INEXPENSIVE WIRELESS TELEMETRY FOR ANIMAL TRACKING

A Design Project Report
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In Partial Fulfillment of the Requirements for the Degree of
Master of Engineering (Electrical)

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Abstract

Master of Electrical Engineering Program
Cornell University
Design Project Report

Project Title: Inexpensive Wireless Telemetry for Animal Tracking

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Abstract: This project explored the feasibility of creating a cost-effective transmitter-receiver pair to replace commercially available 150 MHz devices used in animal telemetry. Distance measurements of test circuits transmitting at 418 MHz were taken over clear ground and in forested areas to demonstrate that 400 MHz radiation is capable of acceptable forest penetration. A transmitter was then designed and optimized for power consumption and cost. The final transmitter has a total current draw of 70 uA. Components for the transmitter-receiver pair are available at considerably less cost than commercial devices.

Report Approved by

Project Advisor: ________________________ Date: ___________________

Executive Summary

This project explored the feasibility of creating a cost-effective transmitter-receiver pair to replace commercially available 150 MHz devices used in animal telemetry. Distance measurements of test circuits transmitting at 418 MHz were taken over clear ground and in forested areas. These measurements show a range of 300-400 feet in forest underbrush and acceptable dropoff over distance, demonstrating that 70 cm radiation can be used in this application. For testing, a 418 MHz Yagi antenna was constructed and shown to exhibit strong directionality and approximately 20 dB gain in the forward direction.

Once it was determined that 400 MHz radiation is capable of forest penetration to the range specified, the transmitter design was optimized for greater battery life. After exploring several potential oscillator designs for transmitter input, an op-amp circuit was designed with appropriate PCB layout. A 433 MHz transmitter/receiver pair was constructed and tested to show signal range at the same level as earlier measurements at significantly lower power consumption rate. The final transmitter has a total current draw of 70 uA. This translates to roughly one and a half months of continuous operation using freely available 70 mAh lithium-ion coin batteries. Components for the transmitter-receiver pair are available at considerably less cost than commercial devices, with component cost for each transmitter at roughly ten dollars and for the receiver at less than twenty dollars.

Design Problem & System of Requirements

Field biologists are often required to track animals for research purposes. In order to do so, wireless transmitters are attached to wildlife and re-released into their native environment. Over a period of days or weeks the field biologist then uses a receiver to identify the location of radio-tagged animals after they have been released. Because the goal is to observe animals with as little disturbance to them as possible, the transmitters need to be optimized for size and weight depending on the animal.

However, the transmitters also need to be somewhat rugged to survive the outdoors, and battery life must be reasonably long so that recapture of animals for replacement of batteries is unnecessary. In addition, the transmitter must be detectable through forest terrain from a significant distance. Depending on the particular application, the receiver must also be relatively mobile, such that it can be carried easily.

Commercially available transmitter-receiver pairs designed for tracking animals typically use 150 MHz radiation, which has a wavelength of approximately two meters. They are fairly expensive, at around $100 each, and the two-meter radiation requires an extremely bulky receiving station and a relatively long transmitter antenna. The intent of this project is to build a prototype transmitter-receiver pair which is less costly and more convenient as a result of using smaller wavelength radiation, while sacrificing as little as possible in size, weight, and receiving distance.

A clear set of design goals can be set for both the transmitter (to be placed on the animal) and the receiver (carried by the biologist). The transmitter should be as small and lightweight as possible with off-the-shelf components. The battery lifetime probably needs several days of continuous operation, at the bare minimum. Finally, the transmitted signal must be detectible through forest or underbrush for a minimum of 100 meters, with 1 kilometer of penetration optimal. In addition, the total cost of parts for each transmitter should be less than $50. The receiver, of course, does not need to be as small as the transmitter. It must, however, be relatively portable (weighing less than ten pounds), and it should likewise be relatively inexpensive.

While a more complex signal might be used later, the goal of the current design was to transmit a simple audio tone. The field biologist can then listen to the output of the receiver in conjunction with the directional antenna receiver to track the location of the transmitter.

Range of Solutions available

Many tradeoffs need to be considered and are inherent to the design of the transmitter. The choice of which wavelength radiation is important, because shorter wavelength radiation results in a shorter antenna, but possibly decreases range of transmission through forest terrain. The current use of two-meter radiation results in transmission and receiving antennas which are overly large. This project focused on transmitter/receiver pairs in the 400 MHz range, as many modules are available at 418 and 433 MHz, while available 900 MHz devices were less likely to transmit to the distance required for this application.

Off-the-shelf components for the transmitter and receiver were selected due to cost efficacy, as the transmitter/receiver pairs will only be produced in fairly small volumes (< 5-10 transmitters per year). The simplicity of the system and cost factors allow the use of a relatively simple transmitter, with either AM or FM functionality.

Because weight and length of usage are both important factors, the choice of power supply was critical. Any power source larger than lithium coin-sized batteries are too heavy for this application. Lithium coin batteries are also quite inexpensive, widely available, and of high energy density. The use of coin batteries requires all components to operate at 3V, for which there are a few OTS transmitters available.

For the antenna on the transmitter, there are only a few practical possibilities. The antenna cannot be too complex, in order to create as little inconvenience as possible for the animal being tracked. In addition, the broadcast transmitter should be omnidirectional. This excludes the use of yagi or a dish being attached to the transmitter. Quarter-wave antennas are commonly used on many currently available devices.

Whip antennas encased in a protective material are frequently used in commercial designs. An interesting alternative made possible by the use of smaller-wavelength radiation is a PCB-based antenna. By routing the antenna onto a circuit board instead of using an external antenna, it becomes significantly less obtrusive to the tracked animal and increases the physical durability of the transmitter. This was not used in the current implementation, but could be a future improvement on the current design.

The waveform being transmitted needs to be an audible tone, ideally in the 1-5 kHz range. To conserve power, the tone need not be constantly on, but instead could send a pulsed audio signal approximately once a second. The circuit generating the signal for transmission should then consist of two oscillators, the first with a duty cycle of approximately 1-2% operating at 1 Hz, which then controls a second oscillator with a 50% duty cycle operating somewhere between one and five kHz.

The circuit required for the transmitter itself necessitates an oscillator input to the RF chip. The easiest way to do this is with a 555 timer chip, a standard IC composed of two internally wired op-amps and only requiring an external resistor and capacitor to generate the time constant defining frequency of oscillation (figure 10). Duty cycle for these chips were also easily configured with appropriate resistor value inputs. Because of the ease of setup, 555 timer chips were initially used in testing the range of the transmitter/receiver setup. However, the op-amps used in the 555 timer chip were not optimized for low-power consumption, and used bipolar junction transistors. As a result, they drew too much current to be considered for the final design.

In an attempt to reduce current draw, a set of NAND gates connected in an RC circuit were considered as an alternative to the use of the 555 timer chip (figure 9). As with the previous setup, duty cycles could be configured using appropriate resistor values. It was initially thought that CMOS, by its operation, would present a low-power solution because of its effectively zero current draw at steady-state. In practice, however, the set of NAND gates did not conserve much power because of the frequent, long transitions between high and low states in an RC oscillator circuit.

Instead of using a pre-built op-amp oscillator such as the 555 timer chip, it is possible to construct an op-amp oscillator made of discrete resistors and a set of low-power op-amps. Selection of appropriate op-amps was based on current draw and speed requirements (linear bandwidth and skew rate limitations).

The receiver design has fewer constraints. A Yagi antenna design was used for relatively high directional gain at extremely low cost (Figure 2). The antenna design was from a publicly available website. (http://www.tfs.net/~petek/rockets/RDF/70ant.html)

Documentation of design and implementation

The power supply for the receiver is not as weight-limited as the transmitter. As such, a 5V power supply was constructed from a simple circuit using a 9V battery. This represents a significant improvement over many currently available receivers in this application, which are typically 6 D-cell batteries weighing approximately one pound.

AM and FM transmitter and receiver test designs were constructed which used lithium coin batteries. Quarter-wave whip antennas were used for both transmitters. The receiver uses a six-element yagi antenna designed for 400 MHz reception. A balun transformer as shown converts the signal as necessary for input to the receiver module. This antenna was used for making range measurements.

The IC used in the transmitter design is the MAX4471, from Maxim IC, which contains two op-amps in a single package. The physical implementation of the transmitter was possible using a small PCB with all circuit components excepting the battery surface-mounted to the board.

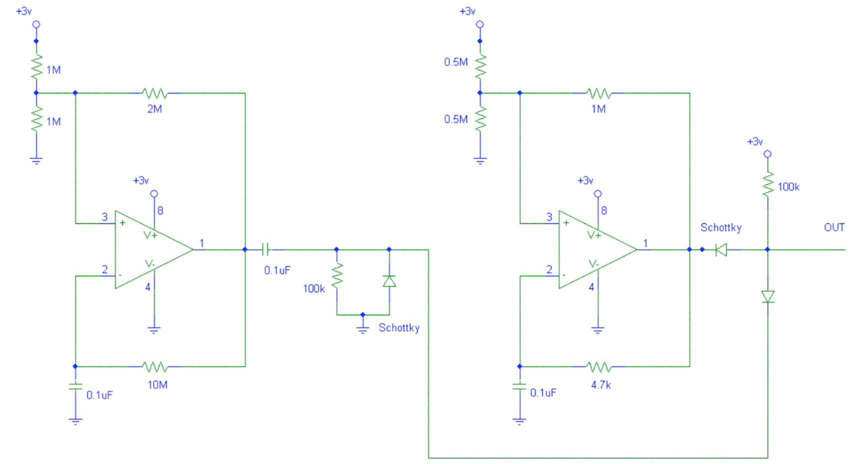
All of the oscillators depend on RC time constants generated by a resistor-capacitor pair. However, the preference for an extremely short duty cycle on the first oscillator introduced some difficulty, as the op-amp oscillator circuit (see Figure 11) was not capable of generating such an oscillation pattern. Instead, the output of a 50% duty cycle 1 Hz oscillator is connected to a simple edge detector circuit, with the width of the edged detection pulses determined by a second RC constant. Because the edge detector produces both a positive and negative pulse, a Schottky diode with the cathode facing ground is in parallel with the resistor in the RC constant. This diode limits the negative pulse on the downward edge to -0.3V.

Once the two oscillators worked individually, it was discovered that the two oscillators interacted with each other in an undesirable fashion when connected together. The diode in between the two reduces the small voltage from the second oscillator which was affecting the behavior of the first. Similarly, the diode and resistor in between the second oscillator and the transmitter are also to produce a cleaner input signal to the transmitter.

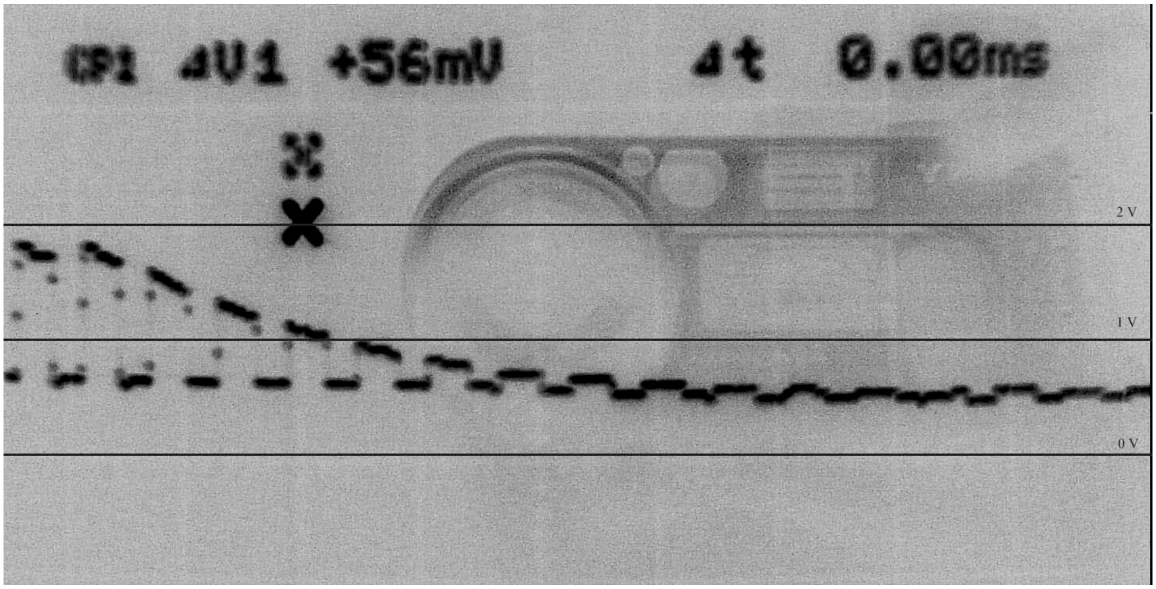
After making these modifications to the circuit, using the first 1 Hz oscillator to modulate oscillation of the second oscillator proved unworkable while building the prototype. While this circuit worked correctly on the breadboard, both oscillators failed to function correctly when parts were placed onto the PCB. In the course of debugging this design, the circuit demonstrated extreme capacitance sensitivity, in that unconnected metal wires touched to various points could affect circuit behavior. Consequently, the method of gating between the two oscillators was modified and a slightly different circuit was used (Figure 12).

The final design submitted relies on each op-amp oscillator circuit to sink current from the voltage source and a resistor load. The battery is connected through a resistor to a single node with three other connections- two diodes, each with the anode terminal facing the output of one oscillator circuit, and the signal input to the RF transmitter chip. When an oscillator output is high, the oscillator circuit is disconnected from the signal input because of the diode in series. If either oscillator is low, the voltage from the battery and resistor in series is sunk into the op-amp. The resistor in series can be used to trade off battery lifetime versus signal strength- a higher resistance lowers signal strength but also reduces current through the circuit, hence increasing battery lifetime.

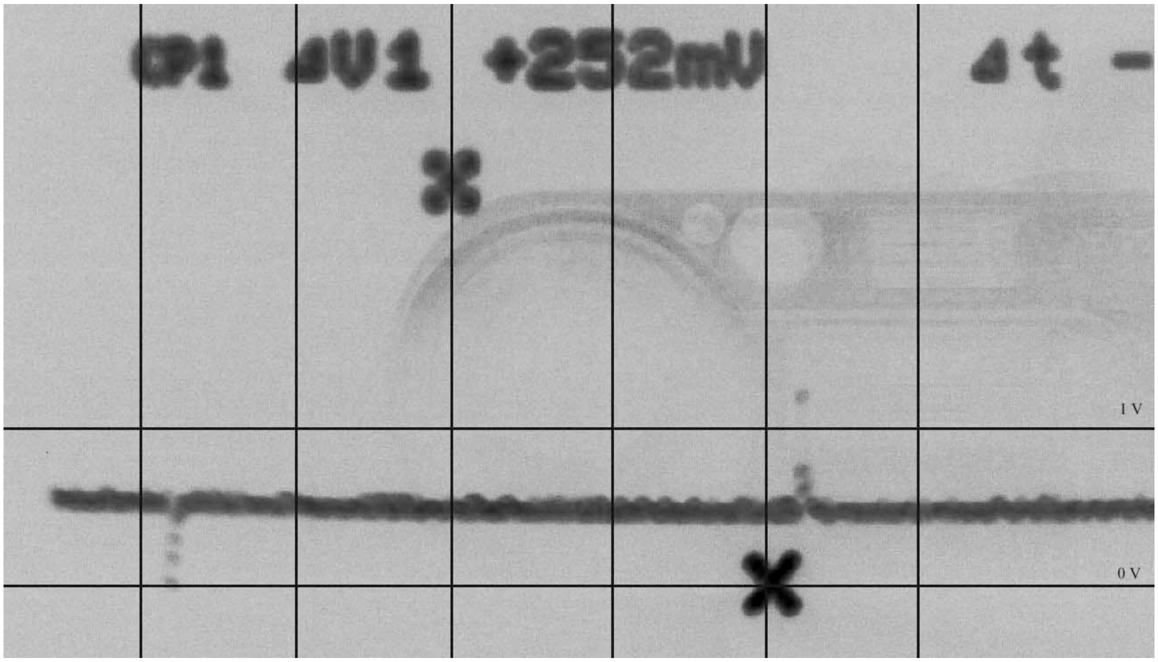
This circuit eliminates several potential issues that may have affected behavior of the previous circuit, such as interaction between the two oscillators and the possibility of the op-amps being unable to source enough current to pull the signal input high. The final circuit design, shown here, is also reproduced in the appendix as Figure 12.



An oscilloscope trace for the signal input to the signal input of the transmitter chip is provided. (The rectangular object in the picture is the reflection of the camera on the front of the oscilloscope.) The nonzero resting value of the circuit is acceptable because the AM transmitter expects a CMOS input. Consequently, the transmitter is not keyed on by the low voltage. Once per second, the oscillator circuits sends a short high pulse which oscillates at 2 kHz. A short pulse is just long enough to be audible at the receiver.



With approximately four cycles above 1V, the transmitted 2 kHz pulse is approximately 2 milliseconds long and hence a 2% duty cycle for the transmitter. A second trace verifies that the pulse is extremely short over the total cycle of the oscillator outputs.



Schematics are provided for all circuits in the Appendix. PCB layouts are also illustrated for the two op-amp oscillator circuits. Specific IC’s used in the field-tested prototypes were the Abacom AM-TX1-418 transmitter and AM-RRS2-418 receiver for the AM distance values. The Radiometrix TXM-418-A transmitter and RXM-418-A receiver were used in determining FM transmission characteristics.

The final transmitter device with op-amp oscillator circuits used the Radiotronix RCT-433-AS AM transmitter and the Maxim MAX407-ESA dual op-amp package. The receiver used the Radiotronix RCR-433-HP. Components for the transmitter-receiver pair used in the final design are available at considerably less cost than commercial tracking devices, with component cost for each transmitter at roughly ten dollars and for the receiver at less than twenty dollars.

System test results

Distance measurements were initially made on the original prototypes constructed, for both AM and FM versions. Most measurements were made on the FM receiver because of a signal strength indicator built into the FM receiver, which was notably lacking on the AM module. RSSI (Received Signal Strength Indicator) values vary from 0 to 3.3 V, and increase logarithmically with signal strength. Values were read out from the device using a digital voltmeter. Before measuring, the noise threshold of the RSSI value was determined to be 0.076. This value was consistently obtained even if the transmitter was not turned on. Consequently, any values measured at or below this value are omitted from graphs and linear regression, but are included in the data appendix for completeness.

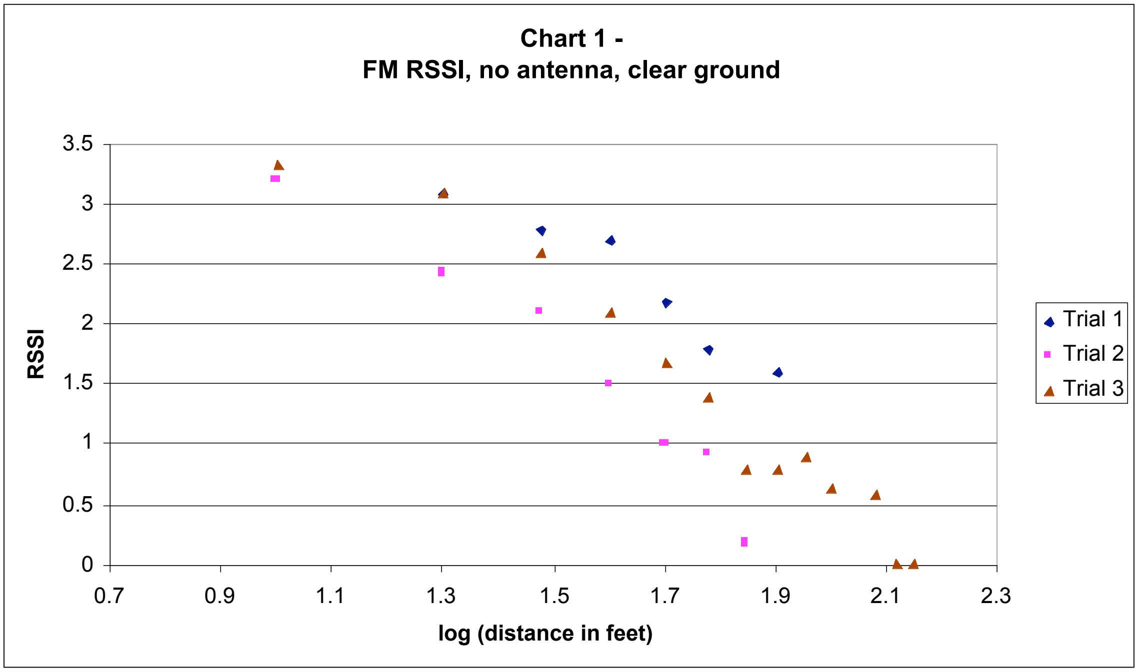
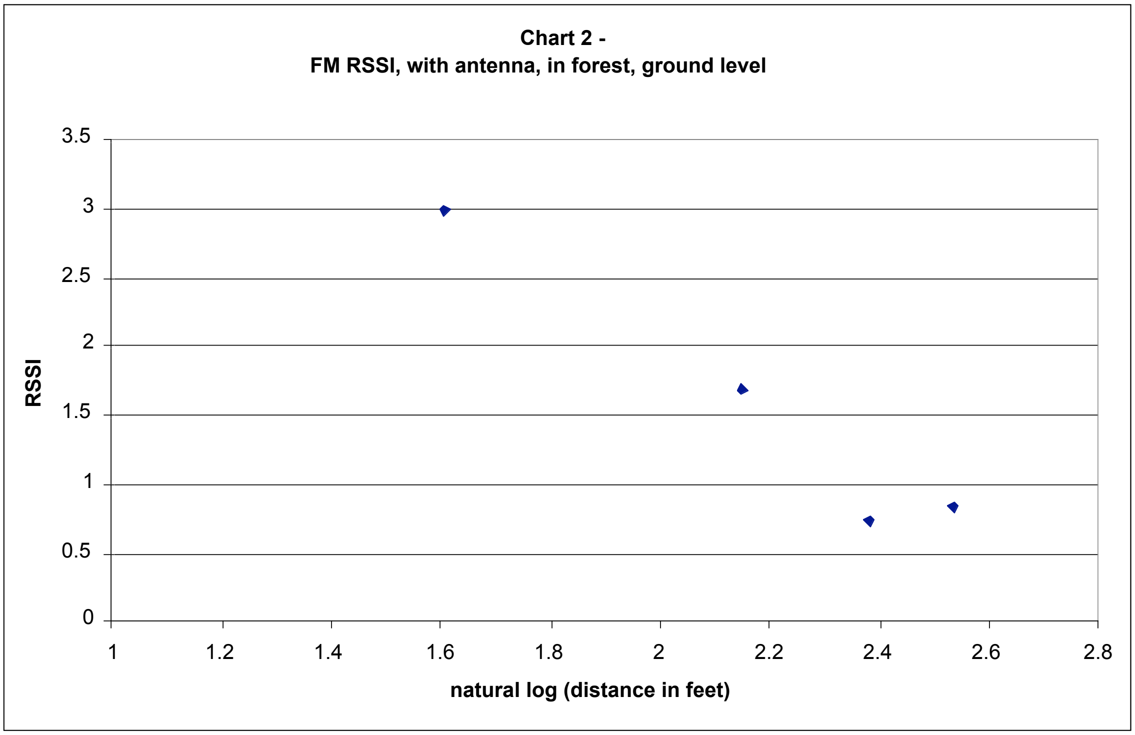


Chart 1 shows the measurement of RSSI on a flat grassy area. The transmitter was placed one foot above the ground, without the quarter wave antenna. Trial 1 was taken on a separate day from trials 2 and 3. The slope for each line, obtained by linear regression, are -2.66, -3.37, and -2.99, respectively. The low values for Trial 2 can be attributed to low battery power, as the transmitter battery failed and had to be replaced shortly after data was taken for Trial 2. The similarity of slope values for Trials 1 and 3 indicate some reproduceability in RSSI measurements. Trial 2 values also demonstrate that, while range is significantly reduced by low battery power, the transmitter will at least still function well enough to produce a measurable signal.



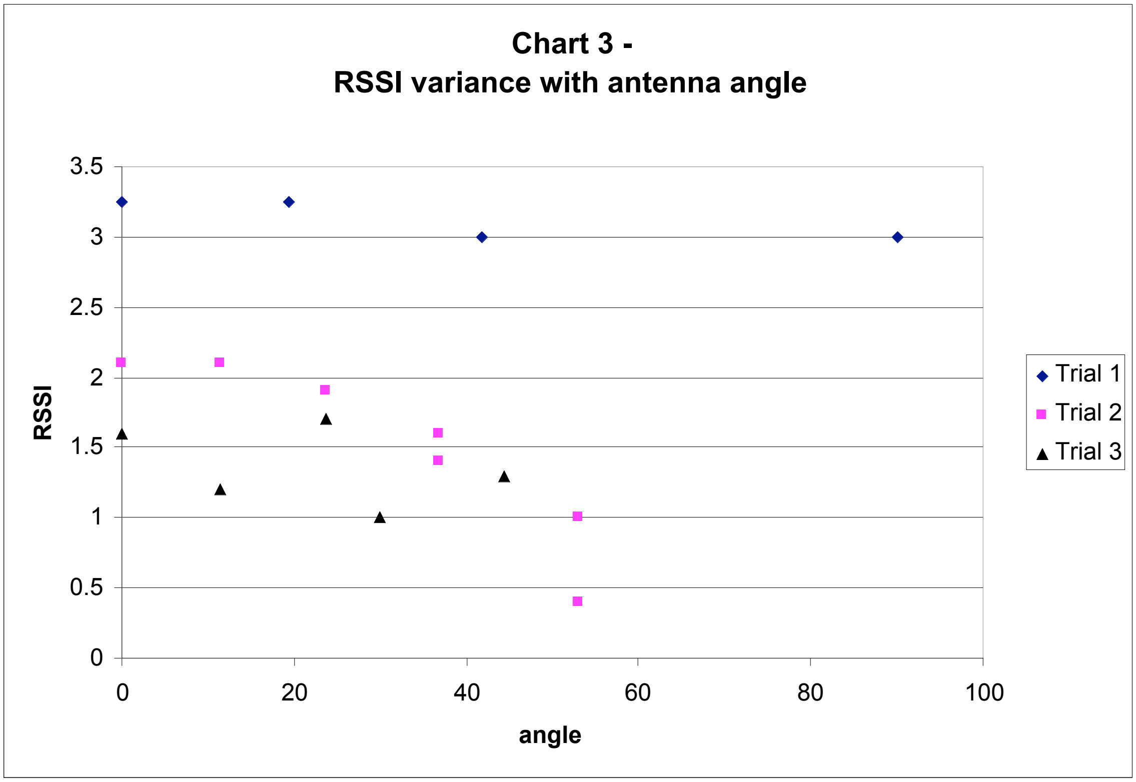
Because the ultimate application of the project is in a forested area, it was important to measure the range of the signal in an area where trees could affect the transmission distance. RSSI in Chart 2 was measured in a forested area near Ithaca with a significant levels of underbrush present. The transmitter was placed on the ground, and the receiver antenna was held roughly 2-3 feet off the ground. Distance measures are approximate. Linear regression provides a slope at -2.51, similar to the rate of dropoff with distance than observed on unobstructed ground.

	regression slope	95% confidence interval (lower bound)	95% confidence interval (upper bound)
Chart 1, Trial 1	-2.661123726	-1.669782682	-3.652464769
Chart 1, Trial 2	-3.366382058	-2.477987702	-4.254776415
Chart 1, Trial 3	-2.991475887	-2.43625003	-3.546701745
Chart 2	-2.506214963	-0.980192165	-4.03223776

A comparison of slopes obtained from linear regression for Charts 1 and 2 show that the values are between -2 and -3, excluding Trial 2. Trial 2, as previously mentioned, exhibits a poorer transmission rate due to low battery voltage. Generally speaking, signal strength should decrease as the square of the distance transmitted, so data values show a rate of dropoff which is slightly higher than expected. Minimum and maximum values for the regression slopes with a 95% confidence interval support a transmission dropoff rate that increases at a rate slightly larger than the square of the distance. The higher rate of dropoff could be due to ground absorption of radiation or the possibility that the RSSI measurement is not strictly a log-base 10 scale.

Max distance ranges for the prototype transmitters were adequate. The data used for chart 2, in the appendix, show that the FM signal was transmitted out to at least 340 feet. The AM transmitter, under the same conditions, was detectable out to 372 feet. This is significantly above the minimum distance acceptable for the application but below the ideal range of 1-2 km.

Directionality of the antenna is also important for the use of tracking a particular transmitter. To verify that the yagi exhibited sufficient directional gain, measurements of received signal strength at various angles at a constant distance from the transmitter were taken. These measurements are shown in Chart 3. Trials 1 and 3, which show relatively little variance of RSSI with angle, were taken at a relatively close distance from the transmitter, and show that directionality is not clearly evident at lower distances, likely a result of multi-path effects. Trial 2 more clearly shows an appropriate dropoff of signal strength with angle. The forward gain of approximately 20 dB is an acceptable value for the Yagi antenna used. Obviously, higher gain may be possible using a more finely tuned antenna design or the use of additional elements in the Yagi.



The data graphed in Charts 1-3 were made using the NAND oscillator circuit at 418 megahertz, but the final design for the op-amp oscillator circuits used a different transmitter at 433 megahertz. Using a whip antenna attached to the receiver, the final design for the op-amp circuit and transmitter was audible approximately 100 feet from the receiver. Using the 418-MHz tuned yagi, this transmitter signal was detected out to 200 feet. These simple measurements indicate a range on par with the earlier measurements, as a yagi tuned to the correct frequency should produce a higher gain. The revised op-amp circuit as shown draws 70 uA. Using a standard lithium coin battery this should result in continuous operation for roughly a month and a half before the power supply would be exhausted. However, this can be tuned as described earlier, with a tradeoff between signal strength and power usage dependent on the value of the resistor in series with the voltage source.

In conclusion, the tracking/receiving pair which has been constructed is a good first step towards development of a system which is considerably cheaper than commercial modules which are currently available, with an acceptable tradeoff in signal detection range and battery lifetime for the desired application. As mentioned previously, a single resistor in the design can be used in the future to exchange signal strength for battery lifetime. Further improvements to signal detection might also obtained by using a more finely tuned receiver antenna or adding noise reduction to the receiver system input.

Appendix

The 5V power supply shown in Figure 1 was used in both AM and FM receivers as well as the final receiver design. The Yagi in Figure 2 was used for all signal measurements where noted. Figures 3, 4, 5, and 6 pertain to transmitter/receiver pairs which were used for collecting data shown in Charts 1-3, but are not pertinent to the final transmitter/receiver pair design. Figures 7 and 8 relate to component parts which are used in the final design, whereas Figures 9-11 represent circuits which were initial candidates for the oscillator design that ultimately failed. Figure 12 shows the circuit which was used in the final design. Figures 13 and 14 show PCB layouts which were made during this project, with the latter being a slight revision of the former. The PCB shown in Figure 14 was used and tested as the final transmitter design.

Figure 1: Schematic of 5V supply from 9V battery

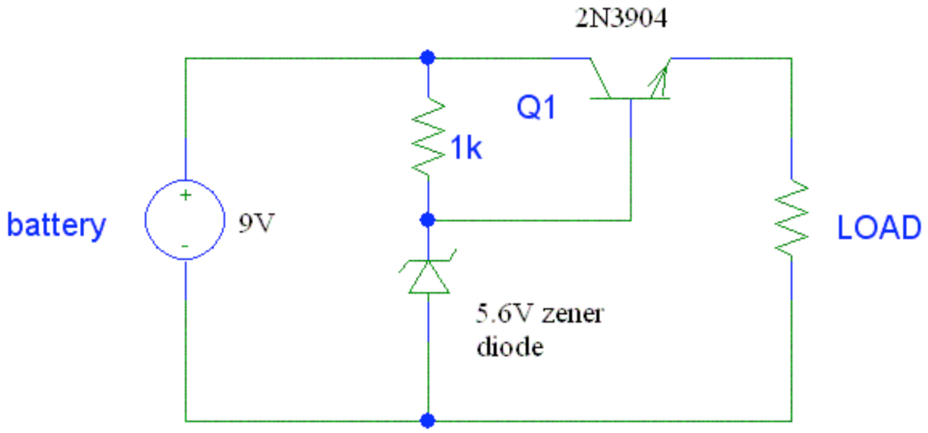
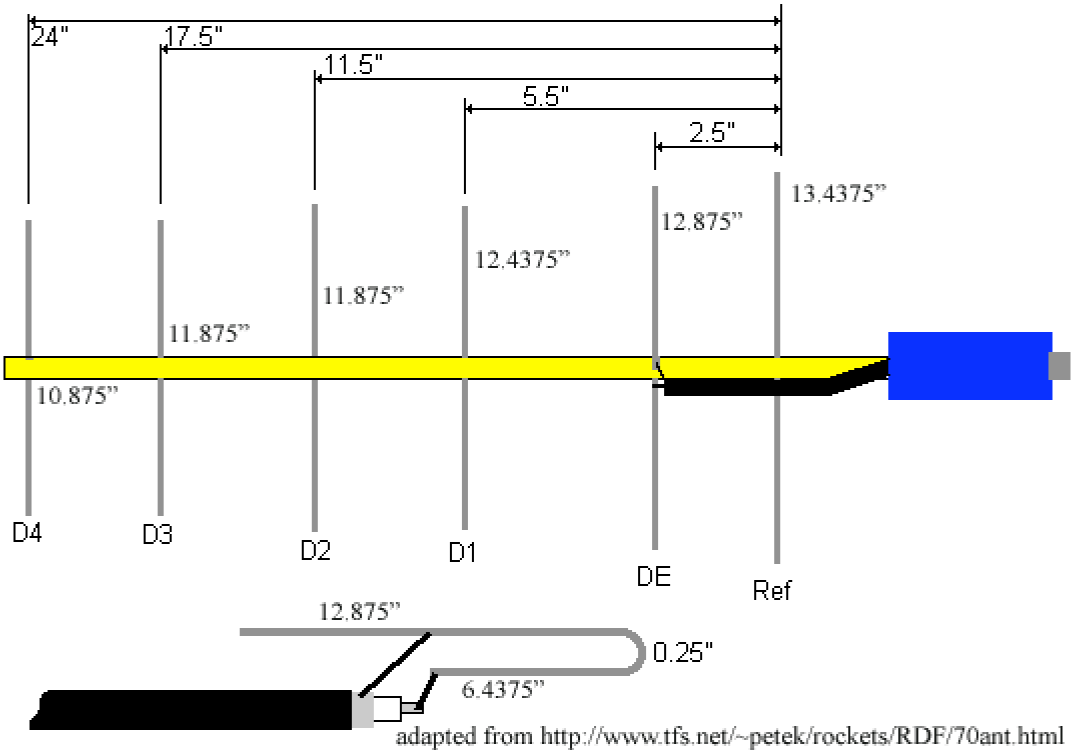
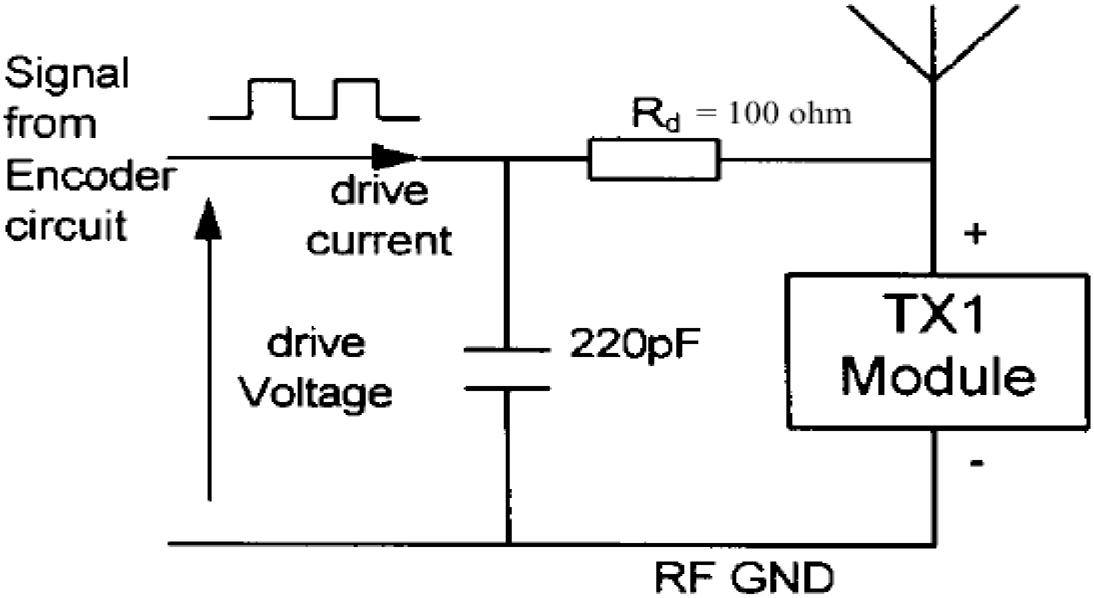


Figure 2: Yagi antenna design



adapted from http://www.tfs.net/~petek/rockets/RDF/70ant.html

Figure 3: Field-tested 418 MHz AM transmitter



from Abacom website: http://www.abacom-tech.com/catalog/amtx1.PDF

Figure 4: Pinout of IC for field-tested 418 MHz AM receiver

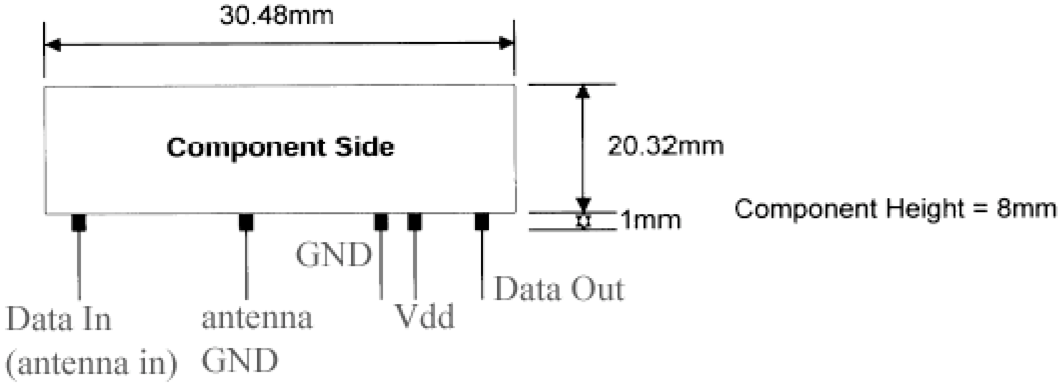


Figure 5: Field-tested 418 MHz FM transmitter

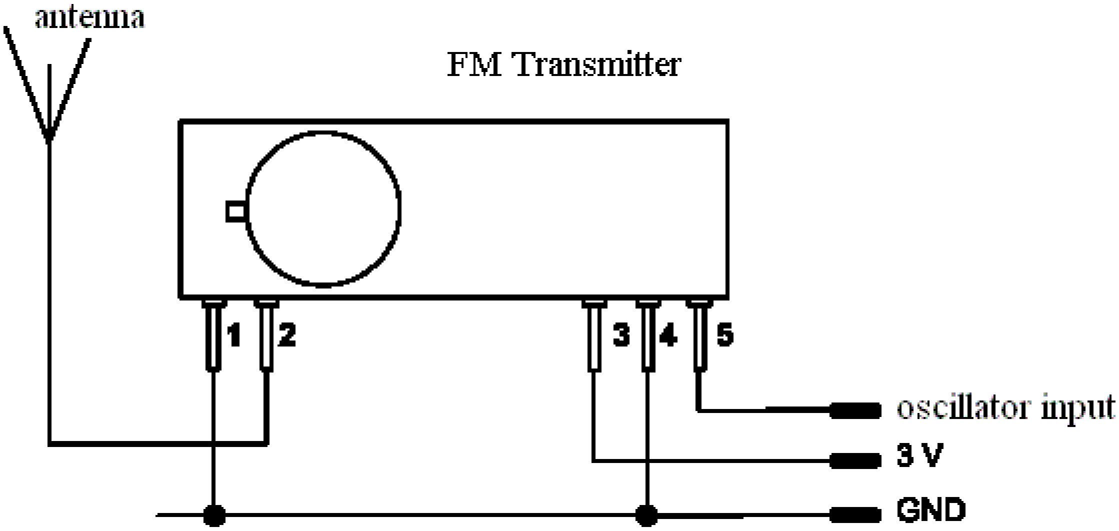


Figure 6: Field-tested 418 MHz FM receiver

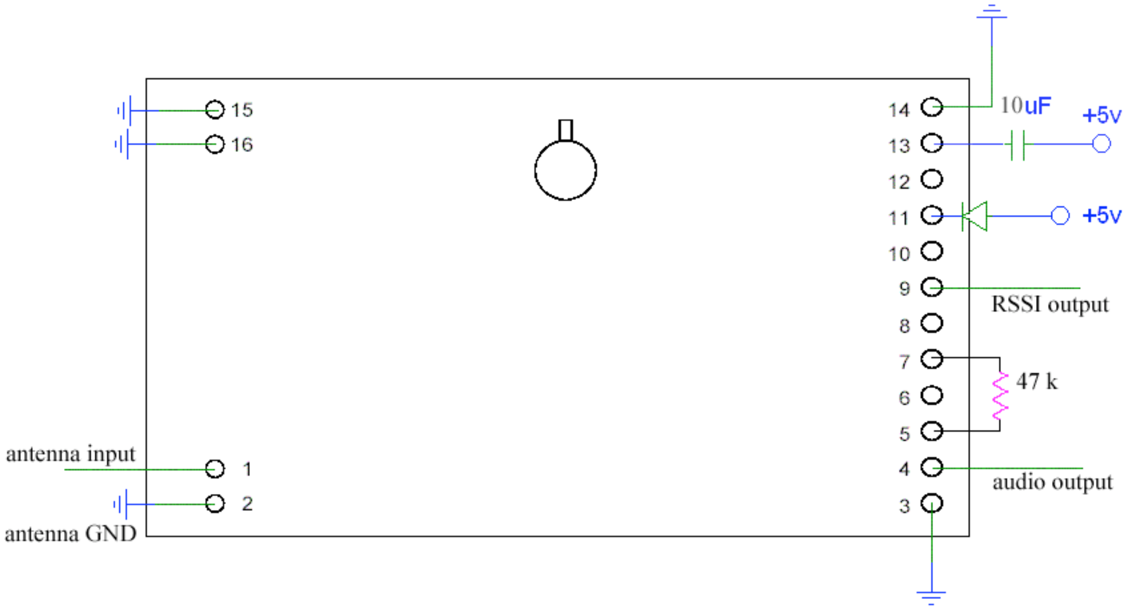


Figure 7: Pinout of IC for final 433 MHz AM transmitter

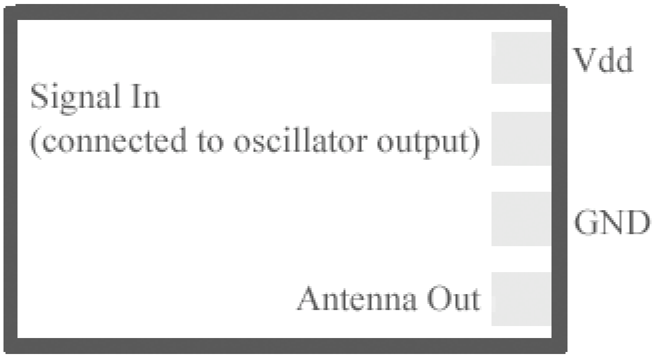
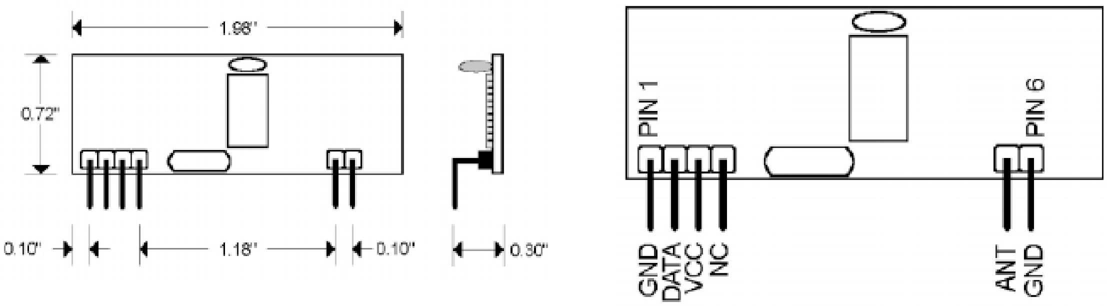


Figure 8: Pinout of IC for final 433 MHz AM receiver



(diagram from http://www.radiotronix.com/datasheets/rcr433hp.pdf)

(data out is connected to audio output)

Figure 9: Schematic of NAND-based oscillator

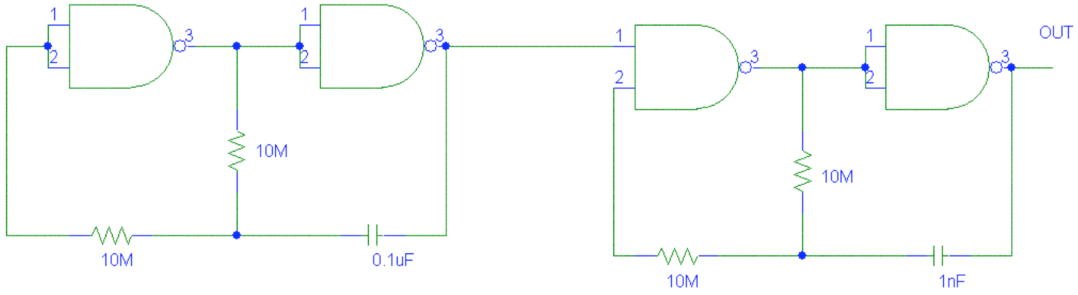


Figure 10: Schematic of 555-timer-based oscillator

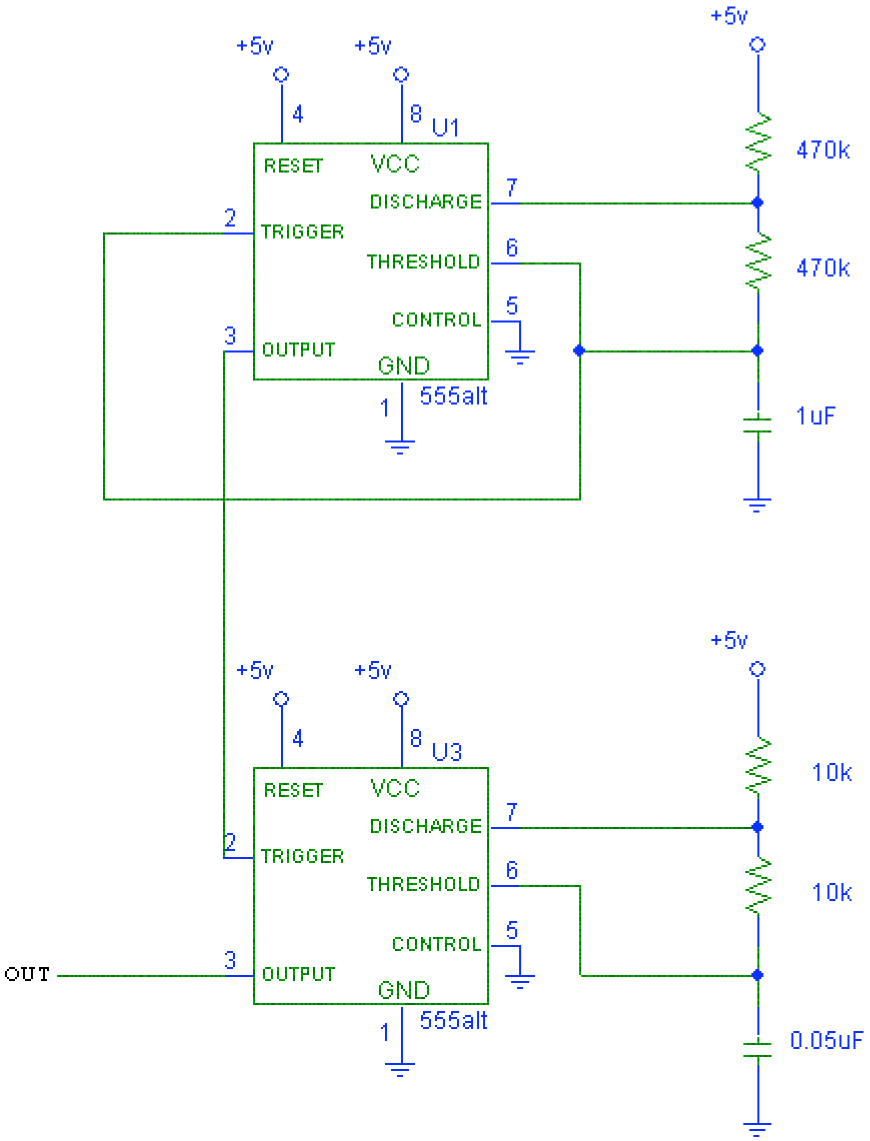


Figure 11: Schematic of first op-amp-based oscillator circuit

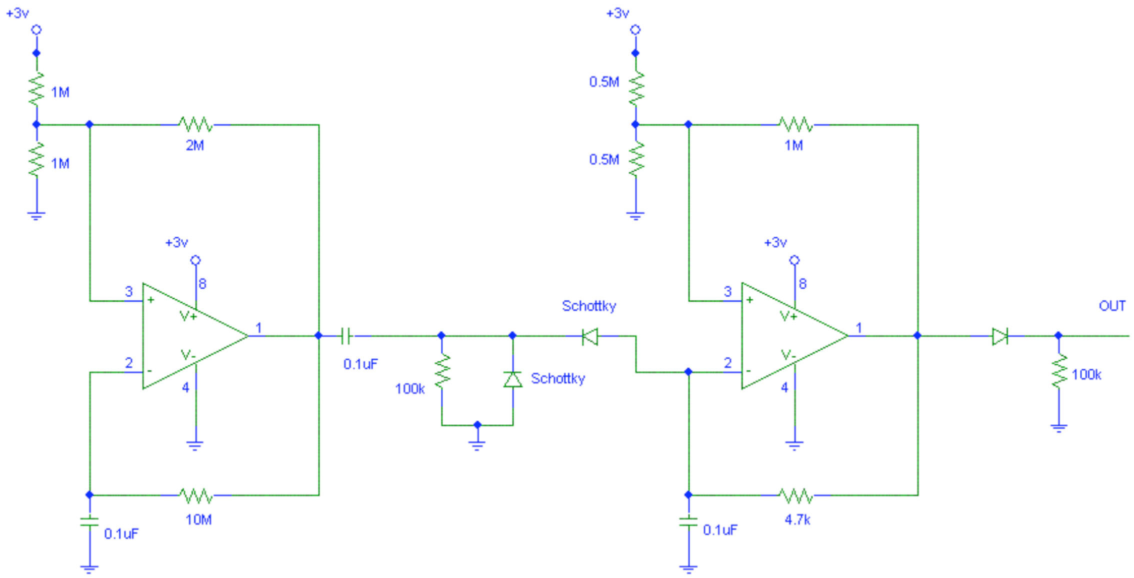


Figure 12: Schematic of final op-amp oscillator circuit

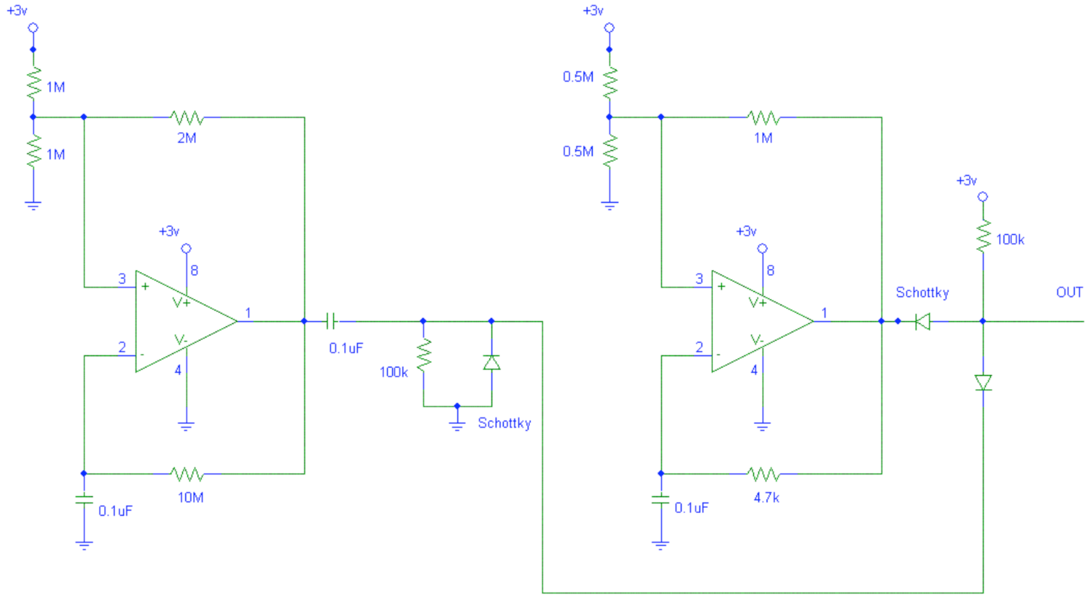


Figure 13: PCB layout for first op-amp oscillator circuit

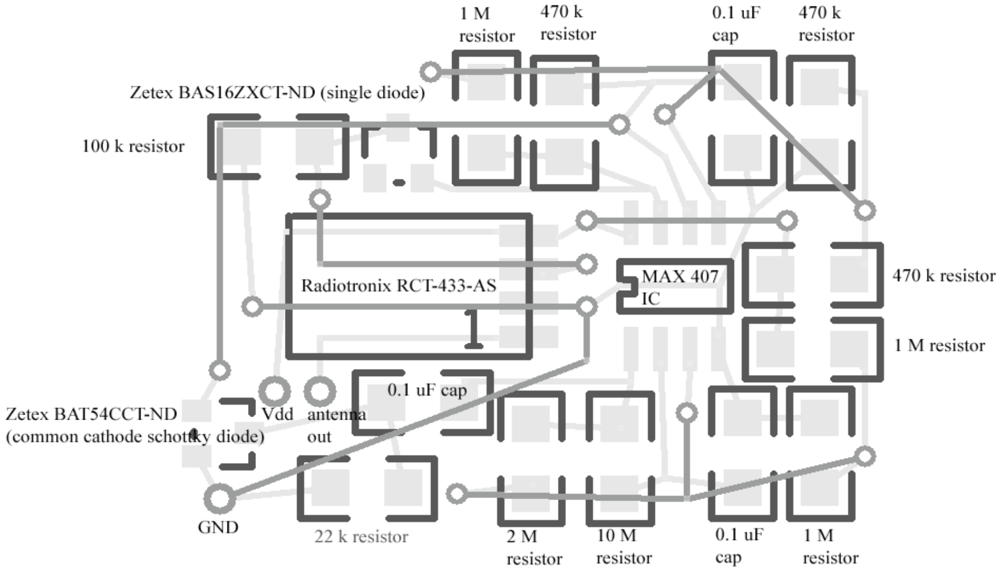


Figure 14: PCB layout for second op-amp oscillator circuit

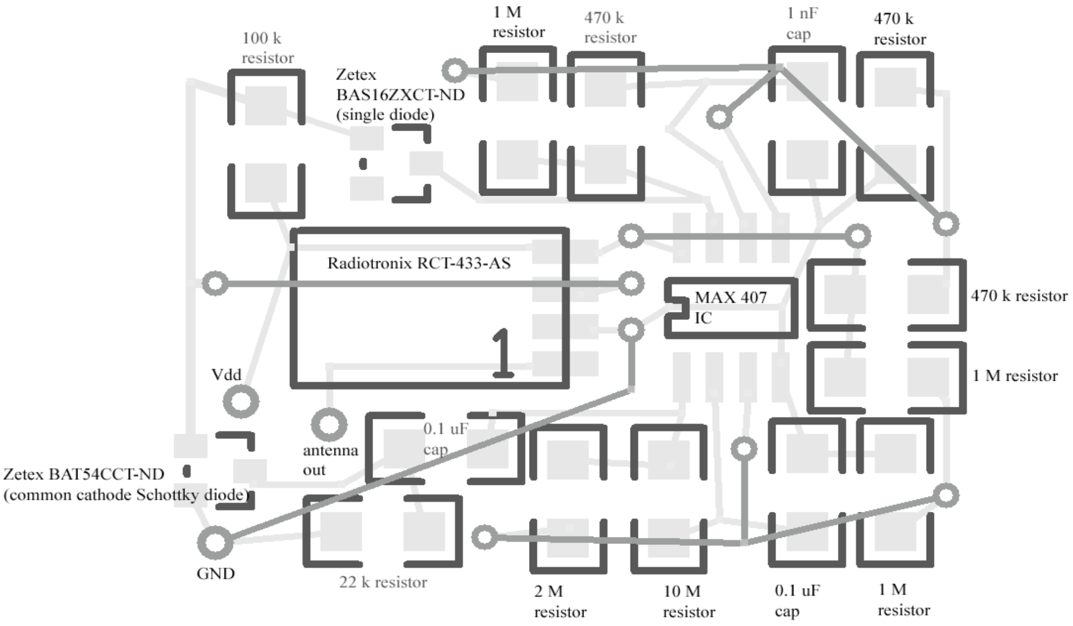


Chart 1 Data

Trial 1 data

distance (ft)	log (dist)	RSSI
20	1.30103	3.1
40	1.60206	2.7
60	1.778151	1.8
80	1.90309	1.6
50	1.69897	2.2
30	1.477121	2.8

Trial 2 data

distance (ft)	log (dist)	RSSI
20	1.30103	2.43
10	1	3.2
30	1.47712	2.1
40	1.60206	1.5
50	1.69897	1
60	1.77815	0.93
70	1.8451	0.18

Trial 3 data

distance (ft)	log (dist)	RSSI
10	1	3.33
20	1.30103	3.1
30	1.47712	2.6
40	1.60206	2.1
50	1.69897	1.7
60	1.77815	1.4
70	1.8451	0.8
80	1.90309	0.8
90	1.95424	0.9
100	2	0.65
120	2.07918	0.6
140	2.14613	0.0076
130	2.11394	0.0076

Chart 2 Data

distance (ft)	log (dist)	RSSI
40	1.60206	3
140	2.146128	1.7
240	2.380211	0.75
340	2.531479	0.85
440	2.643453	0.074

Chart 3 Data

Trial 1		Trial 2		Trial 3	
Angle	RSSI	angle	RSSI	angle	RSSI
90	3	0	2.1	44.4	1.3
41.8	3	11.5	2.1	30	1
19.5	3.25	23.6	1.9	23.6	1.7
0	3.25	36.9	1.4	0	1.6
		53.1	1	11.5	1.2
		36.9	1.6		
		53.1	0.4		