Multi-Year GPS Tracking Using a Coin Cell*

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ABSTRACT

We present a small, light and low-power GPS tracking device. Powered by a coin cell, the novel receiver design enables a tracking lifetime of two years with quarter-hourly position recordings. A snapshot receiver design is employed which allows for arbitrarily adjustable duty cycles. Offloading data processing into the cloud reduces the hardware complexity and the energy consumption of the receiver. Compared to conventional GPS trackers, our design minimizes the tracker's cost, size and weight, which enables new applications. Our prototype implementation weighs 1.3 grams, has a size of 23mm × 14mm and highlights an operating time of 683 days with quarter-hourly positioning when powered by a coin cell.

CCS CONCEPTS

• **Information systems → Global positioning systems**;
• **Hardware → Sensor devices and platforms**;

KEYWORDS

coin cell, Coarse-Time Navigation, Collective Detection, computation offloading, GNSS, hardware, implementation, low power, millisecond, snapshot

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1 INTRODUCTION

Global localization is a driver for so many applications that it is often considered to be a key technology of our time. However, all GPS receivers today have a high energy consumption. Mobile phones and smart watches can run days or even weeks on a single battery charge, but with GPS enabled, they barely make it through a single day. While personal devices such as smartphones can be recharged regularly, GPS trackers cannot.

Applications for GPS tracking include animal tracking, both wildlife and domestic animals. In addition, one may like to track personal items such as wallets or keys. More generally, we believe that the availability of a low energy GPS receiver will open up a unforeseen number of surprising applications, in tracking and beyond. Many of these applications also need a small footprint in terms of size and weight.

Current commercial GPS receivers include a lot of signal processing hardware, mostly so-called correlators, which are used to find and track satellite signals. These correlators collectively consume much power and the hardware is active continuously, because receivers constantly decode timing and satellite orbit information from the satellite signals.

In this paper, we present a novel GPS tracker hardware design. Our design is a snapshot GPS receiver which captures only a few milliseconds of satellite signals for each position computation. The active time of snapshot receivers for a single position request is three orders of magnitude lower than that of conventional receivers. The latter require about six or even 30 seconds of data at startup, depending on available prior satellite orbit information. Snapshot receivers can be designed either with a storage or a wireless communication component. We choose the first option, as it consumes less power and space. Loggers such as our device can be used for applications which do not need real-time positioning, like wildlife tracking, collecting workout statistics or geotagging photographs.

Besides the hardware design, we present a corresponding prototype implementation using a suitable selection of components. An evaluation of the actual energy consumption shows that such a tracker, powered from a single coin cell, is not limited by the energy consumption, but rather by the size of the storage for the recorded signals. The used 2 Gb flash storage can hold 65600 signal snapshots of one millisecond length. This corresponds to a lifetime of 683 days with quarter-hourly positioning. Our prototype GPS tracker weighs a mere 1.3 grams and its dimensions are 23 x 14 mm. This makes it suitable for weight-constrained applications like bird tracking and enables it to be concealed for instance in valuable belongings like wallets, handbags or bicycles.

1.1 Related Work

Commercially, no GPS hardware is available to implement snapshot receivers. One way to test snapshot GPS is to use a *software defined radio (SDR)*. SDRs are relatively large, heavy and consume orders of magnitude more power than a dedicated GPS receiver. Therefore, SDRs are most useful for static testing, but not for mobile scenarios. The same holds for the only alternative, which is using a *SiGe GN3S*[1] USB GPS sampling dongle together with a laptop. This is a problem for the GPS tracking research community, because snapshot receiver algorithms cannot be tested in their intended application environment. So far, mostly simulations or data cut out from longer recorded signal sequences have been used to show the performance of these methods [1, 2, 6].

In research, snapshot GPS receivers are known for several years [1, 2, 6]. They drastically reduce the power consumption of a GPS receiver, because signal processing can be offloaded to a web service [6]. This simplifies the hardware design and moves the most energy consuming part of the receiver into the cloud. However, most proposals focus on the software of such a receiver. While Liu et al. [6] propose a snapshot receiver hardware design, their first version used additional, large hardware for time synchronization. We use the same MAX2769 GPS front-end chip. However, our prototype implementation is almost 12 times smaller than Liu et al.'s second version, *CLEON*, that drops the time synchronization hardware. Also, our hardware draws a standby power of 4.5 µA instead of 2.5 mA [6], effectively increasing its lifetime for long duty cycles by a factor of 500. And our receiver's active power during a signal capture is reduced by a factor of 100, from 62 mJ [6] to 0.74 mJ, while capturing only 10 times less data, namely one millisecond instead of 10, and while improving the localization accuracy.

1.2 Applications

We give two example applications which can directly benefit from the availability of snapshot GPS receivers and do not require real-time positioning. One has to keep in mind that due to the drastic improvements in size, weight and power consumption, snapshot receivers may spark a variety of unexpected applications.

Bird Tracking. Ornithologists use tracking devices to study bird behavior. Large birds like geese or birds of prey can be equipped with traditional GPS tracking devices. Due to weight constraints, batteries can only be small and will thus last for a short time only, limiting the usefulness of such trackers. Small songbirds can only carry additional weights of less than two grams [3], which is not enough for a conventional GPS receiver and a battery. A current technique is to equip such small birds with small and low-power light-level sensors and a real-time clock. Reading the light levels and matching them with timestamps from the clock allows determining the length of the day at a bird's location and thus determining its latitude approximately. Errors are on the order of 200 km or more [3]. This allows for a limited set of studies like observing approximate migratory bird movements and their timing. Our receiver, which weighs 1.3 grams only, fits into the weight budget for equipping such small birds with GPS, while providing several months long observation times. Due to our receiver's accuracy in the range of tens of meters (see Section 4.3), our hardware enables more detailed studies on bird behavior.

Holiday Logging. Many travelers like to tag their holiday photographs with the location where those were taken. Due to the high energy consumption and the multi-second latency from activating a receiver to getting the first position estimate, many cameras do not include a GPS receiver. Therefore, some people buy stand-alone GPS trackers which run a day or two on a single charge and whose computed positions can be combined with the holiday pictures afterwards on a computer. Our receiver eliminates recharging. After initial setup, our tracker can be forgotten about, even for a world tour! In the end, one can extract all positions with 15 minute resolution and has a log of the complete holiday journey.

Summarizing, our work lays the foundation for inexpensive, accurate and low-power GPS localization. It enables a new range of objects and animals to be equipped with global localization.

2 HARDWARE DESIGN

A snapshot GPS receiver samples a few milliseconds of GPS signal and stores or transmits this data for computing the receiver position from it. *Raw* data is needed, meaning I/Q or real samples of the signal and not processed data that commercial GPS chips provide.

The goals of our snapshot receiver design are:

- Capture raw GPS signal samples
- Store them on the device
- Keep track of the current time
- Allow simple configuration and data transfer
- While consuming minimum power

Our design addresses all of these goals and allows for large duty cycles with minimum sleep power.

[1]The product is not available any more: https://www.sparkfun.com/products/retired/10981

Table 1: List of all commercial GPS front-end chips that we found through an extensive search (web, books, emails, phone calls). The following abbreviations are used to denote the different GNSS systems. US: GPS, R: GLONASS, E: Galileo, C: BeiDou.

Manufacturer	Model	GNSS	Sampling rate	Sample format	Max. power	Min. quantity	Price
Analog Devices	ADSST-GPSRF01	US	max. 32 MHz	2 bit real	195 mW	unavailable?	on request
IMST	[unnamed]	US/E	*unknown*	2 bit real	*unknown*	unavailable	*unknown*
Maxim	MAX2769	US/R/E	max. 50 MHz	2 bit I/Q or 3 bit real	62.7 mW	2500?	on request
Maxim	MAX2769B	US/R/E/C	max. 50 MHz	2 bit I/Q or 3 bit real	88.4 mW	2500?	on request
Navika	AST-GPSRF	US/E	16.368 MHz	2 bit real	> 48.9 mW	discontinued	*unknown*
NTLab	NT1065	US,R,E,C	≥ 99.231 MHz	4 x 2 bit real	> 306 mW	*unknown*	*unknown*
SAPHYRION	SM1027U	US/R/E/C	50 MHz	3 bit I/Q	≥ 76.9 mW	*unknown*	*unknown*
SiGe	SE4110L	US	max. 19.5 MHz	2 bit real	> 28.4 mW	1	$ 3.59
Skyworks	SE4150L	US	16.368 MHz	2 bit real	59.4 mW	1	$ 3.20
STA	STA5620	US	16.368 MHz	2 bit real	51.3 mW	221 (obsolete)	$ 4.78
STA	STA5630	US/E	16.368 MHz	3 bit real	25 mW	3000	$ 1.05
Zarlink	GP2015	US	5.71 MHz?	2 bit real	254.1 mW	discontinued	*unknown*

2.1 Sampling

The frequency of the L1 GPS data modulation is 1.023 MHz. Therefore, by the Nyquist-Shannon sampling theorem, a sufficient minimum sampling rate with a single channel (*real*) receiver is 2.046 MHz and half of that for a dual channel (*I/Q*) receiver. Using a higher sampling frequency will usually yield a better quality of the received signal. But more importantly, the Galileo GNSS is also transmitting ranging signals at the L1 frequency, but with a sub-carrier rate of 6.138 MHz. Therefore, it is beneficial if a sampling rate of at least 6.138 MHz (I/Q) or 12.276 (real) is used. In our design, we settle for a real receiver and a sampling frequency of 16.368 MHz, which allows for the simultaneous reception of GPS and Galileo signals, increasing accuracy and robustness.

As seen in Table 1, most GPS front ends use 2-bit quantization levels. Using such low sampling precision degrades the signal-to-noise ratio by only 0.55 to 0.72 dB [7, Section 6.12], while the reduced data size allows capturing more snapshots with the same energy and storage space.

2.2 Component Selection

The main parts required for our hardware design are:

- GPS Front End
- Microcontroller
- Flash Storage
- Battery
- Power Converters

GPS Front End. The front end is the circuit converting the received RF signals into digital samples. Although we spent quite some time searching GPS front-end chips, there seem to be only a dozen manufacturers producing standalone chips. All the models we could find are listed in Table 1. Note that the reason for this short list is probably due to the fact that most GPS receivers in commercial products integrate the position computation and are not designed to output the raw signal samples. Even though some commercial receiver seem to offer "raw" data output, mostly only computed values like pseudoranges to all satellites or navigation data is provided, which is insufficient for our application, which requires raw GPS signal samples. For the front end we selected the Maxim MAX2769 GPS front end as it allows testing a wide range of RF, data format and filter settings. The raw GPS signals are output at 16.368 MHz with two bit precision. Both active and passive antennas can be connected. It uses less than 22 mA at 2.7 V. Unfortunately shutdown current is about 20 µA which requires the use of an external switch to not exhaust the power budget. An alternative would be the SE4150L GPS front end, which requires less external components and therefore is easier to integrate. It also has fewer necessary settings and slightly lower power consumption.

Microcontroller. The microcontroller needs to fulfill two important constraints: 1) It must read incoming samples, two bits at a time, at the designed rate of 16 MHz and 2) it should have a low standby power consumption to allow for long tracking periods with large duty cycles. During inactive times of the receiver without signal sampling, the microcontroller needs to keep track of the current time and all other receiver components can be cut off from the power source to save energy. Thus, the microcontroller's standby power consumption is one of the factors limiting the battery longevity. For our design, we select the Atmel SAM4L, as it offers a *parallel input capture interface (PARC)*, which reads up to 8 bits concurrently at a maximum rate of 24 MHz. The PARC is a perfect interface for reading the data of the GPS front end. At less than 3.1 µA, the SAM4L offers low standby power consumption with activated *real-time clock (RTC).*

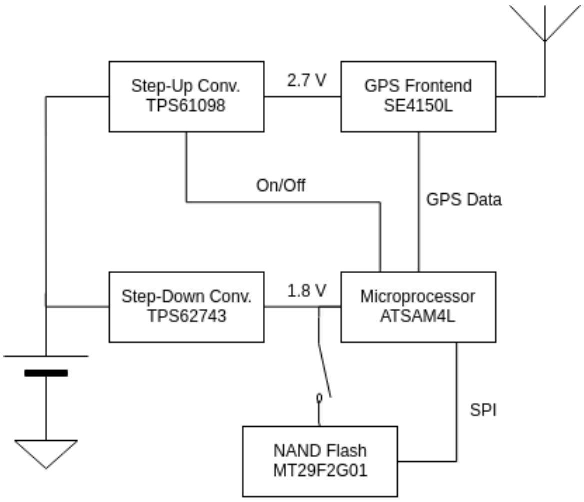

Figure 1: Overview of the components in the system.

Figure 2: Size comparison of our GPS tracking hardware with a wristwatch.

Flash Storage. The flash storage must offer big storage size while consuming little power during write operations. The NAND flash memory MT29F2G01 offers 2 Gb storage and a maximum current during data write operations of 25 mA. At our sampling rate of 16.368 MHz, the flash memory size allows collecting one GPS signal snapshot every fifteen minutes during 683 days. Combined GPS and Galileo snapshots could be captured hourly during the same time period.

Battery. Many conventional batteries are heavy (cylindrical batteries) or have significant self discharge (LiPo cells, supercapacitors), making them unsuitable for our purpose. Coin cells offer high power density, low weight and are cheap, which makes them ideal for our requirements. We use the CR2032 [4] which has a maximum usable capacity of 235 mA h. With a target runtime of 2 years, an average power consumption of 26 µA cannot be exceeded. Accounting for battery degradation, the power consumption has to be restricted to significantly lower values. Real-world evaluations of coin cells [5] show that high peak currents or qualitatively low coin cells often only offer half their rated capacity. To ensure stable operation and account for temperature, coin cell quality and high peak currents, the average power consumption should remain around 10 µA. Our average power consumption of 6 µA (cf. Section 4) is a factor 4 below the maximum of 26 µA and therefore our tracker requires only a quarter of the coin cell's capacity for a two year runtime.

Power Converter. The coin cell offers an initial voltage of 3 V which will drop to 2 V during high load or towards the end of the cell's lifetime. We use two controlled power domains. One domain with 1.8 V for the microcontroller and one domain for the GPS front end with at least 2.7 V. While it would be possible to design the entire system for 2.7 V, 1.8 V reduces the external components required for the processor and minimizes standby power consumption because an efficient step-down converter can be used. The TPS63743 step-down converter powers the 1.8 V domain and its quiescent current is only 360 nA, which allows it to be active continuously. The TPS61098 provides 2.7 V to the GPS front end even when the coin cell voltage drops.

Standby Power Consumption. Both the flash and GPS front end consume a couple of µA during shutdown. While this might be negligible in most applications, the shutdown power consumption of these chips combined will empty the coin cell in less our targeted two years lifetime. Using a controlled high-side load switch like the ADP199, the power consumption during shutdown can be reduced to below 100 nA.

As even ceramic capacitors can have leakage currents in the range of nanoamperes to hundreds of microamperes which will exceed the power budget, it is crucial to remove and minimize all capacitors wherever possible. Resistors have to be planned carefully to not waste any energy too. An alternative is to use different switched power domains, decoupled for example by the aforementioned load switch.

3 IMPLEMENTATION

An overview of the final architecture can be seen in Figure 1. The microcontroller is powered continuously by the step-down converter. To save energy, the NAND flash is connected through a load switch to the power domain of the microcontroller. The switch is controlled by the microcontroller and only enabled when the flash is necessary. Communication with the flash is performed via the *Serial Peripheral Interface (SPI)* at data rates of up to 24 Mbps. The GPS data is transferred in parallel with 16.368 MHz to the capture interface of the microcontroller, where it is first cached in RAM and then written to memory.

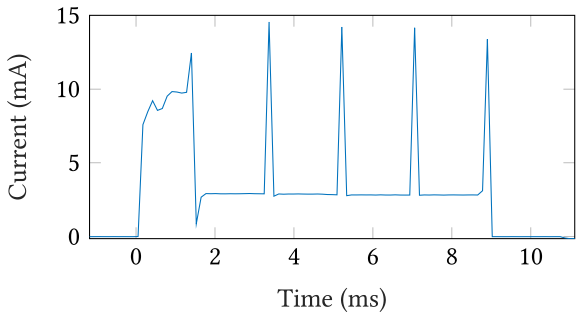

Figure 3: Current consumption of the flash device. After initialization for the first 1.7 ms, four blocks of data are transferred and written. Data writing is clearly visible as peaks in the power consumption.

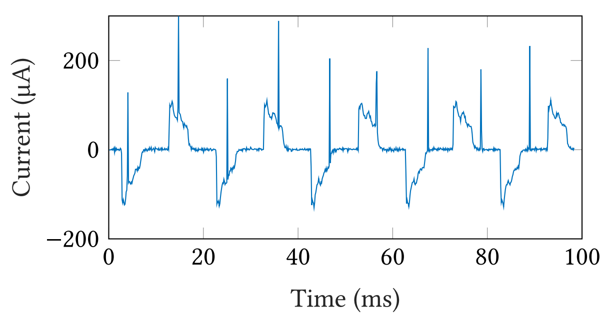

Figure 4: Total standby power consumption of the GPS tracking device. The processor is in deep-sleep mode with only the *real-time clock (RTC)* running, the step-up converter for the GPS front end disabled and the flash disconnected by the load switch. The operation of the step-down converter powering the microcontroller is visible. The average current is 3.2 µA.

3.1 PCB Design

To minimize PCB size and allow using small parts, the board is designed with four layers and a minimum design width of 100 µm. To reduce PCB cost, only vias through the whole stack are used, but no blind or buried vias. Passive components are reduced to the smallest size available, often 01005 (0.4mm × 0.2mm). The resulting board is only 23mm × 14mm big and weighs 1.3g. A size comparison with a wristwatch is shown in Figure 2. GPS front end, power management and microcontroller are mounted on the (visible) top side of the board while the flash chip and USB connector are mounted on the bottom side.

Two challenges are matching the impedance of the antenna connection and reducing the electromagnetic interference of digital signals with the RF signals. The antenna RF connector is mounted on the bottom through an impedance-controlled via buildup. The GPS front end is prepared for a shielding enclosure and RF traces are shielded by surrounding grounded vias and ground layers.

4 EVALUATION

This section gives an evaluation of the power consumption and signal reception. Power measurements are difficult to obtain due to the high dynamic range between the active and standby currents. Even attached debugging circuits can have much higher leakage currents than our device's standby power consumption. Special care was taken during the hardware development to make all debugging circuits detachable for measuring the power consumption. Furthermore, the GPS data is analyzed to verify proper operation of the receiver.

4.1 Standby Power Consumption

During standby only the microcontroller is powered. The boost converter is in low-power mode and the flash memory switched off, which should consume less than 1 µA combined. The microcontroller is powered by the TPS62743 and should consume less than 3.5 µA combined. Therefore, a total standby power consumption of under 4.5 µA can be expected which is well below our maximum power budget.

Our measurements (Figure 4) show that the current during standby varies between -125 and 300 µA over time due to the switching voltage converter powering the processor. The average power consumption measured with different devices showed values ranging from 2.9 up to 5.1 µA and is within the expected range.

4.2 Active Power Consumption

The active time can be split into multiple parts. After wakeup, the processor initializes the GPS front end and starts sampling the received data through the parallel interface. Then, the GPS front end is disabled and the processor formats the data for storing it. The final step is to power up the flash memory, transfer and write the data to the flash memory. The power profile of the flash chip during this procedure is shown in Figure 3. The full process takes around 13.5 milliseconds to complete. To estimate the power consumption, the maximum values from the data sheets are used. At full speed and with the required peripherals activated, the microcontroller consumes approximately 20 mA. This does not account for low-power modes or lower clock rates that could be used to reduce power consumption. The GPS front end and crystal oscillator consume at most 25 mA. During write, the flash memory will consume at most 25 mA. Depending on the efficiency of the power converters and other peripherals, these values can vary.

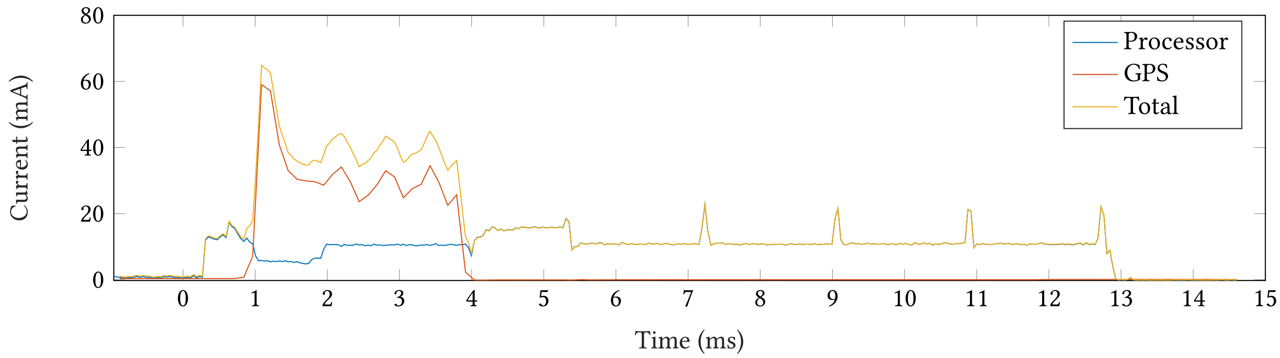

Figure 5: Active power consumption measured before the power converters by a power analyzer. The processing phases are visible. After the processor has run initial setup, the step-up converter is enabled and powers the GPS front end. After a short settling time the processor reads raw GPS data for one millisecond. Starting at 4 ms the processor prepares the data for transfer to the flash. At 5.5 ms to 13 ms the data is transferred in 4 blocks to the flash memory. The peaks in power consumption indicate when the data is written. After the last write has finished, the processor disables all peripherals and returns to sleep mode.

Our measurements (Figure 5) reveal that the power consumption of the flash and microcontroller are in the expected range, while the power consumption of the GPS front end is higher than expected, leading to an initial peak power of 60 mA. This probably originates from the initial charging of the stabilizing capacitors and setup of the GPS front end.

The average power consumption for the 13.5 ms active time is 18.3 mA. Our initial example of storing one GPS signal snapshot per hour corresponds to a duty cycle of $13.5\ \text{ms}/3600\ \text{s} = 3.75\text{e}{-6}$. The contribution of the power during the active time to the average power consumption is $18.3 * 3.75\text{e}{-6} = 68.6$ nA. In case of snapshots every 15 minutes, the contribution increases to 274.4 nA. Both values are negligible compared to the standby current.

4.3 GPS Data Analysis

In a field test, our receiver is positioned on top of a university building. The recorded snapshots with one millisecond of data are evaluated with a branch-and-bound Collective Detection implementation [2]. *All* calculated positions are within 25 meters to the true receiver position. Although we did not do an extensive evaluation of the positioning accuracy, this is an encouraging preliminary finding. In comparison, Liu et al. evaluated the snapshot positioning accuracy with a GPS sampling dongle instead of their presented snapshot receiver and used 10 milliseconds of data instead of one. Still, they achieved less than 25 m error only in about 80 % of all cases and observed a maximum positioning error of 725 m [6]. Our result therefore seems to confirm that Collective Detection improves positioning robustness [2].

5 CONCLUSION

Our hardware design, implementation and evaluation show that low-power GPS receivers which offload the position computation to the cloud are a viable concept. Our receiver periodically takes snapshots of GPS signals and stores them locally. The mean power consumption of the device is under 18 µW, allowing our receiver to run for two years on a single coin cell. This enables new applications that were impossible to date. Our design exhibits a thousandfold improvement in standby power consumption and a hundredfold improvement in active power consumption over previous work.

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