

# Low-power Backscatter Sensor Communications

*NSAP Capstone Project, 2021*

Eli Baum

## Overview

---

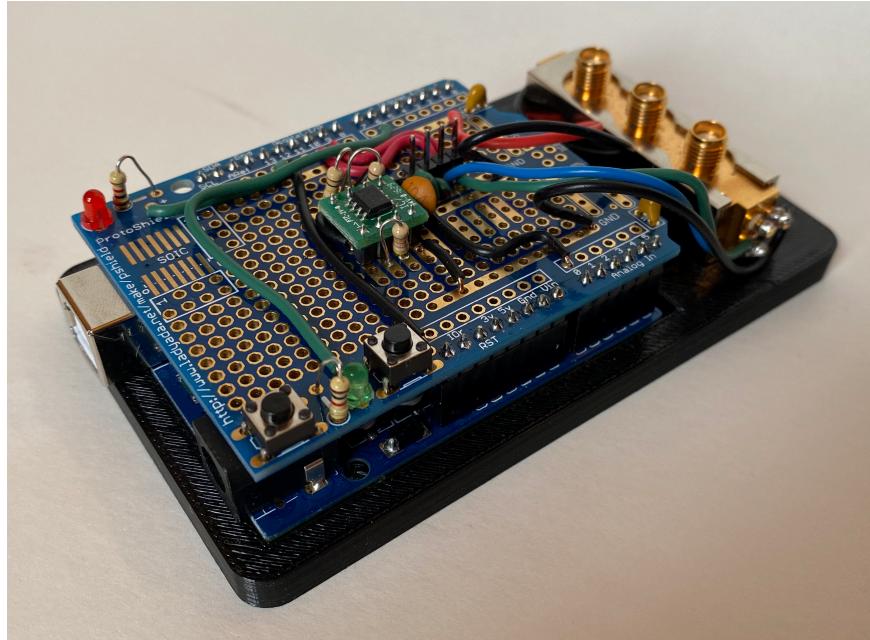
Wireless communications systems require significant power and can be rather large due to the analog circuitry required to modulate radio signals. Here, we propose a method of using *backscatter technology* to build extremely low-power wireless sensors. Without the normal requirements of radio transmitters, these backscatter sensors can be small, cheap, and long-lived; furthermore, since they emit no power, they are difficult for an adversary to detect.

A backscatter transmitter modulates reflected radio signals from another source, rather than radiating signals that it generates. Since the transmitter must do nothing more than switch a transistor at a given frequency, it requires very little power: most of the power and processing requirements for communication are shifted to the signal source (or "illuminator") and receiver, which may be attached to larger ground, air, or maritime platforms, where power and size are less constrained.

Backscatter systems can also be cheaply manufactured to provide distributed sensing capabilities. Warfighters could distribute thousands of sensors across an area of interest and fly data-collection drones over the sensor field. Or, a fixed station could read data in real time from hidden sensors at a distance.

In this prototype, an SDR is used to generate a fixed-frequency tone at 915 MHz. The sensor modulates data at approximately 150 kHz; the receive side of the SDR is therefore tuned to 915.15 MHz. We attach a magnetic sensor to demonstrate one possible Sponsor-focused application. However, this demonstration is not the limit of backscatter sensing technology: academic research has demonstrated the ability for relatively complex backscatter systems to be powered entirely by harvested ambient radio frequency energy, while other studies have

used custom waveforms to receive backscatter signals over distances of more than a kilometer.



*Our backscatter sensor module. The bulk of the current module is an Arduino. The green circuit board is a magnetic sensor; the RF switch is in the rear.*

## Backscatter

---

Backscatter communication may seem counterintuitive compared to standard wireless communication systems. The following analogy may help clarify its operation.

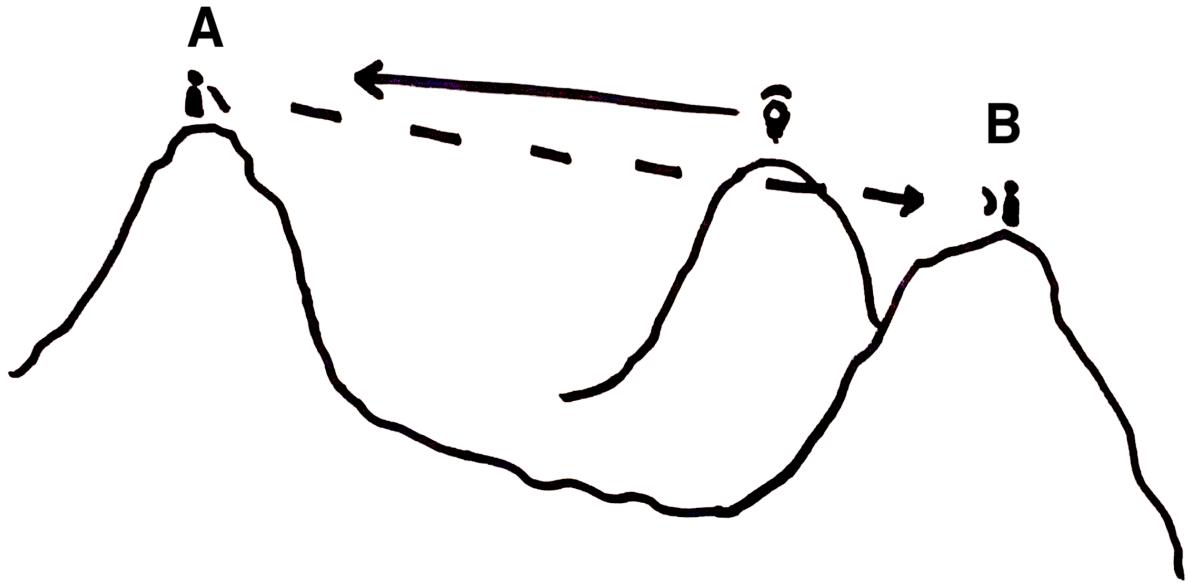
---

Consider two parties, Alice and Bob, who wish to communicate with each other, across some significant distance, at night. (For the purposes of argument, assume a line of sight exists between them.) The simplest method for Alice to send a message would probably be for her to point a flashlight at Bob and turn it on and off under some modulation scheme (say, Morse code). Bob could record Alice's pulses of light and translate them into a message.

However, there are several drawbacks to this system. Alice must carry a flashlight, which may be heavy, require large power supplies, and generate significant heat. Additionally, if Alice would like to communicate covertly (or is trying to hide her location), a flashlight might be too easy for an adversary to detect.

Alice comes up with an alternative scheme: she carries a mirror which she uses to carefully reflect moonlight in Bob's direction. The resulting light will be much dimmer, from Bob's perspective, but Alice no longer needs a flashlight.

Alice and Bob soon run into an issue – if the moon is not in the sky, or it is cloudy, they are unable to communicate. Seeking more reliable communication, Bob sets up a lantern at a third location; Alice can once again either reflect, or not reflect, the light from the lantern towards Bob.



*Alice stands on the left hill with a mirror. Bob places a lantern on the central hill, and stands on the rightmost hill.*

One problem remains: how can Bob see Alice's dim reflections, when the lantern is so much brighter? Perhaps Bob is in a shadow from his lantern. However, imagine a *fluorescent mirror*; that is, one which changes the wavelength of reflected light. Then, Bob could filter the wavelength of light coming from his lantern; only Alice's signal will remain.

---

Many of the concepts (and compromises) discussed above apply to radio communications, as well. The final scenario – where Bob illuminates Alice's color-changing reflector and detects the return signal – closely mirrors how backscatter *radio* communications works.

In this prototype, we use an SDR as both illuminator and detector. The transmit (TX) end of the SDR broadcasts a constant-frequency cosine tone; this is similar to Bob's lantern. The analog of the mirror is an antenna connected to the RF switch, which can either reflect or attenuate the illuminating signal.

For the "color-changing" component of Alice's mirror, we take advantage of constructive interference:

Given two signals  $A$  and  $B$ , with respective frequencies  $f_A$  and  $f_B$ , the addition of those two signals  $A + B$  will appear to have a frequency component at  $f_A \pm f_B$ . (This is often noted in

music, where the perceived *beat frequency* can be used to tune an instrument, but we can just as easily create a frequency-shifting effect at radio frequencies.) In this prototype, the cosine illuminator is transmitted at 915 MHz ( $= f_A$ ); the sensor module is configured to toggle the RF switch at approximately 150 kHz ( $= f_B$ ). Therefore, we expect artifacts to appear at  $915 \pm 0.15$  MHz. By tuning the receive (RX) side of the SDR to 915.15 MHz, and keeping its bandwidth below 300 kHz (we use 200 kHz, the minimum of our hardware), interference from the transmitter is entirely eliminated. At this point, the reflected signal can be modulated in various ways. See [Physical Layer](#), below, for further details.

In the national security domain, backscatter was perhaps most famously used by the Soviet Union during their bugging of the American Embassy in Moscow with "[The Thing](#)." This project is inspired by that use case, but we consider witting, environmental sensing applications (rather than covert espionage uses) for backscatter technology.

## A Word on RFID

Some commercial radio frequency identification (RFID) systems use backscatter technology. These systems are not extensible, and provide no way to transmit sensor data, as was desired here – instead, they generally transmit a fixed identification number – but they may provide future avenues for exploration.

The most well-known of such technologies is passive RFID, commonly encountered in electronic access control systems and contactless payment. In these systems, a tag reader generates an "interrogation" signal which is then reflected, and modulated, by the tag. Often (as in the case of a badge reader), the tag contains no power supply of its own, and instead harvests power from the interrogation signal itself.

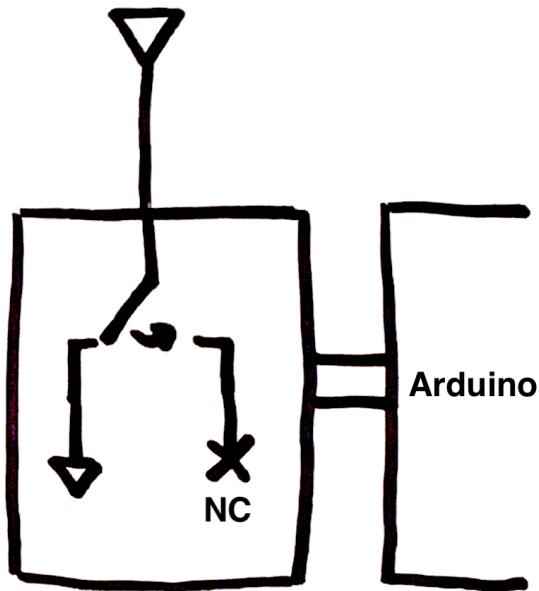
Usually, passive systems work only at sufficiently small distances where the reader and tag antennas can *magnetically couple* (on order of centimeters, and such coupling attenuates much faster); no actual radio signals are exchanged. This is known as the "near field." However, some passive RFID systems *do* indeed work via radio waves (or "far field") in a manner similar to the backscatter communication module presented here – certain electronic toll collection systems are a common example.

Passive RFID contrasts with *active RFID*, which operates more like a normal wireless transmitter. Here, the interrogation signal "wakes up" the RFID tag, which then replies using its own dedicated transmitter. Such systems operate over greater distances, and with lower error, but require their own batteries, using much more power than purely reflective systems.

## Prototype Components

---

The prototype backscatter sensor module consists of an Arduino (with an ATmega328 microcontroller), an RF switch, and a magnetic sensor. We take readings from the magnetic sensor, process them on the Arduino, and transmit data using backscatter. The SDR used was a USRP B210, but any SDR should work.



*A diagram of the hardware setup. The antenna is either grounded (through a  $50\Omega$  resistor), or not connected.*

## Physical Layer

The physical layer consists of the actual modulation of information onto the 915 MHz carrier wave. We chose a simple physical layer for ease of implementation and rapid prototyping.



*The sensor module with antenna attached.*

## Hardware

The centerpiece of this prototype is an RF switch (Minicircuits model ZX80-DR230-S+). The switch is connected to the output of one of the ATmega's timer compare outputs; the timer is configured to oscillate at approximately 150 kHz. We connect an antenna to only one of the switch's ports and leave the others disconnected.

When the switch is in the open position, the antenna is connected to the unterminated center port. Therefore, incoming RF will be reflected. When the switch is closed, the antenna is terminated with an internal  $50\Omega$  load, so all energy will be absorbed.

## Amplitude Shift Keying

We use amplitude-shift keying (ASK) to modulate data; this is the simplest scheme that could be used for the purposes of a viable prototype.

We experimented with frequency-shift keying (FSK) but decided not to move forward with it. FSK provides superior information density but is less noise-tolerant and more computationally complex to decode. Furthermore, the usefulness of an FSK system was limited by the granularity of the microcontroller's internal oscillator.

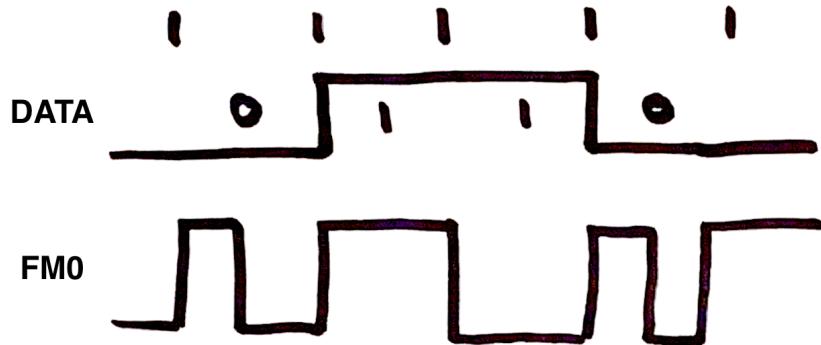
Other schemes, such as phase-shift keying (PSK) and quadrature amplitude modulation (QAM) were not possible with the hardware available on the sensor module. The RF switch contained a purely resistive internal load; phase-related modulations would only be possible with reactive (i.e. capacitive) loads. A fieldable backscatter solution would likely require more advanced hardware capable of these advanced modulation schemes.

## FM0

Once we are able to modulate the signal, the next problem is to actually send bits. In particular, we need a *clock recovery* method – how do we align our receiver's data stream with that of our reflector? In this prototype, we have used *FM0 encoding*, an extremely simple run-length limited (RLL) code. RLL codes are designed to contain sufficient transitions to enable clock recovery; without FM0, a string of identical values could be difficult to differentiate.

In fact, FM0 is quite similar to Morse code. `1` bits are encoded as a long pulse, while `0` is encoded as two short pulses (hence the "FM" or "frequency modulation" in its name). We do not care about the actual level of these pulses, but only their *transitions*: in practice, after every bit, we toggle the signal, but for a `0`, we also toggle halfway through that bit period. For example, to send the data `0110`, we encode:

Data:		0		1		1		0	
Pulses:	SS	L	L	SS					
TX:	...	0	10	11	00	10	10	1...	



While this is not particularly efficient (it takes 2 symbols to send one bit, making FM0 a rate-1/2 code), it is simple to implement and appropriate for prototyping.

At this point, a fieldable system would also include error-detection and correction schemes to ensure reliable communication at a distance. We implemented a Hamming encoder/decoder, but decided not to include it in the final prototype, since it was unnecessary for demonstration.

purposes.

## Packet Layer

Various data-transmission strategies are possible; we chose continuous data transmission, since this is simple and beneficial for demonstration purposes. We designed a packet format, as follows:

```
Access Code [32 bits]
    e1 5a e8 93
Sequence number [8 bits]
    xx
Data Length, bytes [8 bits]
    xx
Data (8 bits per reading)
    xx xx xx ...
    ...
```

The access code, `0xe15ae893`, is a commonly-used non-cyclical access code. This makes it easy for the decoder to synchronize to the start of the packet: the access code correlates poorly with itself at all offsets except 0.

The sequence number provides some level of error detection – it is incremented for each packet (overflowing from 255 to 0); the decoder only accepts a packet if the decoded sequence number is one greater than the previous.

## Sensor Demonstration

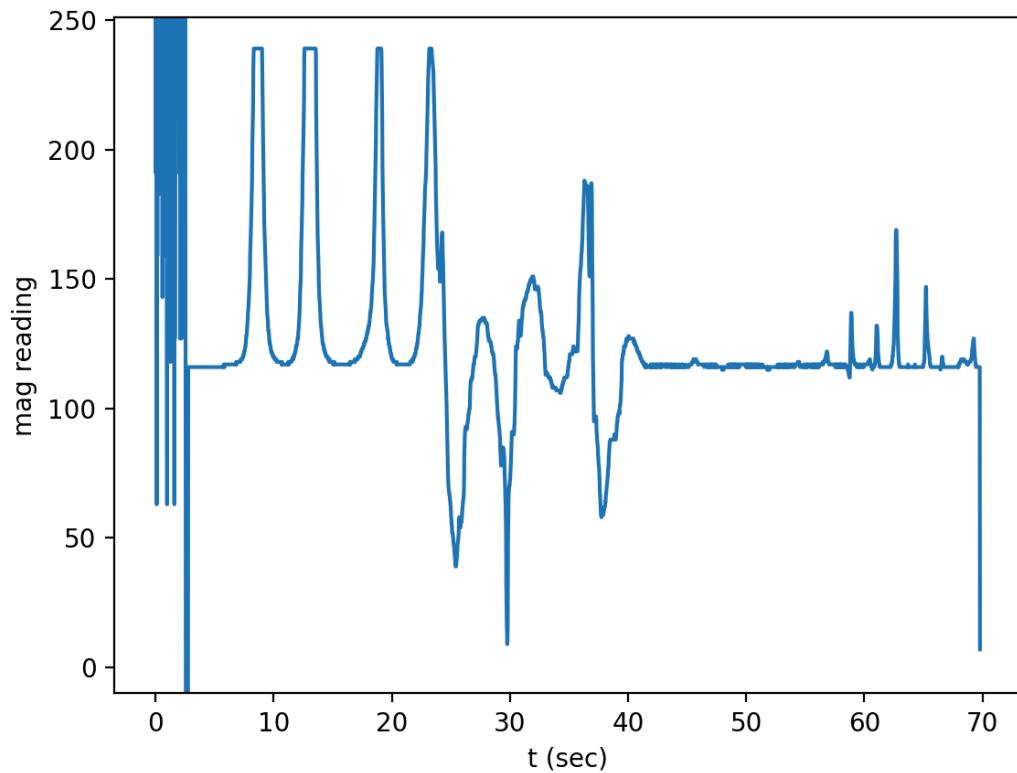
The focus of this project was on backscatter communication itself, not on the particular data sent over the backscatter link. However, to demonstrate real-time communication capabilities, we add a magnetic sensor to the backscatter module. We take a moving average of the sensor readings and send 16 8-bit values per packet. With these parameters, each packet is therefore 176 bits. At a symbol rate of 2000 baud, we can send 1000 bits per second, giving about 5.7 packets, or 91 readings, per second.

## Decoder Implementation

The Python decoder is implemented as a series of layers. Each layer receives data from the one above, provides some processing functionality, and passes data down.

1. **SDR sampling:** GNURadio is used to read samples from the SDR.

2. **ASK decoding:** A simple ASK decoder converts samples into binary values. Since the sampling rate is much higher than the symbol rate (by about two orders of magnitude), there are multiple digitized samples per actual ASK symbol.
  3. **Pulse length determination:** FM0 decoding depends on the length of pulses in the input stream. First, we perform a *coarse* search – this layer simply returns the time between binary transitions.
  4. **Pulse length clustering:** Due to noise and timing inaccuracies, not all pulses will be the expected short or long length. In this step, we cluster the received pulses around their estimated true length, and also account for noise. For example, a burst of noise in the middle of a long pulse of length 2 may make that pulse look like three short pulses of lengths 0.9, 0.2, and 0.9. This layer detects the noisy burst and converts the set of pulses into the correct long pulse.
  5. **FM0 decoding:** Now, we can turn pulses into symbols: two short pulses is a `0`; one long pulse is a `1`.
  6. **Packet decoding:** Each packet begins with the non-cyclical access code. We use a sliding 32-bit window, correlated against the access code, to find the start of a packet (the correlation\* reaches a maximum at perfect alignment). Next, we check the sequence number, and if correct, we read the length, and then the prescribed number of data bytes.
- \*In a later version of the prototype, we use bitwise XOR rather than statistical correlation, since this ends up producing fewer false positives.*
7. **Data graphing:** Finally, data values are plotted in real time with `matplotlib`.



*Initial example of backscatter sensor readings. The sensor was not turned on until around  $t=5$ , so values prior to that point are noise.*

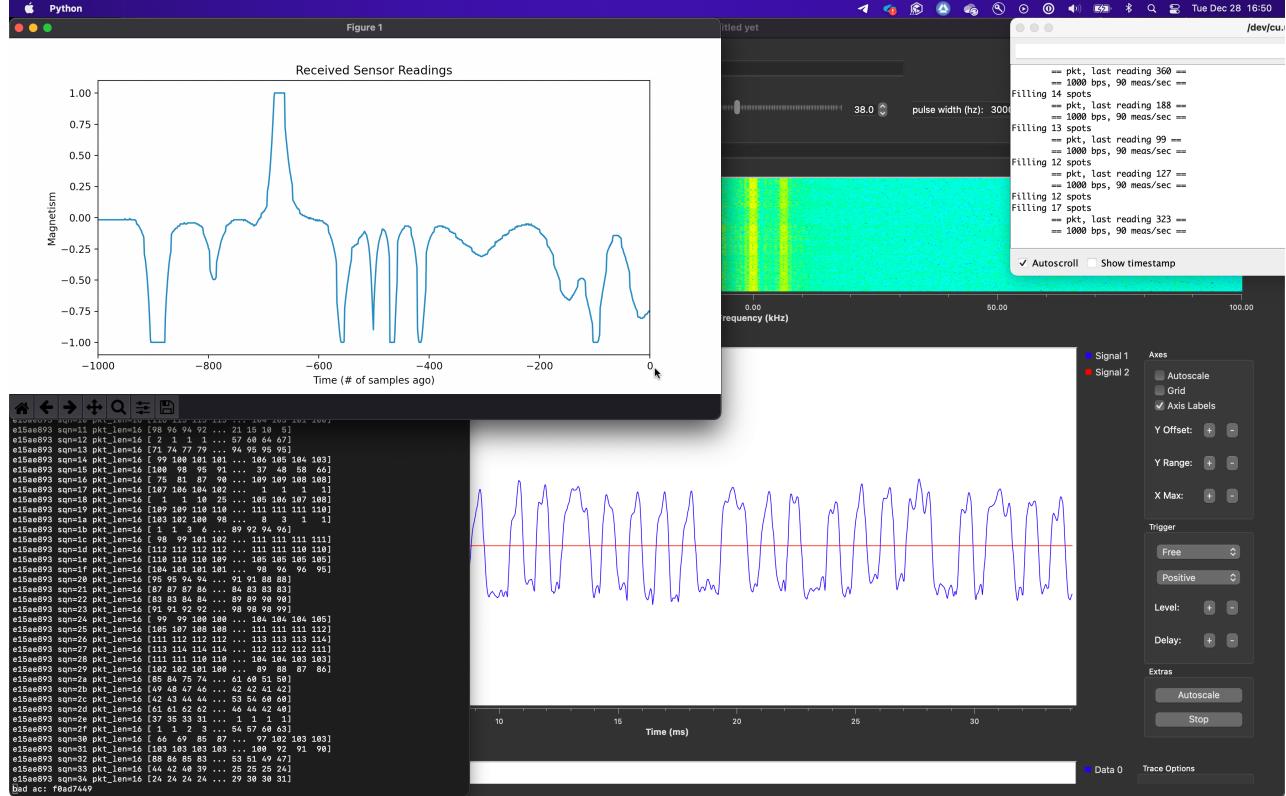
## Results

---



*Garbage truck and sensor module.*

This prototype was meant as a proof of concept for future study, and has demonstrated that backscatter is a viable method for low-power, low-bitrate communications. We hid a magnet inside of a toy garbage truck, and demonstrate how the backscatter sensor module is able to detect the presence of the truck. Of course, with other sensors, various environmental parameters of interest could be measured, recorded, and analyzed.



A screenshot of the full software stack running the backscatter system. Clockwise from top left:  
 1) magnetic sensor readings; 2) debug printout from the microcontroller; 3) a time-domain view of the received ASK waveform; FM0 short and long pulses are visible; 4) debug output from the Python decoder.

A summary of the test parameters follows.

- Physical layout
  - 132 cm between TX and sensor
  - 132 cm between RX and sensor
- RF parameters
  - TX gain: 89 dB (SDR maximum)
  - RX gain: 26 dB
  - Filter width: 3 kHz
  - Frequency calibration: -1.4 kHz

- Packet parameters
  - 2000 symbols per second (therefore 1000 bps)
  - ~ 91 measurements transmitted per second

Placement of the TX and RX antennas in relation to the sensor is an important factor in the successful operation of the sensor module. At very close distances (i.e. on order of the wavelength of the carrier wave), magnetic coupling dominates, and the system is more akin to a passive near-field RFID system. For the 915 MHz carrier used here, one wavelength is 32.76 cm. To ensure we are operating in the RF far-field, antenna separation should be two wavelengths or more.

## Caveats and Future Work

---

After many unreliable tests, we realized (or at least suspect) that due to the short distances used in this demonstration, poor performance was occurring when the backscatter antenna was in a node (or null) of the transmitting tone. The radio waves are not traveling far enough for multi-path effects to make a difference, and since the illumination signal is a single sine wave, there will exist some nulls in the signal strength. We solved this problem by ensuring the backscatter sensor was some multiple of the wavelength away from both the TX and RX sensors (here, about 33 cm). In more realistic environments, frequency hopping or spread-spectrum modulation could help mitigate this problem.

We are also interested in exploring more robust, higher bitrate transmissions. As mentioned above, there are many physical layer modulation schemes, such as FSK or PSK, that could enable faster transmission. Frequency-swept chirps, as used by LoRa communications, have shown success in backscatter systems, with particularly impressive performance over long distances. However, different RF hardware (such as *reactive* components) would be required (as well as a high-precision digital timer), particularly to enable phase shifts. Even so, we caution that high bandwidth communications will likely not be possible with backscatter: since the returned power is much lower than a normal radio transmitter, the channel capacity is necessarily limited.

Additionally, more complex coding schemes (rather than FM0) would allow for a greater symbol rate and more efficient clock recovery; error correction would also be an improvement over naive sequence number checking.

## Conclusion

---

Backscatter technology will not replace standard wireless transmission in areas where it is

currently used. However, due to its low cost, power, and size requirements, it has the potential to revolutionize distributed and covert sensing applications. We demonstrate a prototype backscatter sensing module that is able to wirelessly transmit 1000 bps of data over distances of about a meter. For applications where low-bitrate communications are acceptable, we hope that future research could significantly increase the maximum transmission distance. Alternatively, the maximum bitrate of the system could be improved, opening up the possibility for other kinds of communications data, such as text or audio.

## Possible Use Cases

### Distributed Sensing

Consider a hypothetical scenario where a DoD sponsor wishes to monitor vehicle traffic in a large area. Rather than installing thousands of vibration sensors with high-power transmitters (say, cellular modems), low power *backscatter* sensors could be distributed across the area. These sensors would have much longer lifespans (and be harder to detect); from time to time, friendly vehicles could drive by and offload data from the sensors.

Or, perhaps backscatter sensors could be attached to a field of sonobuoys. Rather than having the transmit data back to air platforms, the buoys could use backscatter to relay data to overflying receivers. This would enable significantly longer operating lifespans, given power supply constraints.

### Covert Sensing

Backscatter sensing also has benefits for covert sensing, since no RF emissions can be detected when an illuminating tone is not present. Consider a facility which the U.S. government suspects of manufacturing nuclear or chemical weapons. An appropriate backscatter sensor could be hidden outside of the facility and take measurements when trucks are entering or exiting, storing the data for later retrieval during periods of low activity, when a drone could be flown past. Notably, even when the drone returns to collect data, the adversary will only be able to detect the illuminating tone; detecting the weak backscattered signal hidden next to the illuminating tone will be much more challenging. Or, a fixed station with highly directional antennas could be installed at a nearby listening post; this setup could prove beneficial for contested or heavily-monitored areas.