Evaluating Batteries for Advanced Wildlife Telemetry Tags

Sivan Toledo
Blavatnik School of Computer Science
Tel-Aviv University

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Abstract

We evaluate miniature batteries as potential power sources for advanced wildlife telemetry tags. These tags are often based on integrated UHF transceivers that are designed for wireless sensor networks and that consume 18-85mA while receiving or transmitting. This current drain is challenging for many types of miniature batteries. We evaluate batteries both on actual tags and in a specialized synthetic-load circuit. Our evaluation focuses on the total amount of energy that the battery delivers until the tag fails, but we also investigate other important issues, such as the ability to withstand immersion in water. Our main findings are that zinc-air cells designed mainly for hearing aids perform extremely well in terms of effective energy density (but are hard to deploy), that lithium coin cells require a reservoir capacitor to deliver their rated energy (which is about half of that of zinc air with the same weight), and that rechargeable lithium polymer cells perform well even without a reservoir capacitor.

1 Introduction

Early wildlife telemetry used simple VHF transmitters (tags) that emitted a short unmodulated radio-frequency (RF) pulse every second or so (see [2] or [5]). Similar transmitters are still in wide use today, for example in applications that require very light-weight tags (down to 0.2g [12]). The smallest such tags only emit a fraction of one mW (sometimes as little as 0.01mW [5]), but tags that emit 1-10mW are also common. Whereas these simple tags use 1–3 discrete transistors, an emerging class of tags use highly integrated radio transceivers and microcontrollers [9, 11, 16]. Tags with such configurations can transmit relatively large amounts of sensor and identification data [16], and/or complex waveforms that are used for automatically determining the location and identity of a tagged animal [9, 11]. The integrated transceivers place a heavier load on the tag's battery than simple VHF transmitters, because they consume significant power just to create the complex waveform, not only to produce RF power. The new tags often have additional properties that make their power use different than that of simple telemetry transmitters, such as built-in voltage regulation and the fact that they require higher voltages than simple tags.

In this work, we systematically investigate batteries options for these tags. We use as a model the Encounternet tag [16], which is based on the 10mW cc1101 integrated UHF transceiver from Texas Instruments. We also explore batteries that can power 100mW transceivers such as the si4463/4 transceivers from Silicon Labs. While there are many similar transceivers from these and other manufacturers, their current consumption and voltage requirements are all similar. These transceivers require 1.8–3.6V to operate, and so do the microcontrollers that are needed to control them (some of these parts need at least 2 or 2.2V). They consume around 18mA during low-power transmit (1mW) and during receive periods, around 35mA when transmitting at 10mW, and around 85mA when transmitting at 100mW. Current consumption when the transceiver is turned off is negligible (e.g., 30nA).

Figure 1 (left) shows the current consumption of a cc1101-based tag before, during, and after an 8ms 10mW (full power) transmission at 434 MHz. The tag's microcontroller wakes up a little less than 2ms before the transmission starts. It wakes up the radio transceiver and instructs it to calibrate its frequency synthesizer. During this preparatory period, the tag consumes 5-10mA. During transmission, the tag consumes about 30mA. The changes in the transceiver's current consumption are abrupt; they appear gradual in the graph because of decoupling capacitors in the tag.

Batteries can react in complex ways such high-current pulses. The graphs on the right in Figure 1 show what happens when a pair of new zinc-air batteries power the same tag. Under no-load conditions, the batteries delivered about 2.75 V to the tag. As the tag started consuming current, the batteries' voltage sagged a bit. At the start of the RF pulse, voltage dropped quite dramatically, and it continued to drop during the pulse even though current consumption remains constant. Two tags powered with this type of batteries transmitted 8ms pulses every second for 11 days and 9 days 15 hours. During some transmission pulses, the battery voltage dropped close to 1.8 V, the

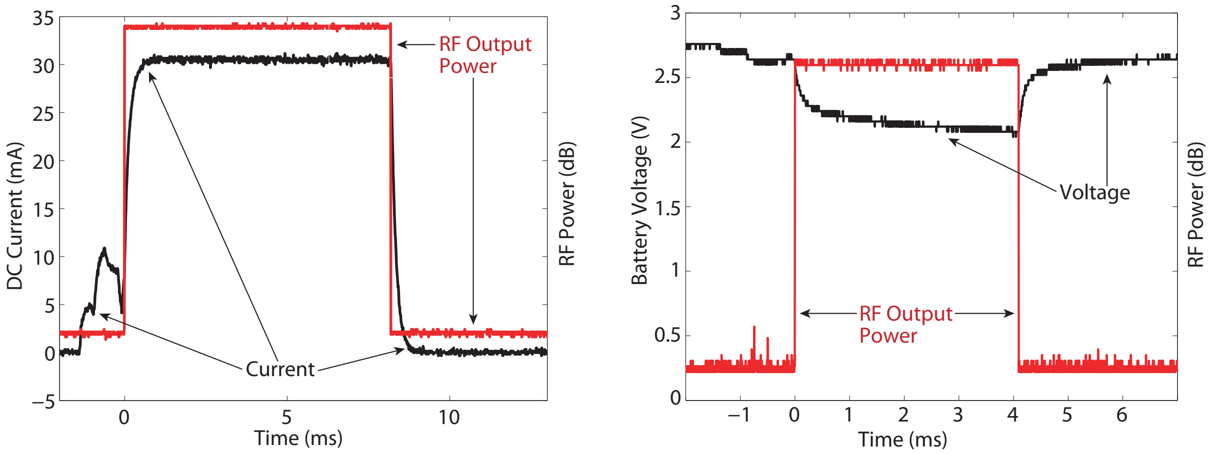

Figure 1: Current consumption of a smart wildlife telemetry tag based on a cc1101 transceiver and an MSP430 microcontroller (left) and the battery voltage drop that this load causes (right). The RF output is around 10dBm (the detector was not calibrated). In the graphs on the left, the tag was connected to a lab power supply running at 3.3V through a 25 Ohm current-sensing resistor. In the graphs on the right, the tag was powered by a pair of zinc-air number 10 batteries. The data for this and subsequent high-sample-rate plots was collected by a Tektronix TDS2014B oscilloscope.

minimal voltage above which the transceiver and the tag's microcontroller are guaranteed to work (they probably work slightly below 1.8 V, but this is not guaranteed by the manufacturer).

These introductory experiments highlight the importance of carefully selecting and evaluating batteries for these emerging tags. A battery that functions perfectly well in a simple VHF transmitter that only consumes 1.8 mA and that is tolerant to low voltages [12] may fail miserably in a tag that consumes 30 mA or more and that requires at least 1.8V.

In this paper we investigate potential batteries for such tags, focusing on tags with total mass of 10g or less. We are mostly interested in primary batteries, but we also explore the use of secondary (rechargeable) batteries that may be able to power tags effectively with or without an on-board charging mechanism (which can rely on energy harvesting from the environment [10]; see also [3, 15, 17] for discussions of energy harvesting on other types of wireless sensors).

The main contribution of this paper is an experimental evaluation of several types of batteries in the context of advanced wildlife telemetry tags, in Sections 4 and 5. We evaluate batteries both in actual tags and in a synthetic load-fixture that can simulate a wide variety of telemetry tags, with and without reservoir capacitors. The pros and cons of each evaluation methodology are discussed in Section 3. The design of our synthetic-load is described and analyzed in the Appendix; the design is novel, but fairly straightforward. Another contribution of the paper are a systematic discussion of the properties of batteries that are relevant to advanced wildlife telemetry tags and the extent to which different battery types have these properties, in Section 2. Our main findings are that zinc-air cells designed mainly for hearing aids perform extremely well in terms of effective energy density (but are hard to deploy), that lithium coin cells require a reservoir capacitor to deliver their rated energy (which is about half of that of zinc air with the same weight), and that rechargeable lithium polymer cells perform well even without a reservoir capacitor.

2 Background

Several types of miniature batteries are available for miniature wildlife tags: silver oxide, lithium coin cells (lithium manganese dioxide and lithium carbon-monofluoride), alkaline (zinc manganese dioxide), zinc air, and lithium ion polymer (lipo). In the past, mercuric oxide (mercury) batteries were also available, but they are now obsolete due to environmental concerns. Some types come in two or more chemical variants that trade off various properties. Alkaline cells offer no significant benefits relative to other types, so we ignore them from here on.

Miniature mercury and silver oxide batteries have been widely used in the past in wildlife tags; miniature lithium cells became available much later (e.g., in 1982 the lightest mercury battery weighed 0.3g whereas the lightest lithium cell weighed 6.5g). Lithium ion polymer are new rechargeable batteries that are starting to be

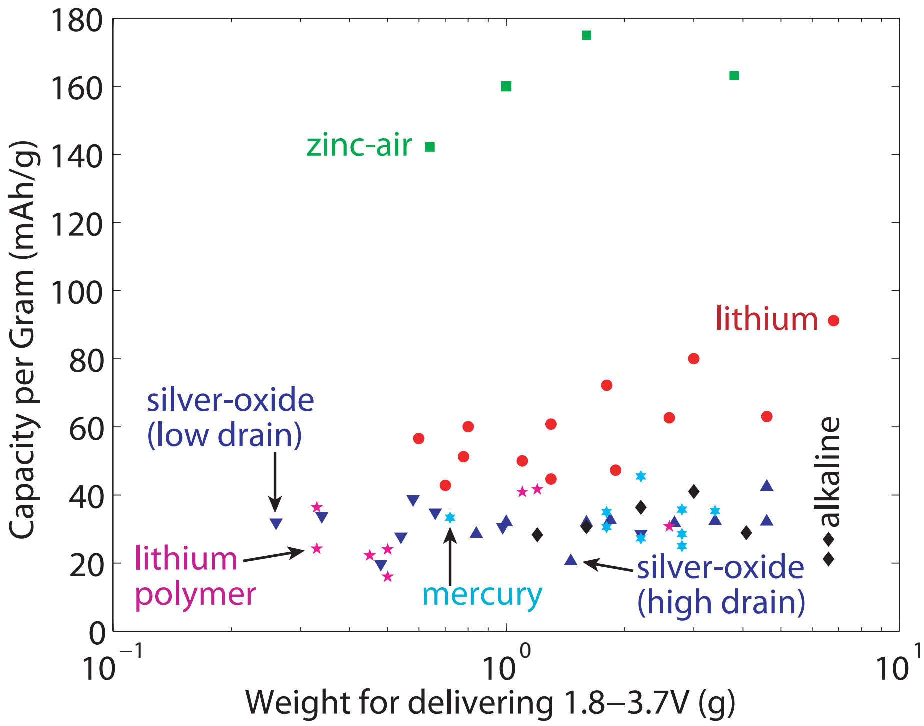

Figure 2: Useful capacity of different types and models of miniature batteries. The weight used is that of one lithium cell, whose voltage is near 3V, and that of two cells for the other types, whose voltage is near 1.5V, requiring two cells to meet the 1.8V minimum. Most of the data is from Energizer data sheets; data concerning lightweight lipo batteries is from PowerStream Technology. Mercury batteries are obsolete but included in the graph for reference.

deployed in wildlife tags, such as the GPS and accelerometer logging tags by Technosmart[1]. Zinc air cells are also beginning to be used [16].

The main properties of batteries that are relevant to our study are explained in the following sections.

2.1 Energy Density

Energy density (watt-hour per gram or per liter) is one of the most important metrics for light-weight wildlife tags.

The number of watt-hours that can be extracted from a given battery model is not a constant number, but a function of the load that is placed on the battery and of the temperature. Some battery types deliver more energy under low load (low current drain) than under high load; others deliver more energy under higher loads, up to a limit. A high-current pulsed load degrades some types but not others. Even when a pulsed load is well tolerated, the properties of the pulses (frequency, pulse duration, and current drain during pulses) can have significant effects on the total energy delivered.

This issue is what makes our study significant, because we study battery capacity under the actual load that modern tags place on the battery. This issue has other implications, e.g. for scheduling tasks and for routing in wireless sensor networks [8].

Battery specify energy capacity in terms of ampre-hour (mAh) delivered to a fixed-resistance load until the voltage drops below a threshold (typically low enough so that very little energy is delivered at lower voltages). The resistance that is used for each battery type is different and is based on the "sweet-spot" of the battery as well as on intended use. Manufacturers sometimes provide more detailed information, but we have not seen any battery data sheet from which one can quantitatively predict the behavior of the battery under a high-current pulsed load. For example, Panasonic's data sheet for the CR2032 Lithium coin battery shows a graph of its capacity under different loads and temperatures [13]. The nominal capacity of the battery is 225mAh (for a 0.2mA load down to 2V); the graph shows that the capacity drops to about 163mAh at 1mA current drain (at 20žC), but there is no information in the data sheet about higher loads, pulsed or constant.

[1] `www.technosmart.eu`.

Figure 2 shows the energy density for batteries of different types and sizes, using nominal mAh figures reported by manufacturers. We have included mercury cells only in order to put the numbers in a historical context. For a given type, heavier batteries are typically denser than lighter ones because the surface-to-volume ratio of small objects is worse than that of large objects (surface scales quadratically with diameter whereas volume scales cubically), affecting the ratio between the mass of the enclosure and the mass of the active material. In some cases, there are several batteries of the same type and size with different capacities. This is due either to shape (flat batteries are less dense than rounder ones because of poorer surface-to-volume ratio) or to a slightly different chemistry (e.g., KOH vs. NaOH electrolyte in silver oxide cells).

What is very apparent from the graph is that silver oxide, lipo, alkaline, and mercury cells have the worst energy densities, ranging between 20–40mAh/g. Lithium cells are denser, ranging from 60 to over 80mAh/g for the sizes considered, but the lightest ones are not as light as silver oxide and lipo (some lithium cells deliver less than 60mAh/g due to their flat shape). Zinc air are much denser than all the rest, between 140 and almost 180mAh/g, because they do not need to carry oxygen in the form of an oxide; they get it from the air. Data on energy density in lightweight batteries that were available in 1980 and 1987 ([6, Table 3] and [5, Table I]) shows that capacity of lithium, silver-oxide, and (now obsolete) mercury coin cells did not improve much in the past 30 years. The capacity of zinc-air cells did improve significantly from 1987.

2.2 Miniaturization

The lightest batteries in Figure 2 silver oxide (0.26g for a pair of size 337), followed by lipo. Lithium cells are heavier, with the lightest one weighing 0.7g (CR1025; the BR1225 is likely to be a better choice, with 60% more energy at 0.8g). The smallest zinc air cells are a little lighter, 0.64g for a pair. A 0.2g zinc air cell used to be available (size 5), but it is now obsolete; it had a much poorer density, about 83mAh/g (for a pair), comparable to that of lithium cells.

2.3 Ability to Deliver High Current and/or High-Current Pulses

The amount of current that a battery can deliver depends on the surface area of its electrodes, so physically small batteries may not be able to deliver enough current to power a tag. This is the main metric that this paper investigates.

2.4 Self Discharge

Batteries leak stored energy even when no current is drawn from them. This affects them when they are stored prior to being deployed in a tag, when stored while connected to a tag that is not yet active (e.g., turned off using a magnetic switch), and in service.

Silver oxide batteries have good energy retention, losing less than 5% of their capacity per year at 20žC (they lose more at higher temperatures). Lithium coin batteries have similar or better shelf lives.

Zinc air batteries arrive from the manufacturer with a tab that seals their air hole(s). Prior to the removal of the tab, their have good energy retention, losing only 5% of the stored energy per year. The tab must be removed prior to use, and once removed the battery discharges to about 50% of the energy after 3–12 weeks even under no-load conditions. After 20 weeks almost all the energy is gone. This happens even if they are re-sealed, which implies that the tab must be removed just prior to deployment of a tag (within hours or at most days), not during tag manufacture.

Energy loss in lipo batteries is high, around 10% *per month*. In addition, deep discharge (below about 3.5V) damages them. Together, these properties imply that they need to be charged periodically while in storage (whether they are connected to a tag or not), with the last recharging occurring close to deployment.

2.5 Operation in Harsh Environments

Tags attached to wildlife experience temperature extremes and periods of high moisture (e.g., rain).

Tags are typically protected from moisture and other contaminants by sealing (potting) the entire tag, including the batteries (materials used include acrylic varnish, epoxy, etc.). Some battery types, including lithium cells and silver oxide cells, can be sealed without any adverse effect, but sealing may be inappropriate to some types of cells.

Zinc air batteries require a small but constant supply of air to operate. Their air hole should not be sealed. They have been used in wildlife tags [16], but as shown below, the cells cannot supply current when water blocks the air holes, which happens during and after submersion. A recent investigation showed that a polytetrafluoroethylene (PTFE or Teflon) membrane allows air to enter the cells but prevents water from blocking air from entry [1]. This technique may be able to allow the batteries to work continuously if submersion periods are short and/or if enough air is trapped with the batteries, but tags will still experience power failure during a long-enough submersion. We are not aware of any wildlife tags using this technique, and in particular, it is not yet clear how to incorporate the PTFE membrane into the seal of a small tag.

Zinc manganese dioxide (alkaline) cells bulge as current is drawn from them. This can cause the seal crack, making them inappropriate for sealed wildlife tags.

3 Experimental Evaluation of Batteries with a Synthetic Load

Obviously, the most reliable way to evaluate how long a particular battery can power a particular tag is to attach the battery to the tag and to monitor tag activity until it ceases to work. We use this approach to validate tag lifetime in the final phase of tag design and implementation. However, this *in-vivo* approach has significant drawbacks when the intent is to explore the space of available batteries and available tag designs, including both hardware design and firmware design (transmission rates and durations, etc):

- The tag under test must be monitored for activity for correct behavior over days or weeks. This is easy for logging tags, as long as the tag's log can be read after the batteries drain out. For transmitting tags, this requires verifying transmission with a logging RF power meter or with a logging receiver designed to log the particular transmissions of the tag. Using an RF power meter to measure an assembled tag (with an antenna) is limited to one tag at a time, since the power meter cannot distinguish between tags (and is subject to interference from other RF sources). Logging the current drawn by the tag is another option, but (a) it does not tell us if the tag is functioning correctly, and (b) the voltage drop across the current-sense resistor causes the tag to see a voltage lower than the battery voltage, which causes the tag to fail before it would fail if connected directly to the battery.

- Testing the battery under different current current drains (corresponding the different levels of RF power or other functionality) and different pulse durations and frequencies requires that the tag can be configured accordingly, which is not necessarily the case.

- We cannot we evaluate batteries for a future or variant tag designs that have not yet been implemented.

We therefore advocate an *in-vitro* approach, in which we replace the tag with a synthetic-load circuit that can be configured to specific current-drain profiles. This allows us to decouple the power characterization of the tag's circuit from that of the battery and to test them separately in the design and battery-selection phases. The circuit is described and evaluated in the Appendix. A similar technique was recently used by Feeney et al. [4] to characterize one battery model (lithium CR2032).

We note that batteries can also be evaluated using mathematical and/or computational modes. See Rohner et al. [14] for an example that focuses on wireless sensors, and the references therein for a wider perspective. We opted for the synthetic-load approach because it combines accuracy with (relative) simplicity.

3.1 Modeling Tag Current Consumption

The current that an electronic circuit draws from a battery or other power supply varies as a function of the battery's voltage. As explained above, battery manufacturers usually model the load as a simple resistor. This is never exactly correct, but it is a reasonable approximation for simple VHF tags, because simple transmitters do tend to consume more current at higher voltages.

However, more advanced tags usually do not follow a monotonically-increasing voltage-current curve model; the current they draw is often almost independent of supply voltage. Integrated transceivers like the cc1101 and si4463/4 contain linear voltage regulators that regulate the battery voltage down to a fixed voltage, often 1.8V. Therefore, most of the circuits in the transceiver always see the same supply voltage, so their current consumption is independent of the battery voltage. The regulators themselves consume very little current. This structure implies that the voltage-current curve of the transceiver is essentially flat. Tags based on such transceivers also require a microcontroller; sometimes the microcontroller contains its own regulator (this is true, for example, for the microcontroller used in the Encounternet tags) but even when it does not, the microcontroller does not consume much current so the voltage-current curve remains almost flat.

We, therefore, model the current consumption of the tags as a constant-current sink, a device that consumes the same amount of power independently of supply voltage. This is a more accurate and more sophisticated than the simple resistive model that is used by the synthetic-load testbed developed by Feeney at al. [4].

We note that some future tags may exhibit a monotonically increasing voltage-current curve (the opposite behavior of that exhibited by a resistor). A tag based on a switching regulator, as proposed by Kuch [7], presents

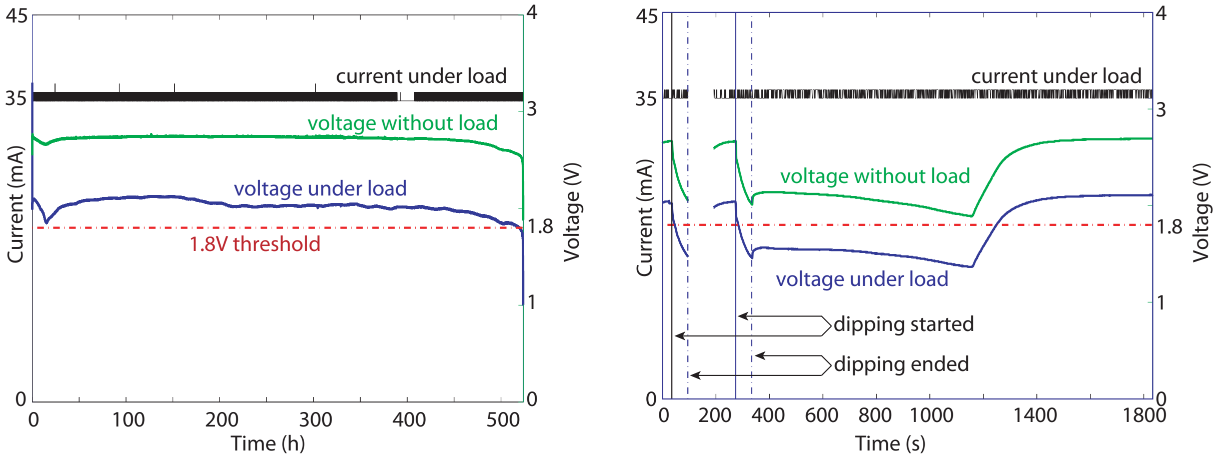

Figure 3: Behavior of a Zinc-Air number 10 battery under 5ms 35mA pulses every second. The graphs on the left show battery behavior in normal dry conditions; the graphs on the right show effect of the batteries in water for 60s. After the first dipping, the batteries were removed from the holder and dried; after the second, they dried passively.

to most of its circuits a constant voltage, but using a power-efficient regulator that uses less current at high voltages than at low voltages. It is possible to program the synthetic load to simulate such behavior, but such tests are outside the scope of this paper, given that we are not aware of such tags.

4 Experimental Results

We now present the results of several experiments with our artificial battery load. We use the data produces by each experiment to create graphs such as the one shown on the left in Figure 3. The graphs show the battery voltage during pulses and at rest (when not supplying current) as a function of time. These graphs allow us to assess the voltage drop due to current consumption as the battery's energy is depleted. The graphs also show the amount of current drawn from the battery during each pulse; this serves as a verification that the battery indeed supplied the required current.

The data presented in the graphs allows us to compute the *effective capacity* of a battery under a given load,

$$E = i \times t_{\geq V} \times d \,,$$

where E is the effective capacity in mAh, i is the nominal current drawn from the battery, $t_{\geq V}$ is the time the battery delivered at least the V volts required to power a tag (continuously, in hours), and d is the duty cycle. For the graph in Figure 3, the effective capacity is

$$E = 35\text{mA} \times 519\text{h} \times \frac{5\text{ms}}{1\text{s}} = 90.9\text{mAh} \,.$$

Table 1 summarizes the nominal and effective capacities of the batteries that we tested. We now comment on each experiment.

Zinc-Air The Widex brand zinc-air number 10 batteries that we tested were able to deliver 35mA current pulses without dropping below 1.8V (for a pair). As the graphs on the left in Figure 3 show, the voltage under load did drop close to 1.8V quite quickly, but then recovered and remained close to 2V for most of the experiment. We observed the same behavior in other experiments with these batteries. The voltages under load and at rest differ significantly, but both remain fairly constant until the battery is nearly depleted, at which point they crash almost abruptly.

As noted above, in experiments with a real transmitting tags that transmitted 8ms 30mA pulses, Widex and Panasonic number 10 batteries lasted only about 10 days, which corresponds to only about 57mAh, not the 91mAh delivered under 5ms pulses in the synthetic-load experiment.

These batteries were unable to deliver 85mA at a voltage above 1.8V, even when fresh. When delivering 85mA pulses, their voltage sagged to 0.98V, too low to power microcontrollers and transceivers directly.

	LI2032	LI1632	ZA10	LIPO60	SO392	SO317
Nominal	225	130	91	60	44	—
5ms, 35mA, 1.8-3.6V	76	36*	91	67	12*	—
5ms, 35mA, 2.0-3.6V	65	29*	—	67	7*	—
5ms, 35mA, 2.2-3.6V	52	15*	—	67	2*	—
5ms, 85mA, 1.8-3.6V	60		—	28		—
5ms, 85mA, 2.0-3.6V	39		—	28		—
5ms, 85mA, 2.2-3.6V	19		—	28		—

Table 1: Effective battery capacity in mAh as a function of usable voltages. Dashes indicate that the battery is not suitable to the load. Blank entries indicate that the configuration was not tested. Asterisks indicate occasional but significant voltage drops; the capacity figures ignore these drops (they are hence optimistic in these cases).

Zinc-air batteries have air holes. The effect of water blocking the air holes or entering the batteries through them is a major concern. We performed many experiments in which we dipped zinc-air batteries in water in different settings (connected to our synthetic-load circuit or to a tag or disconnected, etc) in order to understand the effect or water on them. The graphs on the right in Figure 3 show the results of a controlled experiment in which we dipped a pair of batteries in water for 60 seconds twice while they were connected to our synthetic load. After the first dipping, we took the batteries out of the holder, dried the batteries and the holder and inserted them back into the holder. After the second experiment, we left the batteries to dry in the holder (we dried the holder but did not touch the batteries).

While under water, the voltage of the batteries crashes. If they are left longer in water, the voltage without load reaches values that would not allow a tag to operate (even 60s were enough to drop the voltage under load to well below 1.8V). If the batteries are dried with a paper towel when taken out of the water, the dipping has almost no effect on their voltage both at rest and under load. We obtained similar results from a 5-minute dipping in which the batteries were disconnected from the holder and stirred repeatedly. We observed no adverse no effect once the batteries were out of the water and dry.

However, when the batteries remained in the circuit and left to dry in the air, it took them about 20 minutes to return to normal operation. During most of these 20 minutes, the batteries were not able to deliver 1.8V under load.

It appears that the main effect of water on zinc-air batteries is blocking of the air holes by the water. When the water is removed either by wiping or by evaporation, the batteries continue to operate normally. We note that the voltage drop during the dipping and drying phases is indeed a major concern, not only because a tag would not be functional during these periods, but also because it might draw significant current during these periods (because the software that is responsible for low current consumption is not functioning).

Recent findings by others [1] suggest that a PTFE membrane can eliminate the drying period and that if submersion periods are short relative to the amount of air trapped with the batteries behind the membrane the batteries can function continuously even if the tag is occasionally submerged.

Lithium Coin Cells (Lithium Manganese Dioxide) Figure 4 present the results of experiments with a Panasonic brand Lithium coin battery. The battery was able to deliver pulses of both 35ma and 85mA without a catastrophic voltage drop. The voltage at rest drops a bit initially but stays nearly fixed for most of the useful life of the battery. The voltage under load drops gradually; significant energy remains in the battery even when its voltage under load drops below 1.8V. Table 1 shows that this causes the battery to perform poorly under our high-current pulsed loads, in the sense that its effective capacity is much lower than its nominal capacity. Even if the tag can function down to 1.8V, the battery only delivers 34% or 27% of its nominal capacity (at 35mA and 85mA) before dropping below 1.8V.

A smaller Panasonic battery, CR1632, experienced a more erratic behavior, as shown in Figure 5 (left). It experienced some significant voltage drops early on (to less than 1.8V), but steadied later. Ignoring these early voltage drops, its effective capacity to 1.8V is about 36mAh (useful life under load of about 207 hours), which is consistent with the results of the CR2032, given the 225-to-130mAh capacity ratio.

Summary of Results with Lithium Polymer Packs and Silver-Oxide Cells Our overall characterization of these types of batteries, shown in Table 1, indicate that they are less attractive for high-power wildlife tags, so we omit the detailed results of the experiments from the paper.

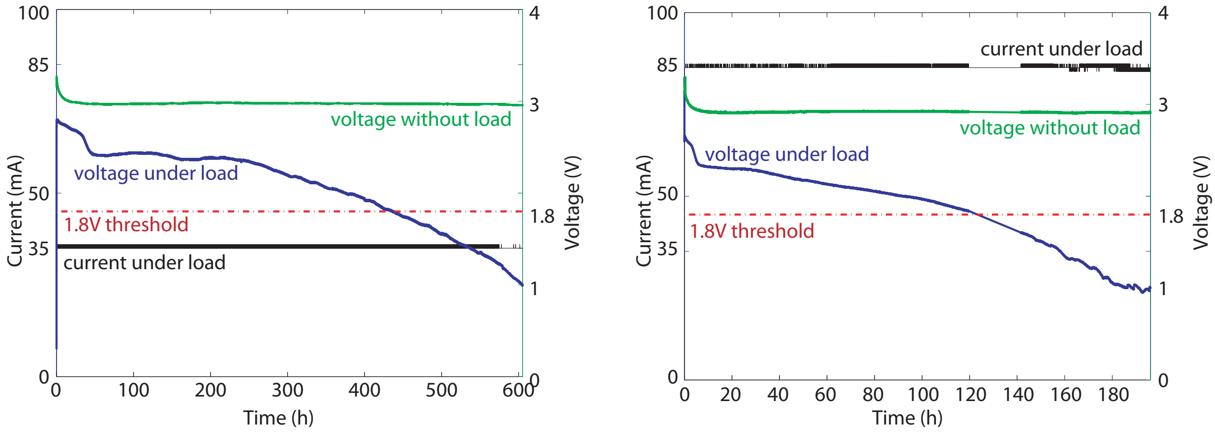

Figure 4: Behavior of a Panasonic CR2032 battery under 5ms 35mA pulses every second (left) and under 5ms 85mA pulses every second (right).

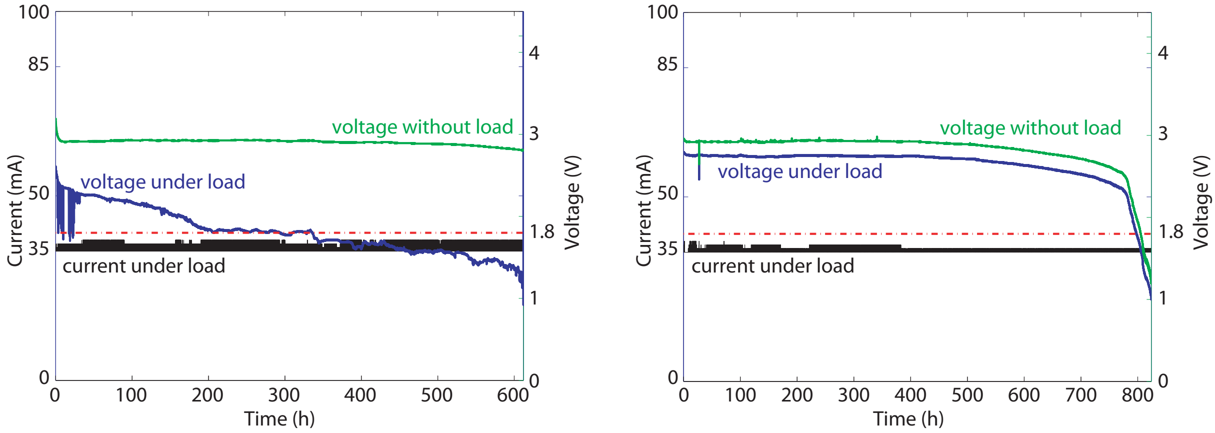

Figure 5: Behavior of a Panasonic CR1632 battery under 5ms 35mA pulses every second. The graphs on the left show the behavior when the battery powered the tag directly, whereas the graphs on the right show the behavior when a 1000μF capacitor was connected in parallel with the battery (see Section 5).

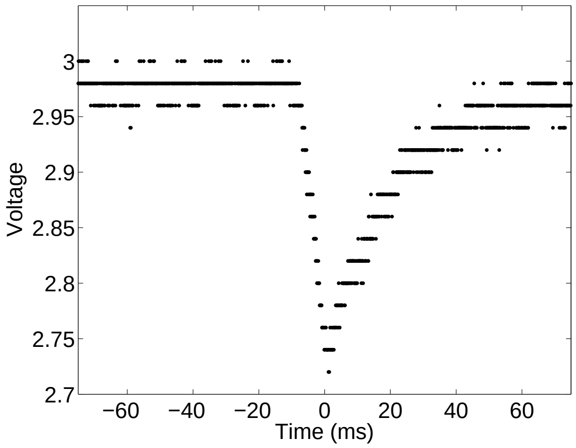

Figure 6: Voltage before, during, and after an 8ms transmission of a cc1101 tag (identical to the tag used in Figure 1). The tag was powered by a new Panasonic CR1632 battery in parallel with a 1000μF Tantalum capacitor (AVX F720J108KMC).

Small silver oxide cells, such as the number 317 cells by Seizaiken/Seiko that Table 1, cannot supply 30 or 35mA at all; their voltage crashes to very low values under such loads. They do work in conjunction with an appropriate reservoir capacitor (this technique is described in the next section) and given their very low weight they may be useful in tags that weigh around 1g.

Lithium polymer cells (we tested a 3.7V 60mAh Lithium polymer (lipo) cell made by Everwin Tech Co[2]) work well under a 35mA load but not under the 85mA load. Their energy density is not particularly attractive but they may be useful on tags designed to be recharged (between deployments, or during deployments using solar/mechanical energy harvesting). They deliver around 4.1-4.2V when full, which means that they require some power conditioning when used in tags that cannot tolerate more than 3.6V; a silicon diode can drop the voltage on acceptable levels, or a more complex regulator can be used.

5 Using a Reservoir Capacitor

A simple way to compensate for the high internal resistance of some batteries is to connect a reservoir capacitor in parallel with the battery. In this scheme, the capacitor provides most of the current for the tag during transmission; following the transmission, the battery recharges the capacitor almost up to the no-load voltage of the battery, assuming that inter-transmission intervals are long enough. This solution is not without drawbacks, however. This section explores the advantages and disadvantages of a reservoir capacitor.

Figure 6 shows the supply voltage of a cc1101 tag (identical to the tag used in Figure 1) during an 8ms transmission, during which the tag consumes 30mA, as shown in Figure 1. The tag was powered by a new Panasonic CR1632 battery in parallel with a 1000μF Tantalum capacitor. The voltage drops during the transmission at a rate of 29mA/s. This shows that most of the current is provided by the capacitor: the tag consumes 30mA = 30mC/s and this discharge rate produces a voltage-drop rate of 30mC/1000μF = 30V per second in a 1000μF capacitor (the 3% error is likely to be a combination of quantization error in the oscilloscope and/or variation in the capacitance). Once the transmission ends, the capacitor is charged through the internal resistance of the battery.

The no-load voltage of Lithium coin cells is about 2.9V, so we could size the capacitor so that the voltage drop is 1V if the tag works down to 1.8V (or 0.7V if it works only down to 2.2V, etc.). For a tag that transmits 8ms pulses at 30mA, the capacitor needs to satisfy

$$1 \geq 8\text{ms}\frac{dV}{dt} = 8\text{ms}\frac{dQ}{dt}\frac{1}{C} = 8\text{ms}\frac{I}{C} = 8\text{ms}\frac{30\text{mA}}{C}$$

or $C \geq 240\mu$F. For 8ms 85mA pulses, the capacitance needs to be at least 680μF. The nominal capacitance of the reservoir capacitor needs to be higher than these figures, to allow for capacitance variations.

The main disadvantages of reservoir capacitors are their added weight and size and the fact that their leakage current drains the batteries even when the tag is in active. The cost of high-quality reservoir capacitors is not high but not negligible either.

[2] http://ewtbattery.com

The leakage current of high-capacitance capacitors is significant and it can have a significant impact on tag life spans, especially if tags are stored for long periods between battery attachment and actual use. Tantalum capacitors like the ones that we use leak at a maximum rate of $0.01CV$ or 0.5μA (whichever is higher) at 20°C. Leakage current increases with temperature: at 85°C, the bound is $0.1CV$ or 5μA. If we assume $0.02CV$ or 1μA at typical tag temperatures (say between 30 and 40°C) and no-load battery voltage of 2.9V, our 1000μF capacitor leaks at a rate of about 58μA. A 330μF capacitor that is more appropriate for an 8ms 30mA tag leaks at 19μA. This leakage current discharges half the energy of a 1.8g 130mAh CR1632 battery in about 20 weeks, and half the energy of an 0.8g 48mAh CR1225 battery in about 7 weeks.

The weight and size of reservoir capacitors is also significant, although the weight still allows production of tags weighing about 2g. The 1000μF 6.3V capacitor that we used in the tag whose behavior is shown in Figure 5 (right) weighs 0.36g and its dimensions are $7.2 \times 6 \times 2$mm. We also weighed a 680μF 6.3V capacitor from the same series; it is thinner but higher ($7.2 \times 4.3 \times 2.8$mm) and it weight more, 0.46g. Choosing a lower capacitance unit does tend to reduce size and weight, but this is not always the case, even within the same series. The size of 330μF 6.3V units from this series is $7.2 \times 6 \times 1.2$mm, not much smaller either.

However, the same manufacturer (AVX) also makes and 330μF 6.3V with a higher equivalent series resistance (ESR) of 600mΩ (F950J337KBAAQ2), which still function very well as reservoir capacitors on these tags. They are much smaller at $3.5 \times 2.8 \times 1.8$mm and much lighter at 0.066g.

The price of the smallest capacitors mentioned in this section (330μF 6.3V with ESR of 600mΩ) is \$0.70 in large quantities and about \$2.5 in small quantities. The other capacitors mentioned have lower ESR and are more expensive, about \$2 in large quantities and about \$3.5 to \$4.5 in small quantities.

6 Discussion and Conclusions

Through extensive experimentation using both actual wildlife tracking tags and a custom synthetic battery load we have evaluated viable battery options for high-power tags and identified the best ones. We performed experiments with both real transmitting tags and in a special synthetic-load circuit. The synthetic load circuit allows us to easily evaluate batteries under a variety of conditions.

Zinc-air cells offer the best energy density and even the lightest cells can power 10mW tags during 5ms transmissions without a reservoir capacitor. These cells appear ideal for very light weight tags that are used over short periods. Use over longer periods of months is not possible with zinc air because they self discharge. Blockage of the cells' air holes by water is also a serious issue; some progress has been reported on this issue using PTFE membranes, but it is not yet clear how to use these membranes in wildlife tags.

Lithium coin cells are also appropriate for this class of tags. They are not as dense as zinc-air cells. Without a reservoir capacitor, the increasing internal resistance of small lithium cells causes high-current tags to fail when the battery still stores significant energy. Reservoir capacitors allow tags to use almost all the energy stored in a battery, but their leakage shortens tag life spans to a few weeks to a few months. Without a reservoir capacitor, tags powered by lithium cells can function for years.

We deployed both lithium coin cells and zinc-air batteries in the field. Deploying lithium cells has been easy, because they are available with soldering tabs, because lightweight retainers are available for cells without tabs, and because they can be sealed in epoxy. Deploying zinc-air cells has proved much more challenging; our attempts were based on attaching them to tags with silver-based conductive epoxy, but the process is cumbersome and prone to failures (electrical disconnects, shorts, and blocking of the air holes).

Lithium polymer cells can power tags, but their voltage is too high to power tags directly, they need to be charged close to deployment, and they self discharge in a few months.

Small silver oxide cells cannot power high-current tags directly, but they should be usable with a reservoir capacitor. Large silver oxide cells can power tags without a reservoir capacitor, but their internal resistance causes tags to fail when the battery still stores significant energy.

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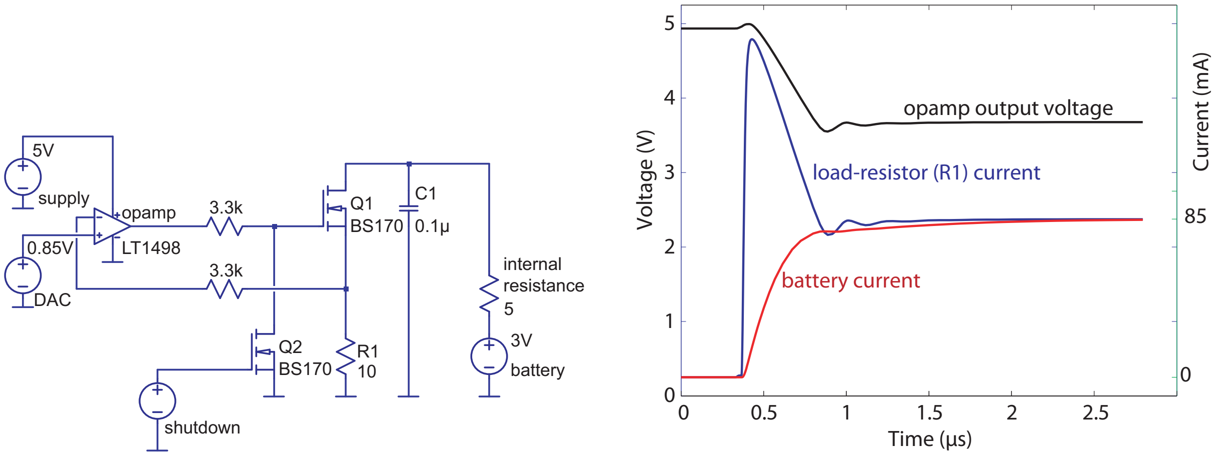

Figure 7: The programmable current sink with shutdown capability that we use to simulate the load that a telemetry tag places on a battery (left) and a A SPICE simulation of the start of a load pulse in this circuit (right).

Appendix: A Logging Programmable Constant-Current Sink

We designed and built an instrument to carry out testing of batteries for tags. The main part of the circuit is shown in Figure 7 on the left. An opamp, MOSFET (Q1) and three resistors (R1, 2, 3) form a constant current sink. The amount of current sunk is determined by the voltage on the non-inverting input of the opamp, which is driven by a digital-to-analog converter (DAC). The opamp-MOSFET subcircuit stabilizes when the voltage across R1 is equal to the DAC's voltage. Since the voltage drop across R1 is exactly equal to the current drawn from the battery, the DAC controls the current sunk into the circuit.

The MOSFET Q2, controlled by a digital output of a microcontroller, shuts down the current source when the shutdown voltage at its gate is high. This grounds the gate of Q2, effectively disconnecting the battery from R1. The capacitor C1 models decoupling capacitors that virtually any tag contains. It eliminates or reduces high current-drain spikes when the current-source turns on, much like it would in a real tag.

To fully understand this issue, consider a spice simulation of the circuit in Figure 7. The graphs on the right in the figure show what happens when the shutdown voltage is released, or dropped from 3.3V to zero.We see that the current in R1 rises well above the 85mA specified by DAC's voltage, 0.85V. This happens because as long as Q2 conducts (the current-sink is in shutdown state), the opamp feedback loop is open. This causes its output to swing all the way up or all the way down. In the simulation, and also in most cases in practice, it swings all the way up, because the voltage across R1 is very close to zero, usually closer than the DAC's voltage, which is usually a fraction of a volt above zero even if we program the DAC to output 0V. If the opamp output is high, it needs to go down to the steady-state closed-loop value, but before it reaches there, it turns Q1 on hard, which allows more current than intended to flow through R1. However, as the figure shows, the current in the battery (measured across the 5Ω resistor that models its internal resistor) rises monotonically and gradually towards 85mA; it does not show a spike. This happens thanks to the decoupling capacitor C1; the RC constant of C1 and the internal resistance is high enough that the spike is filtered and does not reach the battery.

The details of this transient spike depend on the details of the circuit, and in some cases it might cause a current spike to appear at the battery. The factors that affect the details of the spike are the bandwidth of the opamp (how fast it settles once the feedback loop is closed), how fast Q2 turns off, how fast Q1 turns on, and on the relationship between C1 and the battery's internal resistance. However, with the components selected, the spike is short enough that we do not need to worry about it affecting the battery's energy delivery (in the simulation, the spike lasts about 1μs whereas the total pulse length is 5ms).

Figure 8 show this spike in a real circuit as opposed to a simulation. We see a current spike in R1, but as predicted it lasts much less than 10μs; all or most of that current almost certainly was supplied by C1.

The current source is controlled by a microcontroller that sets the DAC voltage, controls the shutdown signal, and measures the voltage across R1 and across the battery. The microcontroller is connected to a PC using a USB-to-serial bridge. The PC specifies the frequency, duration, and current of pulses for the microcontroller, and the voltage threshold under which the experiment needs to be terminated (mainly to prevent rechargeable batteries from discharging completely). The the microcontroller places the requested load on the battery and reports back in each cycle the maximum battery voltage during shutdown periods (the open-circuit battery voltage), the minimum battery voltage during high-current pulses, and the maximum current during pulses. The battery voltage is measured using a second opamp in a voltage follower configuration and a voltage divider at the output of the

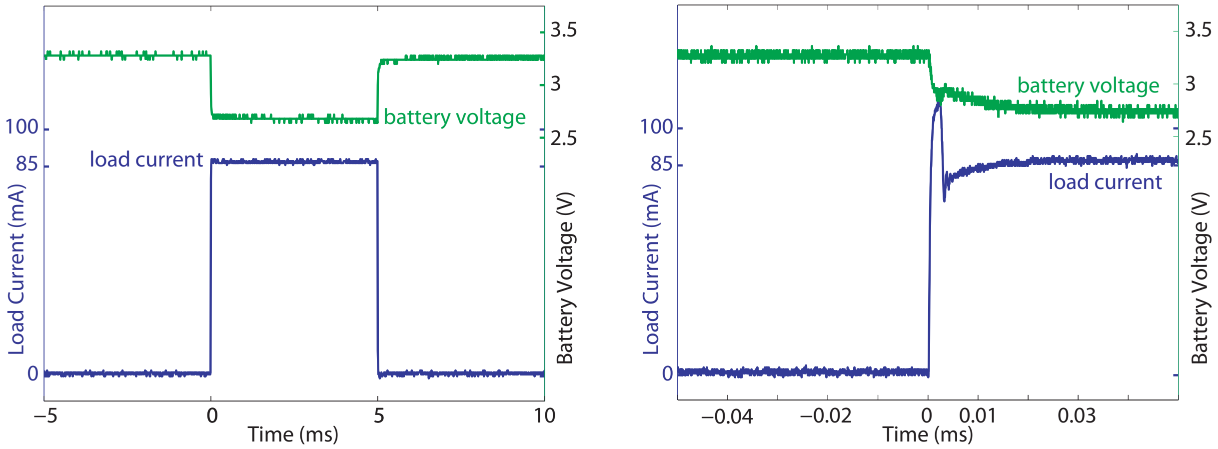

Figure 8: Current consumption and battery voltage during an 85mA 5ms load drawn by our current sink from a generic Lithium CR2032 battery. The graphs on the left show the entire 5ms pulse, whereas the graphs on the right zoom in on the first 50μs or so.

opamp, allowing a 3.3V microcontroller to measure voltages up to at least 4.2V, the voltage of a fully-charged lipo battery. The input impedance of the opamp follower is very high; it draws essentially no current from the battery.