LIGHTWEIGHT LOW-COST WILDLIFE TRACKING TAGS USING INTEGRATED TRANSCEIVERS

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Figure 1: Tag attachment to wild Barn Owl (left, photo Motti Charter) and Common Kestrel (right, photo Ron Efrat).

ABSTRACT

We describe the design, manufacture, and deployment of advanced wildlife tracking tags (transmitters) based on integrated transceivers. The tags weigh as little as 2g and cost less than $20 each in relatively small quantities (tens).

1. INTRODUCTION

Wildlife researchers and managers attach various electronic monitoring devices called *tags* to animals. Simple tags (pingers) that periodically transmit an unmodulated RF pulse have been used since the 1960s to locate animals [1, 2]; they are still widely used today (see, e.g., [4] as well as many commercial offerings). Today, a wide range of different tags are used to track animals (sometimes using GPS receivers) and to collect physiological, environmental, and behavioral data.

This paper describes the design, production, and deployment of lightweight tags that include a sophisticated integrated RF transceiver and a microcontroller (MCU). These tags can be used in many ways, thanks to the flexibility afforded by the MCU and the transceiver. They can be used as simple unmodulated pingers, as coded pingers, or as RF proximity detectors (as in the Encounternet wildlife monitoring system [3]).

Our tags cost $11 each to manufacture in a batch of 100, or about $15 in a batch of 25. This is the cost of a complete PCB; the antenna and battery add another $1–2. Some battery types require a reservoir capacitor that costs $1.5–3.5 at similar quantities. For comparison, the price of commercial lightweight pinger tags is $150 and up.

Our tags weigh 0.75g, and the lightest batteries (good for about 2 weeks of 8ms pings every second) add another 0.64g, making sub-2g tags possible. This enables us to use these tags on animals weighing about 40g and up. The tags are 12-by-19mm in size but the design can probably be reduced in size by switching to smaller passives and/or to a denser packing of components on the board.

The tags can be easily programmed by the end user using a low-cost programming cable.

We have tested these tags extensively and have thus far deployed them successfully on wild animals, including Barn Owl (*Tyto alba*), Common Kestrel (*Falco tinnunculus*), Spur-winged Plover (*Vanellus spinosus*), and Coypu (*Myocastor coypus*).

We freely share the design of the tag with other research groups, who can purchase assembled tags (without batteries or antenna) directly from the manufacturer (prices are obviously subject to change, but the current pricing is the one listed above)[1].

Similar tags were designed for and used in the Encounternet system [3]. The Encounternet tags also include an FRAM chip for data logging (our tags do not), and they are physically smaller than our tags. However, the smaller size comes at a significant price: in our experience the Encounternet tags are much harder to program and to deploy because their programming and power connections are fragile. They also appear to be much more expensive to produce because of the extreme miniaturization.

2. CIRCUIT DESIGN AND INITIAL PROTOTYPING

The circuit design of our tags is straightforward and is based on the reference design circuits for the transceiver and the MCU (or the wireless MCU when the tag uses one). We began prototyping using the Value-Line MSP430 Launchpad platform featuring an MSP430g2452 or an MSP430g2553, coupled with an 433MHz CC1101 module purchased from eBay (many versions of these modules are available). We mounted both modules on a prototyping board and wired them together.

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[1] See `http://www.tau.ac.il/~stoledo/tags` for details

Apart from the MCU and the transceiver and their supporting passives, our tags only include an LED indicator. We normally use it to flash a few times when the software starts, to indicate to the end user that the battery has been connected properly and that the tag is functional.

We later tested similar setups with other MCUs (MSP430g5529 and Tiva-C Lauchpads) and transceiver modules (a CC1200 in a TI evaluation module).

We also used TI's evaluation platform for the CC430 wireless MCUs, the Chronos watch, to port the software to the CC430 (the CC430 line includes a high-end MSP430 MCU and a CC1101 transceiver in a single package).

These initial prototypes allowed us to develop the software, to verify that the tags can be received by our receivers (we use several different receivers depending on the functionality of the tag), and to verify the lifespan of tags powered by small batteries. We tested current consumption both using a shunt and an oscilloscope and by measuring the time it takes a tag to completely drain a small battery (e.g., a lithium coin cell).

3. SOFTWARE

The initial software requirements for the tags were relatively simple. We wanted tags to be able to repeatedly transmit a sequence of transmissions, where each transmission is fixed (e.g., the first transmission in the sequence is always the same, etc). Tags have transmission slots of 0.25s, 0.5s, 1s, or longer, and transmissions should start in the beginning of a slot with good accuracy (sub 1ms), to allow a receiver to lock onto the transmission schedule. Each transmission in the sequence can be different (but there can be repetitions), and some slots could be empty (no transmission, or a reception attempt). We wanted to allow for long coded transmissions, which meant that we needed to use the infinite-length packet mode of the CC1101. Both the MCU and the radio should be in deep sleep state between transmissions, to conserve battery power. Finally, we wanted the same code to run on different hardware configurations (transceivers and radios).

Our software is currently completely custom; we do not use an existing wireless stack. The code consists of a main loop that wakes up at least 4 times every transmission slot using the MSP430 interval timer. During the first wakeup of the slot, the tag transmits a ping from the sequence (or goes back to sleep if the slot is empty). Normally, the tag goes immediately back to sleep at the other wake ups of the slot. However, if transmission failed due to a buffer underflow at the radio, the tag uses the other wake ups in the slot to increase the clock (the DCO) that drives the processor and the SPI peripheral. More specifically, in case of an underflow the tag estimates the DCO's clock frequency by comparing it to that of the crystal controlled 32768Hz oscillator that drives the interval timer. If the frequency of the DCO is low, the tag increases it a little bit. The tag attempts to keep the frequency below the limit at which the processor can function correctly at 1.8V, to prevent early failure when the battery voltage drops to 1.8V (6MHz for the MSP430g2452 that most of our tags use). We also ensure that the maximum SPI frequency of the CC1101 is not exceeded.

Figure 2 shows the current consumption of our tags before, during, and in-between transmissions. Tags wake up from deep sleep state (LPM3) about 1ms prior to the beginning of the transmission slot. During that time, the tag prepares for transmission and explicitly calibrates the frequency synthesizer of the CC1101. We perform this calibration explicitly to ensure that transmission starts exactly at the start of the slot, not immediately when calibration ends. During this preparation phase, the tag consumes about 15mA. During transmission, the tag consumes 30mA on average with a maximum of 36mA. By running tags until batteries run out, we verified that current consumption between transmissions is negligible.

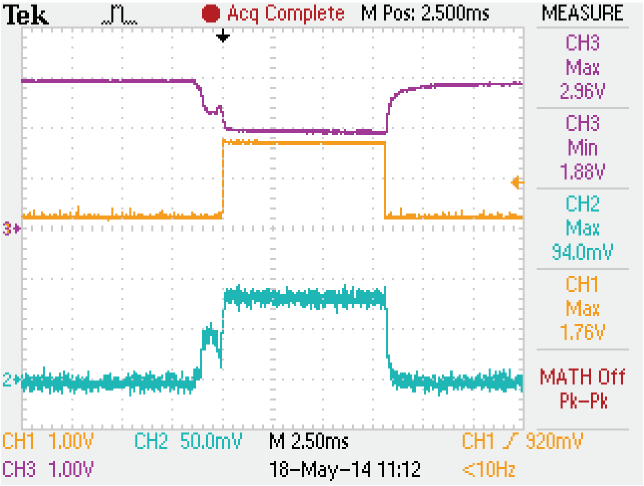

Figure 2: Current consumption of our tags during an 8ms transmission at 10dBm and the resulting drop in battery voltage. The oscilloscope traces show the battery voltage (channel 3 in purple, top trace), RF field strength (channel 1 in orange, not calibrated), and current consumption (channel 2 in cyan in a scale of 3.3V/A). The tag was one of our production tags consisting of a CC1101 and an MSP430g2452. In the top capture, the tag was powered by a used CR1632 lithium cell. The cell is partially discharged but it can still power the tag (but voltage drops to 1.88V, close to the 1.8V limit of the MCU and the radio). The traces were captured on a Tektronix TDS 2014B and the field-strength meter was an LT5534 logarithmic detector.

The transmissions of each tag are usually unique to it. The differences between transmissions of different tags can be in the code (for coded transmissions) and the frequency (for simple pings). We configure the transmission sequence of each tag in a single configuration file. A Java program processes this file and generates header files for a specific tag. We then compile the tag's software including these tag-specific files in Code Composer Studio and program the tag. The configuration of tags in the database also allows us to instruct tags how to flash their indicator LED and whether or not to print diagnostic information to the UART.

We are now working on additional software features for the tags, mainly the ability to receive commands via the radio and to switch between two transmission sequences. Another feature that we believe many users will find useful is the ability to upload the transmission schedule to the tag's flash memory via the radio, to allow tags to be "personalized" without compiling the code and without an MSP430 programming hardware.

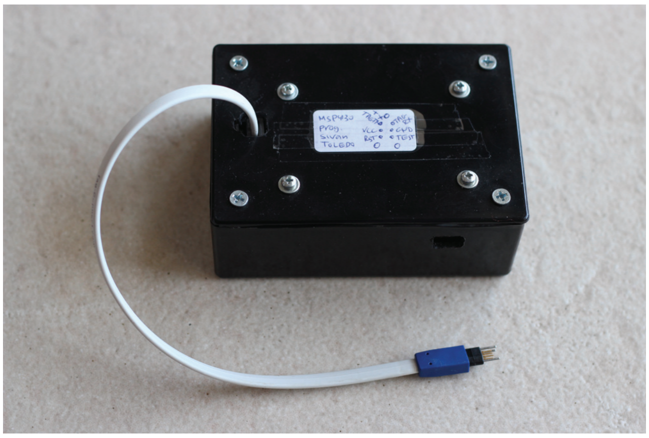

Figure 3: The Launchpad-based programmer with the *tag connect* cable.

4. MANUFACTURING AND DESIGN FOR PRODUCTION

The initial prototypes driven by our software demonstrated that the circuits (both the MSP430+CC1101 and the CC430) could produce useful wildlife tags. At that point, we proceeded to design a version that would be lightweight and that could be manufactured in larger numbers.

Designing a small PCB for the tags presented two challenges. One was the antenna matching network and the other was the connector to the MCU programming circuit.

The reference design for the CC1101 and CC430 contains a fairly elaborate antenna matching network consisting of 10 inductors and capacitors. TI recommends specific units and recommends a specific PCB layout which is not particularly small. We opted for an alternative solution that uses an integrated balun and low-pass filter made by Johanson Technology [5]. This single tiny component is design specifically for the CC1101 and the CC430 and is recommended by TI. It reduces the PCB area required for the transceiver and its supporting components by a factor of 2–3 [5]. Johanson produces these units for 433, 868, and 915MHz (we used 433MHz units).

We decided to use a product called *tag connect* (www.tag-connect.com) to program the PCBs. Tag connect is a cable that can be reliably attached to pads on the PCB, eliminating the need for a connector. We use the compact 6-pin version (TC2030-MCP-NL), which costs about $34. The required footprint on the PCB consists of 6 exposed pads and 3 alignment holes, taking an area of 6 by 3mm. The 6 connections are used for power, ground, spy-bi-wire (programming), and UART transmit and receive. We wired the tag-connect cable to the corresponding pads on an MSP430 Launchpad evaluation board, as shown in Figure 3. We have used this setup to program numerous boards (many of them multiple times) without a single problem.

With these issues resolved, we designed two-layer PCBs for two different tags. One tag uses a CC1101 and an MSP430g2452. We used this particular MCU because it is physically the smallest in the MSP430 family, at least in the QFN package type that we wanted to use. We also designed a PCB for a CC430f5137. We designed the boards so that prototype tags could be hand assembled, which meant using 0603-size parts (using smaller parts such as 0402 or even 0201 would make the boards a bit smaller; it is also possible that 0603 decoupling capacitors would not function well at 868 or 915Mhz). We ordered a few blank boards (from www.oshpark.com) and the parts to populate them and assembled a few tags using solder paste and a toaster oven. We used a high-end toaster oven with good temperature control (Breville BOV800) and monitored temperatures using a thermocouple, to ensure that the temperature profile roughly matches the profile recommended by the solder paste manufacturer. This soldering process works well with many boards, but the yield on the tags is only about 50%. Most of the soldering problems that we encountered involved the balun and the rest involved the QFN ICs and the tiny crystals that we use. Even with the low yield we could verify that the tags function properly. These tags, along with the production tags that we produced next, are shown in Figure 4.

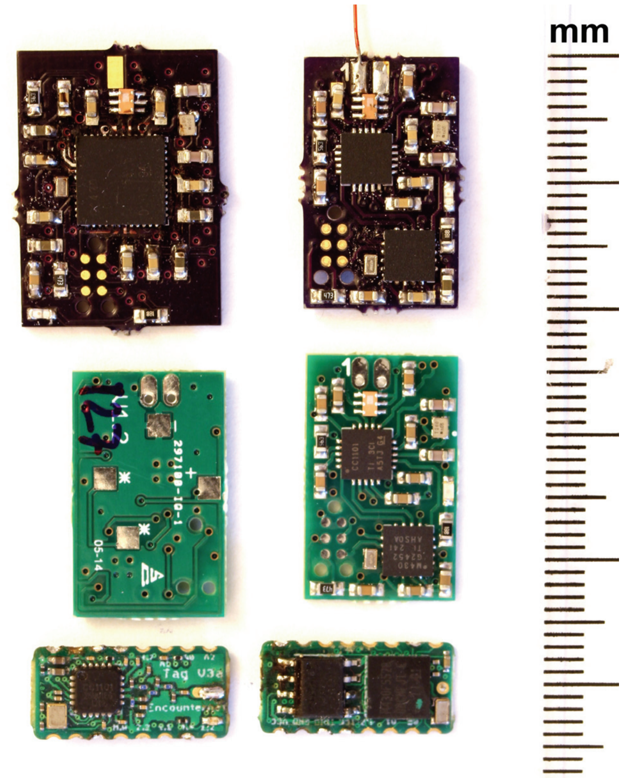

Figure 4: Hand-assembled prototype tags (top row, a 22-by-16mm CC430-based tag on the left and a 19-by-12mm CC1101-based tag on the right) our production tags (middle row, both sides shown, same layout and size as the top-right prototype), with Encounternet tags for comparison (bottom row, both sides shown, 15.5-by7.5mm).

Once we tested the prototypes and knew that the PCB design was correct, we ordered a batch of 80 CC1101-based tags from a turn-key assembly house called CircuitHub (www.circuithub.com). CircuitHub handled the manufacturing of the PCBs, procured all the parts in the BOM, and handled the assembly of the boards. We ordered these tags on a 1mm PCB (the prototypes were built on a more standard 1.6mm board). This makes them much lighter and does not appear to affect their performance. We paid about $25 each, but CircuitHub subsequently dropped their prices to $15 each for 25 and $11 each for 100 (the price continues to drop to

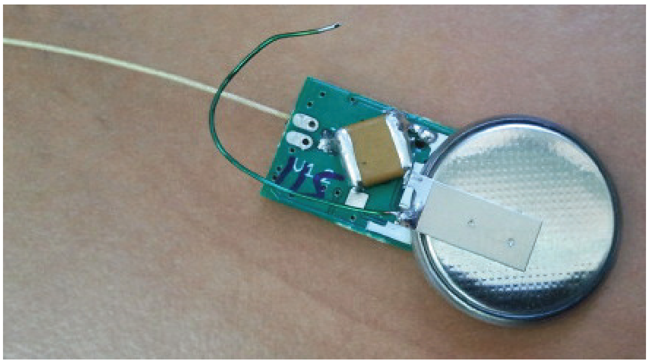

Figure 5: A tag with a tantalum reservoir capacitor and a tabbed CR2032 lithium cell. To deploy the tag, the wire is soldered to a ground connection and the entire assembly is coated with epoxy.

less than $7 at large quantities). Figure 5 shows one of these tags being prepared for deployment.

With the current pricing on CircuitHub, building the first prototypes by hand no longer makes sense. A single tag costs $114 and 8 cost less than $25 each, so it makes more sense to order assembled PCBs.

5. ANTENNAS

Small wildlife tags invariably use short monopole antennas (most other antenna can get stuck in vegetation; large collar tags can use loop antennas). We experimented with several antenna materials, including some that were recommended in manuals and in on-line forums.

Single-strand stainless steel fishing wire made by Malin (www.malinco.com) is lightweight, stiff, and nylon coated. It comes in several diameters. However, we failed to solder it. We also failed to solder multi-strand steel fishing wire. It is apparently possible to solder both types, but this requires a very acidic flux designed specifically for steel.

We eventually settled on using multi-strand nylon-coated wire designed for beading. It is available in a number of diameters and metals. The one we use is a 0.024-inch 49-strand 24kt gold plated stainless steel wire sold by *the bead smith* (www.helby.com). It combines the strength of steel, the conductivity of gold (at UHF current flows only on the surface of conductors so the composition of the inner core is irrelevant to current flow), and the protection of a nylon sheath. It is flexible. A spool of 10 feet costs about $16, or about $1 per antenna. We also had success with lower-cost beading wire with a "gold color" or "silver color". All types solder well once the sheath is removed from the end of the antenna with a wire stripper.

Theoretically, a $\lambda/4$ monopole for 433MHz should be 16.5cm long. We chose the length of the antenna experimentally by attaching a longer than necessary antenna to a blank tag PCB and attaching an coax cable to the tag. The other end of the coax was connected to a UHF transmitter with an SWR meter and the SWR was recorded for several antenna lengths. We placed the tag on a human hand for these experiments, to simulate a tag attached to an animal. We measured very low SWR values (about 1.1:1) with lengths of 18-16.5cm, and higher values (about 2:1) at 16cm. We use 17cm antennas. The SWR was significantly higher when the tag was far from a human body. We acknowledge that the coax connected to the tag influences the results of the experiment, but we could not come up with a better way to assess the matching. (Experiments with a logarithmic field strength meter were inconclusive).

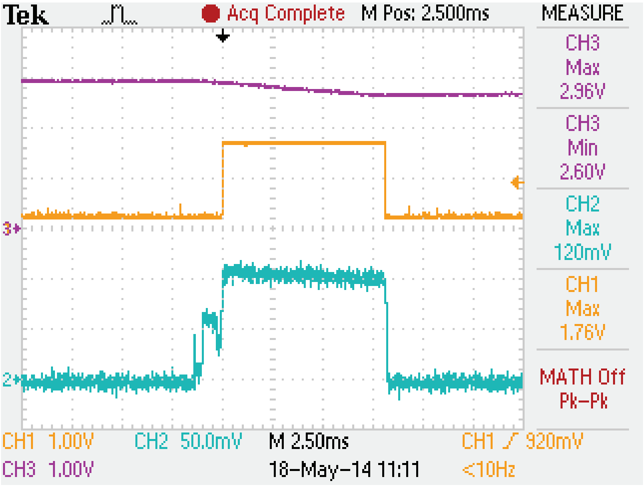

Figure 6: Current consumption of a tag with a 1000μF tantalum reservoir capacitor. Setup is otherwise the same as in Figure 2. The capacitor essentially powers the tag during transmission.

6. BATTERIES

The tags can be powered by 3V lithium coin cells or a pair of 1.4V zinc-air cells. The lithium cells come in a wide range of sizes and capacities and with or without soldering tabs. We powered the tags successfully with CR1225, CR1632, CR2032, and CR2477 lithium cells. Our CC430 tags have pads for a metal retainer for CR1632 cells. We attach lithium cells to our smaller tags using the cell's soldering tab or using a wire that we either solder to a tab or glue to the cell using a silver-based conductive epoxy.

Zinc-air cells packs almost as much energy as lithium cells, but they have air holes that must be kept shut (with a sticker) prior to deployment, and that must not be blocked during deployment. Our small tags have pads that were designed for gluing a pair of zinc-air cells using conductive glue. This worked well in the lab but failed in the field (we experienced both shorts, disconnects, and blocked air holes). We are trying to address these difficulties but for now we refrain from deploying zinc-air cells. We note that they have been used successfully by other wildlife researchers to power similar tags [3].

The 30mA current drain of the tags causes significant voltage drops across the internal resistance that some batteries develop as they discharge, causing the tags to fail prematurely. This is a significant issue with the smaller lithium cells, as shown in Figure 2. We address it by including a 300uF-1000uF tantalum reservoir capacitor to the tag; these capacitors add 0.3–0.42g and $1–5 to the weight and cost of the tags. Figure 6 shows the mitigating effect of a reservoir capacitor. Zinc air cells function well (in the lab) without these capacitors.

7. CHOOSING BETWEEN ALTERNATIVES

There are many choices for both microcontrollers and for integrated radio transceivers. In this section we describe some of the alternatives that we evaluated and why we decided not to choose them.

We decided to not to produce the CC430 tags (yet) because the radio on the CC430 can only operate at battery voltages of 2.0 or 2.2V and up (the documentation is a bit unclear on this issue), whereas both the MSP430g2452 tags and not the CC430 work down to 1.8V. Operation down to lower voltages means that batteries last longer. The same is true for MSP430s based on FRAM (they do not operate down to 1.8V).

The CC1200 produces more RF power (up to 14dBm at 433MHz) and is more energy efficient than the CC1101, but an integrated balun+filter is not available for it, making tags based on it much larger than CC1101 tags. In addition, its power amplifier operates in class E, which means that an antenna mismatch may affect it more than it affects the CC1101. This is a serious issue for wildlife tags, in which the animal's body affects antenna impedance.

We also considered the CC1110 wireless MCU, which consists of an 8051 MCU and a CC1101. We decided not to use it because its CC1101 does not support the infinite-length packet mode (long packets). The 8051 MCU is also a drawback, but one that we might have accepted if all packet modes were supported.

8. RESULTS AND EXPERIENCES

We tested our tags extensively at all development stages. Field testing in the field started with battery-operated tags that were left in the field for weeks or months in plastic containers and were monitored by remote receivers. We encountered several failures with early prototypes but as the software matured, tags became very stable.

We then tested tags carried by humans. This allowed us to evaluate signal strengths when the tag is placed in various positions on a living creature (tags attached low on the body are more difficult to receive because the line of sight to the receiver is obstructed more often). One problem that we encountered during these experiments was a significant warming of one tag that transmitted an 8ms ping every 250ms. The CC1101 got hot and this caused its frequency synthesizer to drift up. This may be caused by too few vias under its thermal pad.

Testing so far shows that under line-of-sight conditions, the tags can be easily received from at least 8.5km away when the receiver is equipped with a standard hand-held 6-element Yagi antenna. This is true for both simple pings and coded pings. Signal strengths at these distances is good enough to allow wildlife researchers to estimate the direction of arrival and thereby to track animals. These results are consistent with the path loss of about -104dB at this distance and frequency, with the nominal 10dBm output of the tag, with the gain of the Yagi, and with the sensitivity of the receiver (AOR AR8200 in the case of CW pings), which is around -106dBm.

In early May 2014 we started tagging wild animals (Figure 1 and Section 1). By mid July, we have tagged 20 animals (12 owls, 4 kestrels, 3 coypus, and one plover). Tags carried lithium batteries (1632, 2032, or 2477) and some included reservoir capacitors. Our attachment method (glue) did not work well on kesterls, who were apparently able to remove the tags within a day or so, but tags attached to the plover and most owls functioned for 2-3 weeks before detaching. Tags attached to coypus have been functioning for almost 2 months and are still operating.

Further characterization of the effectiveness of the tags for wildlife research are beyond the scope of this paper.

9. CONCLUSIONS

We have demonstrated the feasibility of designing and manufacturing advanced, lightweight, low-cost wildlife tracking tags at a modest academic lab. The use of integrated UHF transceivers, either in conjunction with an MCU or as part of a wireless MCU, results in flexible tags that are frequency agile, that can use a variety of modulation and packet formats, that can both transmit and receive.

The main drawback of these advanced transceivers is a higher power consumption than that of traditional pinging tags. In simple applications, this simply reduces tag lifetime (for a given battery). However, the ability of the tags to receive and to adapt their behavior under software control enables sophisticated power-saving strategies, such as pinging only when prompted to do by a control transmitter.

The low-cost, ease of manufacturing, and flexibility of these tags can transform wildlife tagging both by enabling many research groups to experiment with advanced data collection techniques (e.g., an Encounternet-like sensor network) and by allowing many more tags to be deployed at a given budget.

Furthermore, the low-cost of automated manufacturing of the tags, even at small volumes, makes specialized variants (e.g., tags that include an accelerometer) feasible; the main barriers are the hardware-design and software-development efforts, not manufacturing.

Acknowledgements This research was supported by the Minerva Center for Movement Ecology and by equipment donations from Texas Instruments. We thank Rob MacCurdy and Julian Kapoor for advice on antenna materials and batteries. We thank John Burt for allowing us to experiment with Encounternet tags.

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