation due to unintended feedback on DC power supply leads etc.

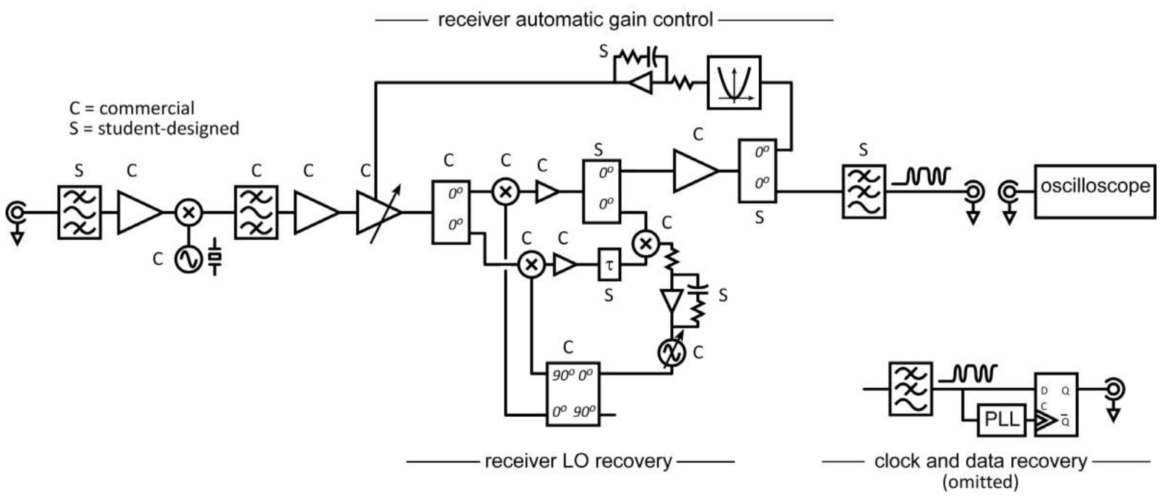


Figure 5: Superheterodyne receiver

A superheterodyne design, (Figure 5) with its gain stages at RF, intermediate frequency and baseband, could have 30 decibels gain in each, and would be less prone to oscillation problems. *In addition to being more complex, you will need additional parts which we must order for you. For example, With the transmitter crystal oscillator set at 915 MHz, If you set the intermediate frequency at for example 70 MHz, then you will need a (915 MHz- 70 MHz)=845 MHz crystal oscillator, a 70 MHz IF filter, and a 70 MHz VCO for your PLL*. Please let us know quickly if you intend to make a superheterodyne receiver.

Board design and construction

We will use commercial printed board services To fabricate the boards. I will give you a set of suggested web links for places which students in the past have obtained boards quickly and simply. These organizations will also provide simple computer based programs to generate the board layouts.

It is critical to get the designs completed quickly so that the boards can be ordered in time.

The boards will be made out of common FR4 printed circuit board material. FR4 has a dielectric constant that varies between 3.8 and 4.8 depending on the glass weaving style, thickness, and resin content. You will have to design using a value in the middle of this range. this will cause some small error in the characteristic impedance of your 50 Ohm interconnect lines, but it's doubtful that the error will cause significant performance variation in your Overall transmitter or receiver

Assignment and Schedule

You are to design, build, and test the transmitter of Figure 3 and the receiver of Figure 4 or Figure 5.

The notations "S" for student designed and "C" for commercial are suggestions; You are free to design more of fewer blocks yourself. I suggest keeping the number of student designed blocks to a minimum because the system is so complex.

I'll give you circuit diagrams for simple things like power splitters. And a circuit diagram for the power detector.

We must manage time carefully or we will run out. Hence the schedule below:

April 15: CAD layouts of printed circuit boards and block diagrams of transmitter due. Place your order of the transmitter printed circuit board on or before this date.

April 29-30: Check off in the lab of your functioning transmitter with the teaching assistant. You will also need to have assembled a PRBS unit at that time.

May 13: CAD layouts of printed circuit boards and block diagrams of receiver due. Place your order of the receiver printed circuit board on or before this date.

June 3-4: Check off in the lab of your functioning transmitter with the teaching assistant.

If we change the due dates, This will be reflected in the class web page. In that case the web page will disagree with this document; use the dates on the web page.

Utilities

Here is a handy table that converts peak to peak, peak, and RMS signal amplitudes to signal power in Watts and in dBm. This assumes sinusoidal signals and 50 Ohm load resistance.

Vpp	Vpeak	VRMS	W	dBm
1.00E-02	5.01E-03	3.54E-03	2.51E-07	-36.00
1.12E-02	5.62E-03	3.97E-03	3.16E-07	-35.00
1.26E-02	6.31E-03	4.46E-03	3.98E-07	-34.00
1.42E-02	7.08E-03	5.00E-03	5.01E-07	-33.00
1.59E-02	7.94E-03	5.61E-03	6.30E-07	-32.00
1.78E-02	8.91E-03	6.30E-03	7.94E-07	-31.00
2.00E-02	1.00E-02	7.07E-03	9.99E-07	-30.00
2.24E-02	1.12E-02	7.93E-03	1.26E-06	-29.00
2.52E-02	1.26E-02	8.90E-03	1.58E-06	-28.00
2.82E-02	1.41E-02	9.98E-03	1.99E-06	-27.00
3.17E-02	1.58E-02	1.12E-02	2.51E-06	-26.00
3.56E-02	1.78E-02	1.26E-02	3.16E-06	-25.00
3.99E-02	1.99E-02	1.41E-02	3.98E-06	-24.00
4.48E-02	2.24E-02	1.58E-02	5.01E-06	-23.00
5.02E-02	2.51E-02	1.78E-02	6.30E-06	-22.00
5.63E-02	2.82E-02	1.99E-02	7.94E-06	-21.00
6.32E-02	3.16E-02	2.24E-02	9.99E-06	-20.00
7.09E-02	3.55E-02	2.51E-02	1.26E-05	-19.00
7.96E-02	3.98E-02	2.81E-02	1.58E-05	-18.00
8.93E-02	4.47E-02	3.16E-02	1.99E-05	-17.00
1.00E-01	5.01E-02	3.54E-02	2.51E-05	-16.00
1.12E-01	5.62E-02	3.97E-02	3.16E-05	-15.00
1.26E-01	6.31E-02	4.46E-02	3.98E-05	-14.00
1.42E-01	7.08E-02	5.00E-02	5.01E-05	-13.00
1.59E-01	7.94E-02	5.61E-02	6.30E-05	-12.00
1.78E-01	8.91E-02	6.30E-02	7.94E-05	-11.00
2.00E-01	1.00E-01	7.07E-02	9.99E-05	-10.00
2.24E-01	1.12E-01	7.93E-02	1.26E-04	-9.00
2.52E-01	1.26E-01	8.90E-02	1.58E-04	-8.00
2.82E-01	1.41E-01	9.98E-02	1.99E-04	-7.00
3.17E-01	1.58E-01	1.12E-01	2.51E-04	-6.00
3.56E-01	1.78E-01	1.26E-01	3.16E-04	-5.00
3.99E-01	1.99E-01	1.41E-01	3.98E-04	-4.00
4.48E-01	2.24E-01	1.58E-01	5.01E-04	-3.00
5.02E-01	2.51E-01	1.78E-01	6.30E-04	-2.00
5.63E-01	2.82E-01	1.99E-01	7.94E-04	-1.00
6.32E-01	3.16E-01	2.24E-01	9.99E-04	0.00
7.09E-01	3.55E-01	2.51E-01	1.26E-03	1.00
7.96E-01	3.98E-01	2.81E-01	1.58E-03	2.00
8.93E-01	4.47E-01	3.16E-01	1.99E-03	3.00
1.00E+00	5.01E-01	3.54E-01	2.51E-03	4.00
1.12E+00	5.62E-01	3.97E-01	3.16E-03	5.00
1.26E+00	6.31E-01	4.46E-01	3.98E-03	6.00
1.42E+00	7.08E-01	5.00E-01	5.01E-03	7.00
1.59E+00	7.94E-01	5.61E-01	6.30E-03	8.00
1.78E+00	8.91E-01	6.30E-01	7.94E-03	9.00
2.00E+00	1.00E+00	7.07E-01	9.99E-03	10.00

Part Supply (we will substantially subsidize)

Parts will be available to you from the electronics shop. Most of these will have been purchased at no expense to you using funds from Professor Rodwell's discretionary accounts. ***But you need to be aware that the parts are in fact expensive***. *So beyond the free supplied versions given to you,, additional versions copies that you might need because of your inadvertently damaging devices will have to be purchased*. I have not defined a policy for this yet but that may involve either you paying the full cost, or I may slot split the cost of additional parts with you 50%/ 50%. We will discuss this in class.

I provide the linkages below so that you can track down data sheets and specifications. Also so that you understand the full cost of the items.

<u>Cheap PCB-mountable coaxial connectors (about $0.5 each)</u>
You will use these at the input and output of each major functional block of the transmitter and the receiver so that you can break the signal path and test the receiver and transmitter block by block. It's likely that you will have about 14 of these on your printed circuit board.

These are extraordinarily cheap, much less expensive than normal SMA connectors. Let's be sure to discuss that issue in class.
https://www.amazon.com/GDQLCNXB-Launch-Straight-Connector-Adapter/dp/B093SR18Z8/ref=sr_1_14?dib=eyJ2IjoiMSJ9.DaTgHqUeIUpr47A5ZK2YberPj-HFXcXICdpYjTcbiRNoNJPnQncNhDWWGXM0GaTy372Z-vwOZ9cKWQcALAC5Atn274L9Yq7JlJ1PcoAqAJEuHtd0n0JziuRJGekF0UEjfB9_nnYky0448xhFPXfzIkejMasOkguhSfXPMCrSdw_zBXPocughomhKlbhqOtfs6lBox0kLzDV-IhkOU7sZfZlc-X41P2BRXnHie6FCr5w.K5RtO6yaQum4PBkjUVA50FkKSFJ3ZuulJwZg-u37U0o&dib_tag=se&keywords=sma+connector&qid=1709758913&sr=8-14

<u>Cheap connectorized coaxial cables (about $2.50 each)</u>
These will be used to connect Between blocks on your overall transmitter and receiver so that you can break your overall transmitter and receiver into individual testable blocks.

You will need about 7 cables per group.

These are extraordinarily cheap, much less expensive than normal SMA connectors. Let's be sure to discuss that issue in class.

https://www.amazon.com/SDTC-Tech-Coaxial-Assembly-Extender/dp/B07NCLZWHH?source=ps-sl-shoppingads-lpcontext&ref_=fplfs&smid=A1QLGMVB669WW&th=1

Crystal oscillator (about $2.86 each)
This is the local oscillator for the transmitter. Its frequency will set the transmission center frequency, And given FCC regulatory issues it is critical that the frequency be precisely set. Hence we will use crystal oscillators.
You will need one of these per project.
https://www.mouser.com/ProductDetail/Renesas-Electronics/XLL536915.000000I?qs=itIaUkCn8qDJ0ra%252Bz6%252B8pQ%3D%3D

The output of this is LVDS (Low voltage differential signaling). Here's a document that describes this:
https://www.ti.com/lit/an/snla165/snla165.pdf?ts=1712839893999&ref_url=https%253A%252F%252Fwww.google.com%252F

you will need to work out the output amplitude from the crystal Oscillator.

baseband filters
We really should use something approximating a root raised cosine filter here, but such devices won't be commercially available as ready made filters. A Bessel Thompson filter would come close, but again I can't find a commercially available unit.

So we will use simple commercially available filters that are probably pretty close to Butterworth. https://www.minicircuits.com/WebStore/dashboard.html?model=SCLF-4.7%2B

Receiver VCOs (about $34.00 each)
The receiver must phase lock to the transmitter, and you will be designing and building a phase locked loop. One component of this is the voltage controlled oscillator. Unfortunately, I could not find a commercially available VCO chip at reasonable expense. However this part has the right tuning range and really good phase noise. Again we will sell this to you at nominal cost, but you must not break it, because the cost of the replacement unit will be significant
https://www.minicircuits.com/WebStore/dashboard.html?model=ROS-1410%2B

Transmit bandpass filters (about $0.80 each)
Modulation of the transmitter signal with information will spread the spectrum, and if there's something wrong with your transmitter design you may spread the spectrum by more than is allowed by the FCC frequency allocation. So to prevent violating FCC rules we will use very narrow band very high performance filters at the output of the transmitter.

Need 1 filter per group for the transmitter. It might be helpful to use a similar filter in the receiver. In that case you will need two per group.

https://www.digikey.com/en/products/detail/qualcomm-rf-front-end-rffe-filters/B39921B3726U410/3492652

Mixers (about $4.24 each)
You will probably need about five mixers per project.
You may possibly use one as a variable gain block in your automatic gain control loop.
$4.24 each. In stock
https://www.minicircuits.com/WebStore/dashboard.html?model=ADEX-R10LH%2B

90 degree hybrid power splitters (about $5.00 each)
You will need one of these per group.
https://www.minicircuits.com/WebStore/dashboard.html?model=QCS-981%2B

0 degree power splitter high frequency. (about $12.00 each)
You will need one of these per group for power splitting at high frequencies.
https://www.minicircuits.com/WebStore/dashboard.html?model=SBB-2-10%2B

There are in fact a number of points where you need to split power, But in all but one case this is at the base band not at the radio frequency. For the baseband power splitters we can use resistors. We will discuss in class

Receiver medium-power amplifier for LO driving, etc. (about $3.00 each)
This is a relatively high power amplifier workable over DC to 1 GHz .
You might need as many of four of these per project.
https://www.minicircuits.com/WebStore/dashboard.html?model=GALI-74%2B

Receiver Voltage controlled attenuator (about $16.00 each)
You might need one of these per group. Or you might need zero: There are alternatives.
$16.38 each 0-28 dB 10 MHz-2 GHz.
https://www.minicircuits.com/WebStore/dashboard.html?model=MVA-2000%2B

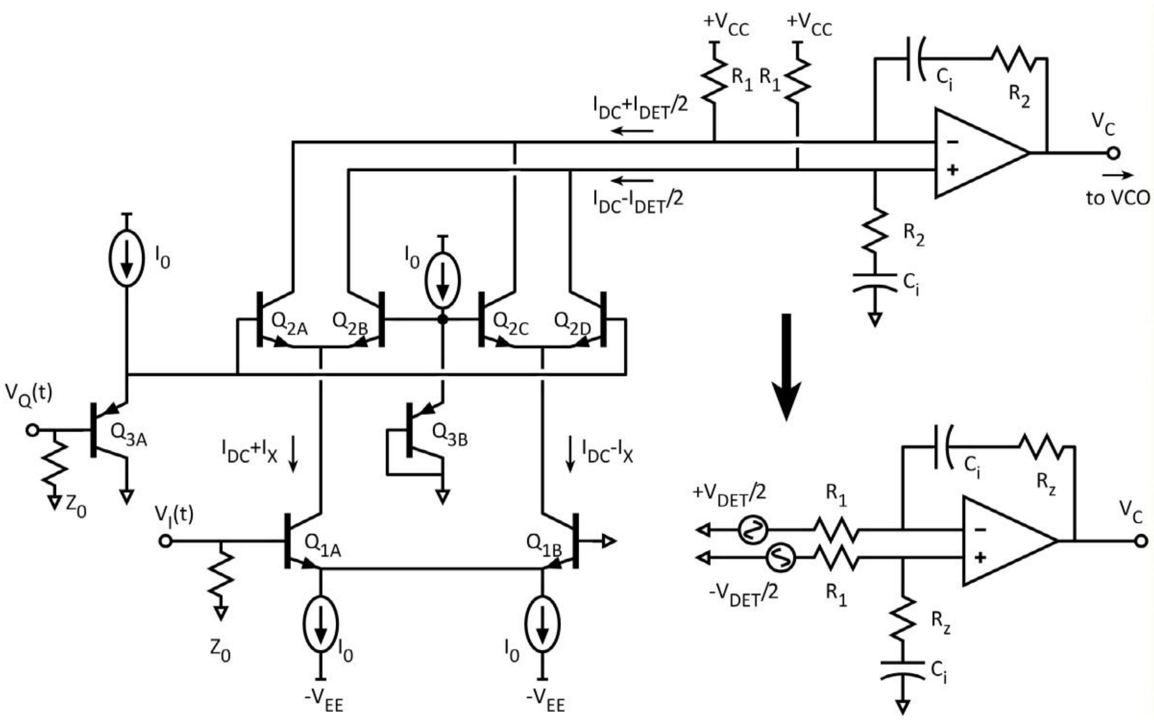
Receiver peak detector
You will figure out how to do this with two radio frequency transistors, or even two low frequency transistors. No need for custom parts.

baseband gain blocks, also LNA (about $1.50 each)
You might need as many of 10 of these per project.

Fortunately these are cheap, and have quite good performance.
https://www.minicircuits.com/WebStore/dashboard.html?model=MAR-1SM%2B

Third mixer for the carrier PLL

The transformer coupled mixers will not work for this application because the mixer must work down to DC. I recommend the circuit below:



The circuit should be reasonably fast in otherwise should work as a frequency detector up to the maximum frequency difference, which might be as much as 150-200 MHz. So we need reasonably fast transistors. For the NPN's, use the MRF901,
MRF951, or Infineon-BFP181. For the PNPs, use the ONSEMI MMBTH81.
The bias currents in the bipolar transistors should be selected to give reasonable transistor bandwidth. Perhaps 5 mA or 10 mA each: Check the data sheet curves of ft versus current.

Printed circuit boards (about $5-10-20 each)

You can do some prototyping by hand constructed printed circuit boards using copper tape to run connections on the signal side of the board and using ground connections on the continuous ground plane on the opposite side of the board. Boards for this purpose will be available from the shop, and they are made out of fiberglass, either FR4 or a similar material. you can model them as FR4 in your simulations. (Please look up the dielectric properties of FR4; It's an industry standard material). To make it easy for you, boards will be available with a pre drilled set of holes at 1/10 inch pitch.

It will be advantageous for you to have your final circuit board commercially made. We will discuss options in class. Students from previous years have found several services available over the Internet that can do this relatively cheaply and relatively quickly. Further the mask layout for the printed circuit board can be done in easily used free software available for this purpose.