A Small and Lightweight Ultra-Low Power GSM Cell Tracker

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***Abstract*— In this publication a logger is introduced that is small and lightweight enough to be carried by bats. It tracks the GSM downlink spectrum, enabling coarse localization. The logger contains a Sub-GHz transceiver, a microcontroller and a DC/DC converter assembled on a flexible printed circuit board (PCB) that is directly mounted on a lithium coin cell battery. The total weight is approximately 2.1 g and the size is comparable to two stacked 1 Euro Cent coins after coating the logger with epoxy resin. A flexible nickel titanium wire antenna is used for receiving GSM signals and for transmitting in the European 868 MHz short-range devices (SRD) band. In a short-term field test the functionality was proven.**

I. Introduction

Tracking the migration of bats over a long time is an unresolved topic both in biological and engineering sciences. To this day aluminum bands are attached to the wrists of bats containing a logged number. Researchers re-catch bats randomly and log the numbers into an online platform enabling the drawing of conclusions about their activities and ranges. That way it was revealed that some bat species in Europe migrate between summer and winter habitats, sometimes up to 1000 km apart [1]. There is no deeper knowledge about the migration route and influencing factors like weather, wind and temperatures, due to the lack of long-term loggers. The most crucial point is the limited resource of energy. Since bats are mainly active during nighttime and hide during daytime photovoltaics can not be used as an energy source. Other energy harvesting methods cannot be applied due to weight and volume constraints. The logger's total mass must be below 10 % of the animal's body weight (typically 20. . . 35 g) and the form factor should not exceed the size of two stacked 1 Euro Cent coins. These constraints solely leaves a coin cell battery as the only energy source.

GNSS solutions consume too much energy and cannot be considered for long-term loggers. Especially cold starts require a long active time of several seconds to obtain a fix [2].

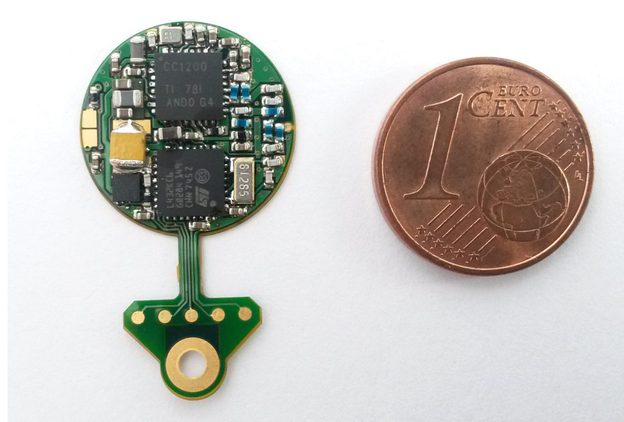

Fig. 1. Assembled PCB in comparison to a 1 Euro Cent coin. The flag gets folded around the battery for connecting the plus pole.

II. Concept

A. Localization

Since it is not necessary to localize migrating bats with an accuracy of a few meters, a much more energy efficient approach is chosen: The logger scans the E-GSM-900 downlink band for base stations, decodes their broadcast channels and saves the distinct cell IDs. For a reconstruction of the route, the animal needs to be re-caught in order to obtain the logger and read out its memory. By consulting a database of GSM base station sites, the migration route can be calculated offline on a PC.

B. Components

The system consists of commercially available parts that amount to approximately 20$ at a quantity of 50:

A CC1200 Sub-GHz transceiver by Texas Instruments was chosen for the RF part. It is respectively reprogrammed for a setting for receiving GSM broadcast channels between 925 and 960 MHz [3] and a packet based communication with our base station on 868.7 MHz. The transceiver derives its frequency from a 40 MHz crystal.

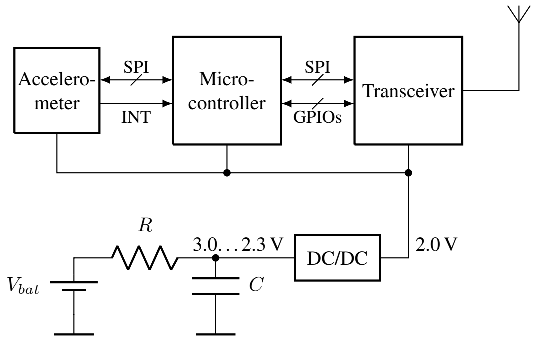

Fig. 2. Block diagram of the voltage supply and interconnections.

A potential frequency offset is calibrated by determining the frequency correction channel (FCCH) of the strongest GSM base station.

The microcontroller is a STM32L432 with Cortex M4 architecture. It both initializes the transceiver for the respective modes, and performs extensive signal processing when decoding the GSM protocol [4]. All measurements are saved in its on-board flash memory. In the linker script the flash was divided into 32 kByte for the program code and 224 kByte for measurement data. For having a time stamp for each measurement a real-time clock (RTC) is active at all times. The initial time and date are set via radio by our base station just after the system was started.

During standby mode the content of the RAM is lost. In order to contain certain variables the SRAM2 content retention was enabled.

The microcontroller is clocked by a low speed external (LSE) crystal conditioning an internal RC oscillator with a phase locked loop (PLL). As the GSM protocol requires a high temporal accuracy, a 32.768 kHz crystal with 5 ppm was chosen.

For reducing the current drawn from the 3 V lithium battery, a DC/DC converter to 2.0 V is applied. A tantal capacitor buffers the voltage during the active phase and is slowly recharged during inactivity.

Furthermore, an accelerometer is included on the logger, but not used yet. For further operations the so far fixed measurement rate of 30 minutes will be made adaptive, depending on the animal's physical activity.

C. Energy management

During TX the transceiver draws approximately 36 mA and 23 mA in RX, all at 2.0 V. The microcontroller consumes about 11 mA during full operation at 80 MHz. While transmitting, the microcontroller can be operated in a low-power mode; only during receiving GSM signals the full clock rate is needed for real-time signal processing. Therefore, the maximum current amounts to approximately 36 mA in TX.

TABLE I
MEASURED STANDBY CURRENT AT 3.0 V

component	**current**
CC1200 (powerdown)	0.0 µA
STM32L432 (standby with RTC, LSE and SRAM2)	0.6 µA
DC/DC	0.4 µA
tantal leakage current	0.5 µA
total	1.5 µA

The total capacity of lithium coin cell batteries decreases when drawing high peak currents [5]. Hence, the tantal capacitor buffers current peaks and is designed to enable 10 ms of activity after 1 s of inactivity and recharging. This limitation implicates that operations are either short enough or need to be fragmented into multiple shorter tasks with corresponding pauses in between.

With a low duty cycle between activity and inactivity, low power modes during sleep are obligatory in order to obtain a long run-time. Especially the SPI and GPIO interconnections between the devices are critical and require careful setting, since currents over pull-up and pull-down resistors needed to be avoided.

The current consumption of all devices was measured at room temperature on a test PCB with jumpers in series of every chip and is shown in table I. A non-negligible contribution is the tantal's leakage current with 0.5 µA. The total standby current amounts to 1.5 µA with wake-up capability either from timed alarms or accelerometer interrupts.

D. Spectrum analyzer

GSM base stations can be found by scanning the downlink spectrum and finding channels with constant power, since empty timeslots are filled with dummy bursts in case. Traffic channels, however, vary over time since it is very unlikely that all time-slots are used at all times. The CC1200 provides access to a RSSI register that can be read out continuously. By changing the frequency in between, a spectrum analyzer can be implemented. One complete band scan between 925 and 960 MHz took 125 ms. For suppressing traffic channels, the band is scanned three times applying a minimum hold function.

The energy for one spectrum scan can be estimated:

$$E = 2\,\mathrm{V} \cdot (23\,\mathrm{mA} + 11\,\mathrm{mA}) \cdot 125\,\mathrm{ms} \cdot 3 = 25.5\,\mathrm{mJ} \quad (1)$$

Due to the maximum active time constraint, the spectrum scan is cut into 27 operations, requiring 27 seconds. Since writing the flash takes several microseconds, after another second of recharge time is required. The message starts with a magic number followed by the length in double words (64 bit), since the flash can only be accessed in double words.

III. Hardware Design

The printed circuit board (PCB) was designed to have a round shape with a diameter of 16 mm (see fig. 1). It can be directly placed on top of a CR1620 lithium battery. For saving weight and height, the PCB was fabricated on a dual layer flexible polyimide substrate. All components are placed on one side only, so the back side can be directly connected conductively to the minus pole of the battery. Therefore, the coin cell also provides mechanical stability to the circuit. The plus pole is connected by a foldable flag that is also used for programming and debugging and gives access to the single wire debug (SWD) interface of the microcontroller. Those pins can be accessed by a series of five spring loaded pins in a fixture.

For receiving the E-GSM-900 downlink band between 925…960 MHz and communicating with our base station in the 868 MHz SRD band, a simple $\lambda/4$ nickel titanium wire antenna with a length of 8 cm was chosen. The material is superelastic and does not deform when the animal rubs against objects. For a steady mechanical and electrical connection to the PCB the end of the wire was bent into a hook shape and put through a via. A discrete matching network between transceiver and antenna was designed for the respective frequency bands.

The whole circuit was molded in black epoxy resin for protecting the electronic components from rain, excrement and mechanical damage, also rounding sharp corners. The circuit can be started right before attachment on the bats in order to have zero current drain beforehand. Therefore, a pad on the top side was left uncoated from epoxy resin and connected by soldering in the field. I a future design the starter pad will be placed on the foldable flag, since the assembled side lies on the skin of the bat.

A CR1620 lithium battery was chosen for the best trade-off between volume, weight and capacity and contributes most to the total weight. All electronic parts, the antenna and the PCB contribute less than 25% to the total mass. The molding in epoxy resin was done by hand and the added mass slightly differs between the loggers. In total the limit of 2.0 g was slightly exceeded and further weight saving is necessary for future long-term applications on migrating bats.

TABLE II
Listing of components' masses

component	**abs. mass**	**rel. mass**
CR1620 battery	1.32 g	62.9%
electronic parts	0.31 g	14.7%
epoxy resin	~0.3 g	14.0%
PCB	0.15 g	7.1%
antenna	0.03 g	1.3%
total	2.1 g	100%

IV. Field test

The logger in this publication was programmed for a short-term field test for proving the concept of an ultra-low power GSM cell tracker for a future long-term deployment in 2019. For debugging and fast feedback a communication with our base station in the 868 MHz short-range devices (SRD) band was implemented. Every 30 minutes a cell scan was performed and the raw spectrum data was saved in the flash memory.

For a proof of concept a three-day field test was conducted in July 2018 near Bonn, Germany. 19 bats of the species *Myotis myotis* were equipped with loggers by glue on their back (see fig. 3). The bats were caught by hand from a bat roost in a certain attic. The individuals were chosen in respect to their condition and weight in order to keep their stress level low. All bats were registered and treated professionally by biologists.

Fig. 3. Bat with attached logger. (photo: A. Brinkhoff)

After several days the loggers were removed or found on the floor in the attic and the collected data was read out. Due to a programming error in the flash routine only 149 measurements were saved in the memory, resulting in 74.5 hours or 3.1 days of acquired data. The detached loggers operated further for three to four weeks and were accessible via our 868 MHz base station.

Figure 4 shows the acquired spectrum over time of logger ID 9, where the channel number N corresponds to a channel center frequency f with the relation:

$$f = 925.2\,\mathrm{MHz} + N \cdot 200\,\mathrm{kHz} \tag{2}$$

Channel 75 contains an interference that is constant over time and makes this channel unusable. From the spectrum of logger 9 the animal's activity can be derived: The bat left at approximately 23:30 and returned home at 03:30. Those times correlate well with the astronomical twilight in July near Bonn, Germany. During daytime the base stations on channels 30, 48, 56, 89, 101, 116 and 132 stay constant. This implicates that the individual always returned to the same attic.

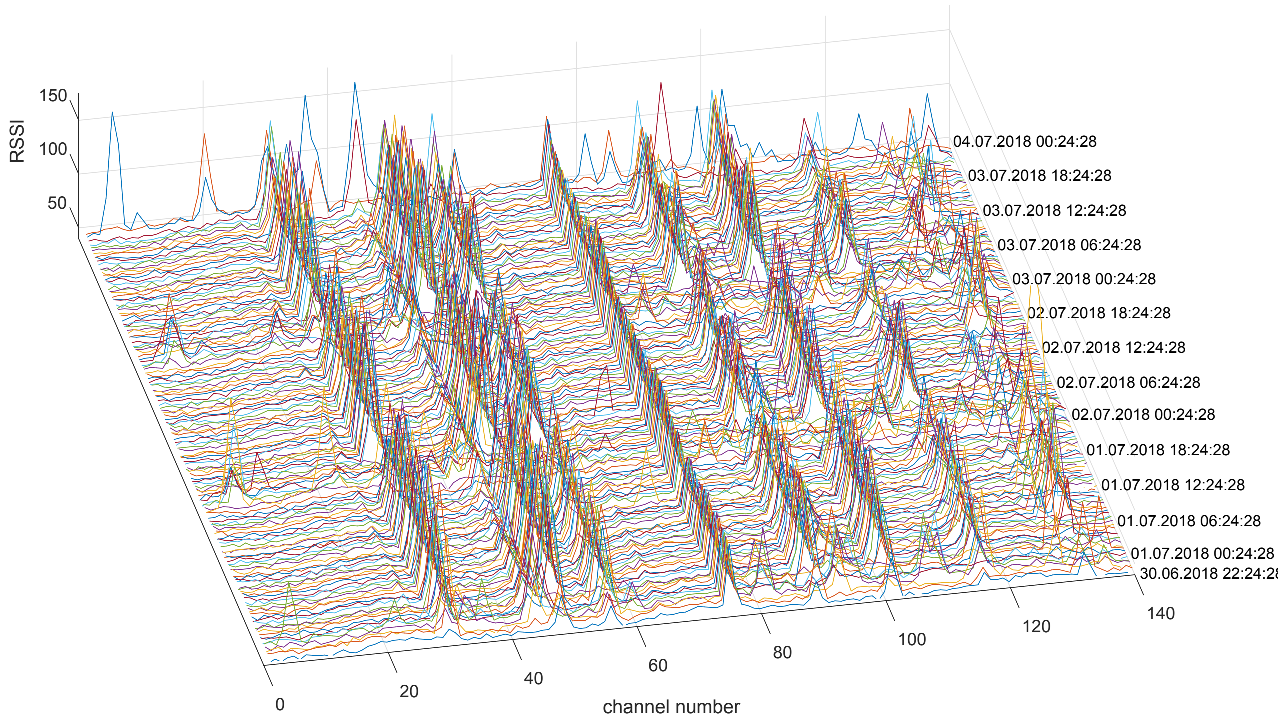

Fig. 4. Scanned spectrum over three days of logger ID 9. All times are CEST.

For this field test the exact positions of the received GSM base stations were unknown and thus no geographic coordinates and detailed movement profiles could be reconstructed. Due to the sparsely populated and hilly test area, the measurements are plausible. For the long-term application those channels with spectral peaks have to be received individually and the respective cell-IDs need to be decoded.

V. Conclusion

In this publication an ultra-low power airborne GSM tracker carried by bats was demonstrated. During a short-term field test the loggers additionally transmitted debug messages to a 868 MHz base station. The run-time was three to four weeks, whereas the field test already ended after three days. From the recorded data the animal's activity could be derived. It was shown that the system is suited for future long-term deployments with minor changes.

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