Physical-Layer Protocols for Lightweight Wildlife Tags with Internet-of-Things Transceivers

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***Abstract*—Most species of birds and bats must be tracked with tracking tags weighing less than 10g and many require tags weighing less than 1g. Tags based on commodity internet-of-things system-on-chips (SoC) can be be mass produced at low-cost, hence allowing many individuals to be tracked. We report on the design and performance of two communication protocols that enable long-range communication with such tags. One is a unidirectional protocol, in which tags transmit unique codes that can be reliably detected from 15km away and that can be used for time-of-arrival and angle-of-arrival localization (tracking). The other is a bidirectional protocol that allows tags to transmit short data packets to low-power low-cost basestations and to receive commands from them. Data packets in this protocol can be reliably received from tags that are 8km away and sometimes from up to 15km, and commands packets can be received by tags from up to 4km away. These protocols have been implemented in low-cost tags that can weigh less than 1g (depending on the choice of battery) and using only about 60uJ per transmission.**

Our results have been gathered by tagging wild bats. The same tags have been used for time-of-arrival localization of wild bats and birds by several different research groups in 3 countries.

I. INTRODUCTION

The design, manufacture, and use of tracking tags for wild animals remains a significant technological and scientific challenge. *Tags* are electronic devices that are attached to animals in order to track their movement and sometimes also to sense their physiology and their environment. The challenges stem from weight constraints (many species of interest cannot carry tags weighing over 1g), from power constraints (arising from the weight constraint), and from the mobility of animals, which often requires long-range tags.

This paper reports on the performance of two long-range communication modes for miniature wildlife tags. The first, called ATLAS mode, is designed primarily for the ATLAS reverse-GPS tracking system [8], [7], but it can also be used for angle-of-arrival tracking, for homing-in, and for presence sensing. It is a unidirectional communication mode in which tags transmit periodic pings that are received by specialized base stations. The second, called ID mode, is designed to allow tags to transmit short data packets, primarily for identification, to low-power low-cost base stations, as well as to receive commands from such base stations.

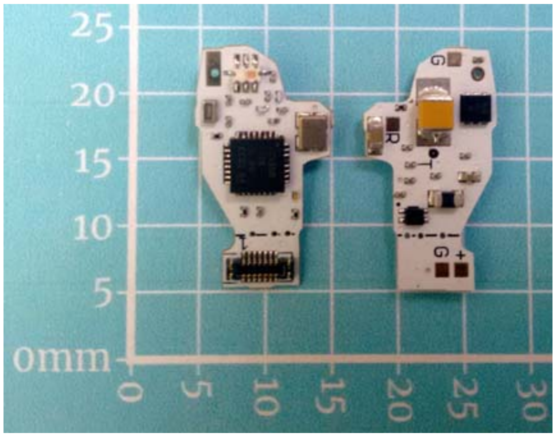

Fig. 1. CC13X0-Based Vildehaye tags. The board weighs 0.3g.

These modes have been designed for our *Vildehaye* tags, that weigh down to 0.75g (including batteries, coating, and antenna), which are designed around integrated Internet-of-Things transceivers. Due to the use of these transceivers, the tags are inexpensive, with assembled PCBs costing around 22 USD in quantities of 100. The communication modes use short activity slots that allow operation with tiny silver-oxide batteries. Transmit slots are up to 8ms long and receive slots up to 15ms long. The use of such batteries also requires activity slots to be spaced several seconds apart; both modes support this.

Real-world experiments reported in this paper show that ATLAS-mode transmissions are reliably detectable at distances of 15km, that ID transmissions are reliably detectable at distances of 8km and sometimes from much further, and that tags can hear commands sent by base stations 4km kilometers away. The experiments were carried out by attaching tags to wild bats.

Results from the same experiments also indicate that the ability of tags to receive commands from remote base stations is adversely impacted by the lack of bandpass filtering and by the noise figure of the receivers of tags. Both weaknesses can be addressed, but at the cost of increased weight and power consumption.

II. DESIGN

Vildehaye tags use a CC1310 or CC1350 RF microcontroller from Texas Instruments (TI). We currently use two different hardware designs, both for the 434MHz license-free band; the smaller of the two designs is shown in Figure 1. The circuit design is based on TI's reference design, but

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with the following modifications: (1) the RF low-pass filter is implemented by an integrated ceramic passive, not using discrete capacitors and inductors; (2) a 330μF reservoir capacitor enables the use of tiny batteries [5]; in the smaller design the capacitor can be disconnected from ground using a MOSFET, to prevent leakage during storage; a Hall-effect sensor tells the processor that the tag should go into storage mode. The antenna is a 1/4-wavelength wire.

The tags support three communication modes. In ATLAS mode, a tag transmits a single tag-specific 8192-bit pseudo-random code using FSK modulation, symbol rate of 1Mb/s, and deviation of ±380kHz. This is a transmit-only mode. ATLAS transmissions are detected by ATLAS base stations, which also estimate the time-of-arrival (TOA) of the transmissions so that the tags can be localized. ATLAS base stations use a sampling receiver and a computer to perform signal processing; see [8], [7] for details.

Identification (ID) mode is designed for long-range unidirectional or bidirectional communication with low-cost base stations. ID-mode base stations use a tag as a radio (or a TI evaluation board) and a Raspberry Pi computer; total cost is about 100-200 USD, depending on the choice of antenna and amplifiers. ID mode utilizes one of the so-called long-range mode (LRM) that CC13X0 devices support. ID mode uses spreading by a factor of 8 with chip rate of 500kb/s and an $r = 1/2$ error-correction convolutional code, giving a data rate of 31.5kb/s. The parameters for ID mode have been selected to enable tags to send packets of roughly 128 data bits (an ID of up to 64-bits and some additional status fields) in less than 8ms, the length of ATLAS-mode transmissions.

Tags also support a DATA mode, which runs 500kb/s with no spreading or error correction, using the same base station hardware as ID mode. This mode is designed for data download at short ranges and is not relevant for this paper.

The MAC layer of ATLAS mode is very simple: tags transmit their code periodically, with up to 2 different ping rates. Receivers perform FSK detection and correlate the result with the tag's pseudo-random code to detect pings and to estimate their arrival times. The tag inverts the code in the slower ping rate to let the receiver know which of the two ping rates is used. Once the receiver detects a ping, it tracks the pings and performs signal processing only on windows of samples that are highly likely to contain a ping.

In tags, the MAC layer for ID and DATA modes is constrained to operate within regularly-spaced activity slots, to allow the tag to be powered during these slots by their reservoir capacitor. For example, a particular tag configuration may use 4 slots spaced 2s apart every minute, with even slots used for transmission and odd ones for reception. The tag announces in every transmission the spacing of the slots and whether it uses the next one for reception, so base stations can respond in the tag's next reception slot.

Base stations for ID and DATA modes listen continuously (except when they transmit). Given the low power consumption of the CC13X0, this still allows extended periods of operation using batteries. When a base station hears a tag that indicates that it will listen in its next slot, it determines whether a response is required. If so, the base station transmits the response during the tag's next activity slot.

III. EVALUATION

A. Sensitivity

We measured the sensitivity of different modes. The sensitivity is a rough indicator of the useful operational range of different modes.

In the main experiment packets transmitted by one CC1310 transmitting at 10dBm were attenuated and fed to a second CC1310 that served as a receiver, or in the case of the ATLAS mode, to a USRP B210 sampling receiver with appropriate signal processing software. The noise figure of the CC1310 is 7dB[1] and the noise figure of the B210 is specified as being at most 8dB. ID and DATA packets were 10 bytes long and contained a tag-state field and a 6-byte tag identifier. Packet delivery rates indicate that DATA transmissions can be reliably received down to less than -80dBm, ID transmissions down to less than -100dBm, and ATLAS transmissions down to less than -120dBm. These correspond to distances of about 1.7, 4, and 10km from a 10dBm transmitter, assuming only free-space path losses (that is, assuming that ground-reflection losses and antenna gains/losses all cancel out). As we shall see below, results in the field are even better due to the use of gain antennas and low-noise amplifiers (LNAs).

B. Remote Detection of Tags on Wild Bats

To assess the real-world range of ID and ATLAS modes, we tagged 7 wild Egyptian fruit bats (*Rousettus aegyptiacus*) with Vildehaye tags in the Hula Valley in northern Israel. The tags were tracked by 3 ID-mode base stations as well as 9 ATLAS-mode base stations that that can localize tags to within tens of meters or better [8], [7]. The tagging was carried out in two batches about 3 weeks apart. Tags weighed 5g, all inclusive (~3.5% body mass). The 7 tags were received for 31, 30, 29, 11, 5, 2, and 1 days; The tags that kept transmitting 31 and 30 days appear to have fallen off the bats after 19 and 16 days, respectively; the others appear to have remained attached until their transmissions disappeared.

The tags transmitted a ATLAS code every second and an ID packet every 10s. In comparisons of ATLAS and ID modes below we decimated the ATLAS transmissions to one every 10s to facilitate comparisons.

Two of the base stations were receive-only base stations. They used vertical antennas with omni-directional azimuth coverage and gain of about 7.8dBi in the elevation plane, placed atop 50m towers located in a flat valley. They also used a masthead LNA with noise figure of 1dB or less, a 5MHz-wide bandpass filter, an N200 USRP receiver for ATLAS mode, and a tag for ID mode (using a splitter). The third base station, number 3, was a transmit-receive base station. For ATLAS mode, it used the same RF hardware as base

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[1] This does not appear in the data sheet, but was specified by a Texas Instruments employee on a support forum.

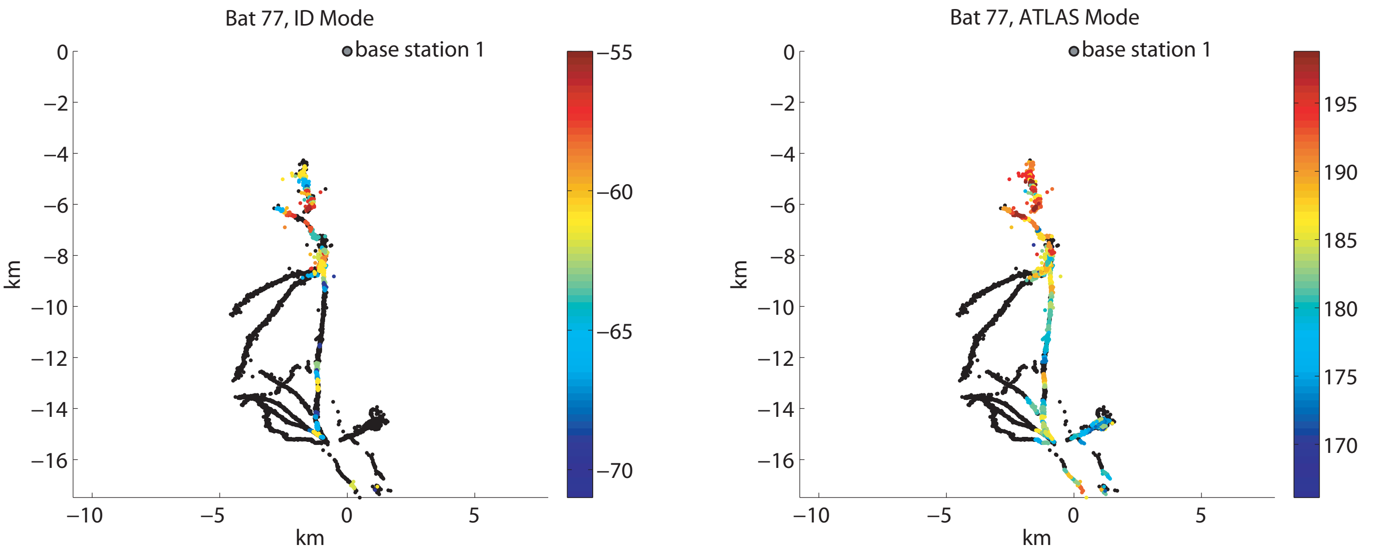

Fig. 2. Detections of transmissions from a tag attached to a fruit bat over two nights by a base station in relative coordinates $0, 0$. Black dots represent locations from which none of the transmissions were detected by base station 1 (but the bat was localized by other base stations); colored dots represent detections, and the color represents the received signal strength (RSS). Locations at the western part of the area (easting coordinates less than about -2km) are in a hilly area from which many locations do not have line of sight to the basestation. Locations to the east of this line are in a fairly flat valley.

stations 1 and 2. For ID mode, it used a tag as a radio with no amplifiers or filters and a vertical $\lambda/2$ dipole antenna. Both antennas were atop a 30m tower at the top of hill, about 290m above the valley floor.

The tag-to-base-station results one bat and one base station are shown in Figure 2. Results from other bats and from the other receive-only base station are similar.

The results indicate that when there is a line of sight, ATLAS mode can be detected from distances of more than 15km. ID mode is fairly reliable up to distances of about 8km; it is sometimes detected from 15km away. In both modes, the RSS values tend to drop as distance grows, as expected, but they are not reliable indicators of distance. The results indicate that the sensitivity is better than what we measured in the lab. This is due to the use of the LNA, which improves the system noise figure from 7-8dB to less than 1dB, and due to the gain of the receiving antenna.

C. Two-Way Communication with Tags on Wild Bats

To test the ability of tags to receive commands from base stations, we added a stationary beacon and programmed both the tags and the receive-transmit base station in a particular way.

The beacon was placed on a tree about 8m above ground with an antenna identical to those used in base stations 1 and 2. It transmitted an ATLAS code every 1001ms and an ID packet at random times with an average rate of 1Hz. The ID transmissions contained an identifier and a do-nothing command.

Base station 3 replied to every ID-mode transmission that it heard with the same do-nothing command. Base stations recorded all the ID packets that they received.

Tags were programmed to listen for ID-mode incoming commands during 15ms slots every 10s, exactly 5s after their ID transmission. In ID mode, tags transmitted an identification number and the amount of time Δ since they last heard a do-nothing command.

Given the length of the beacon's ID transmissions, its average beaconing rate, and the 15ms receive slot, the expected time to hear the beacon if a tag is in reception range is about 1000s (17 minutes).

We analyzed the data, identified the set (possibly subset) of events in which the tags heard a command, and classified the events into commands from the random beacon and commands from the transmit-receive base station. We identify a command delivery to tag i at time t when the logs contain a packet from i at time $t + x$ with a Δ value of x. Note that many different packets can identify the same event, and that the same packet can be recorded at more than one base station. We classify the events by inspecting the log of the transmit-receive base station. If this log indicates that the base station received tag i at time $t - 5$, we assume that the command received at time t was sent by the base station in response to a tag's transmission. Otherwise, we assume that it came from the beacon. Classification as a beacon-originated event is certain; if base station 3 did not hear the tag, it did not respond to it. Classification as a base-station-originated event may be erroneous, but because the beacon transmits at random times, the error probability is low (about 0.01).

Figure 3 (left) maps locations at which tags attached to wild bats received a wake-up command from base station 3 or from the beacon. It is clear that tags can hear commands, at least some times, from distances of over 4km. It is also clear that they can receive commands both from beacons that transmit at random times and from base stations that respond to their own transmissions.

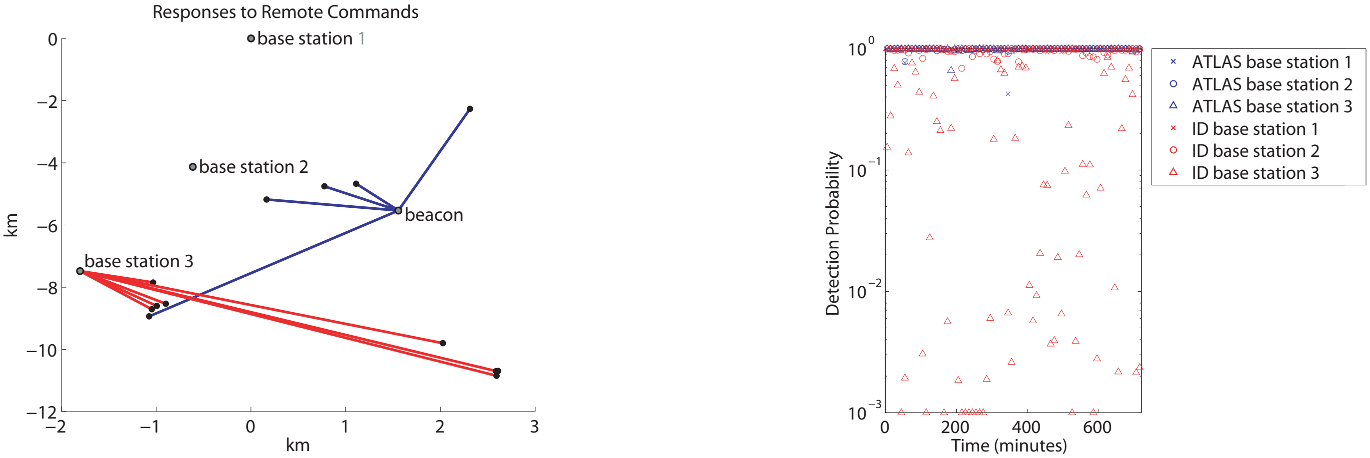

Fig. 3. The map on the left displays locations (black dots) at which tags attached to bats received wake-up commands. These locations are connected by lines to the transmitter (open circle) from which the command was sent. The graph on the right shows the fraction of beacon transmissions that were detected by different base stations over a span of 12 hours. Each marker represents a time span of 10 minutes.

Our analysis indicates that bats flying in the coverage area of the base station usually receive at least one command every night, sometimes many. Hearing the beacon is more patchy, probably due to the fact that the bats spend most of the time foraging fairly close to the ground (feeding/resting on trees) and only short periods (minutes) flying at high altitudes, where the path losses are lower.

However, the reception performance of base station 3 allows us to demonstrate the challenges of receiving remote commands with simple RF hardware. The graph on the right side of Figure 3 shows that the ID-mode receiver at base station 1, which is simply a tag attached to a dipole, performed much worse and with much higher variance than the ID receivers at base stations 1 and 2, which had a antennas with more gain, LNAs, and band-pass filters. This receiver also performed much worse than the ATLAS receiver at the same location, which did have a high-gain antenna, an LNA, and a filter. These results suggest that the patchy ability of the tags to hear remote commands is due to the mediocre noise figure of the CC1310, due to the lack of selectivity (tags that only have a harmonic-suppression low-pass filter), and possibly due to the tags' inefficient antenna. Replacing the low-pass filter by a SAW filter should improve the selectivity dramatically, but will further degrade both noise figure and emitted power.

IV. RELATED WORK

Dressler et al. describe a different technique to enable long-distance low-power communication with tags on bats, namely erasure coding, but they do not report on distances, probably because they did not track the location of bats [2]. Our own earlier tags [6], which have been widely deployed (around 1000 tags), used an integrated transceiver (CC1101) and implemented ATLAS mode and DATA mode, but not the long-range ID mode because the older transceiver did not support long-range modes.

Support for long-range modes is emerging in other families of low-cost low-power integrated transceivers, as part of the Internet of Things. Perhaps the most notable example is LoRa, a proprietary long-range mode developed by Samtech [1].

Older designs of VHF pingers are still widely used by ecologists, because they are lightweight, available commercially and easy to use. Uncoded CW pingers are used today primarily for homing in [4]. Coded OOK pingers are used for automated proximity detection. One distributed proximity detection system, Motus [3], has gained popularity and lists about 320 deployed receivers in the Americas.

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