Implantable Wireless Ultra-low Power Data Logger for Temperature Measurements in Animal Brains

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Abstract

This paper reports on the development of an implantable, microcontroller based, ultra-low power data logger for temperature gradient measurements in animal brains. In contrast to commercially available systems the device uses a wireless interface allowing the readout and reprogramming of the data logger after the implantation. To ensure low power consumption, a wake-up receiver is integrated in the system, aside a dedicated power management system, reducing the power consumption to 43 µW at one temperature sample/min/channel.

1 Introduction

The fundamental principle of a data logger is recording and storage of measurement values from any kind of sensor, with a specific sampling rate and over a longer period of time. Typically, the data logger is placed at the sensor's operation site, i.e. at the place where the data are acquired, left in an autonomous operation mode, and data are read out after the measurement task is completed. This approach implies a lot of limitations in comparison to a sensor connected to a remote data acquisition system: The sample rate is fixed and a readout of data, e.g. for a plausibility check during the measurement, is not possible, and also an interruption of a measurement in favor of dynamically reprogramming sampling rate or runtime may not be feasible, while the system is in operation with a running task. In most of the applications this is not a real issue because the data logger is accessible all the time to change parameters or make a real-time plausibility check. Also, a retrieval of data can be made in multiple forms, e.g. via the exchange of memory cards or through a wired connection to the data logger. The same accounts for the power supply, which can be in form of exchangeable batteries or by connection to a power grid.

However, these aspects come into effect, if the data logger is not easily accessible, as for example after a medical implantation. In these cases, only a wireless data transfer is possible, and the power supply of the data logger and its wireless interface has to be done via batteries in the implant. In any case, this calls for a low power consumption to ensure a sufficient runtime and/or programming flexibility of the implant.

To address these challenges, a data logger with a wireless interface, specifically tailored for operation as an implant, has been developed in this study. To ensure low power consumption, respectively a long operational lifetime of the data logger, the wireless interface for data readout is turned on and off remotely by an integrated ultra low-power wake-up receiver. Another unique feature of this system is the possibility to reprogram the software wirelessly from outside. This allows, e.g., for dynamic readjustments of sample rates and measurement intervals. Besides a wireless readout and reprogramming of the data logger during a measurement, it can also be set into a live mode, where it continuously measures and transmits data. This feature is very helpful during implantation because it enables an easy control of the placement of a sensor, a functionality testing, as well as a calibration of the sensors. In addition to the sole recording of measurement values, the system can also be used as a monitoring system that gives an alarm when the measured value exceeds or falls below a programmed threshold. Furthermore the system is easy to adapt for other applications like the measurement of pressure, heart rate, humidity or conductivity due to its design based on a versatile microcontroller.

2 System architecture

The architecture of the data logger is shown in the block diagram in figure 1. For the control unit a microcontroller is used, which is responsible for the power management, the digitalization of the analog sensor output, the storage of the measurement values, as well as the handling of wireless communication.

The data logger is designed for implantation into an animal, therefore a wired programming and readout is not possible for reasons of animal health. One possible solution would be the usage of the data logger IC MLX90120 from *Melexis,* which uses a Near Field Communication (NFC) interface for data and power transmission. However, ethical and experimental reasons may speak against an approachment of the animal with a NFC reader, which has to be placed into close proximity of the implant, enforcing, virtually, subcutaneous implantation. Therefore, it is desirable in any case to have a long-range wireless interface available.

The problem of such a long-range wireless interface is a significantly higher power consumption. One main problem of a continuous data link is that the receiver in the implant needs to remain on in a listening mode, to be able to receive commands all the time. It is possible to decrease power consumption, if the receiver is only reachable for a specific time interval every day, but this would restrict usability and flexibility. Another approach to keep power consumption at an acceptable level is the usage of a wake-up receiver, as done in this study. These receivers consume almost no power and are able to turn on the more power-hungry wireless interface when they receive a dedicated wake-up signal. After handling of the communication request the wireless interface is turned off by the microcontroller, thus reducing power consumption to a high extent.

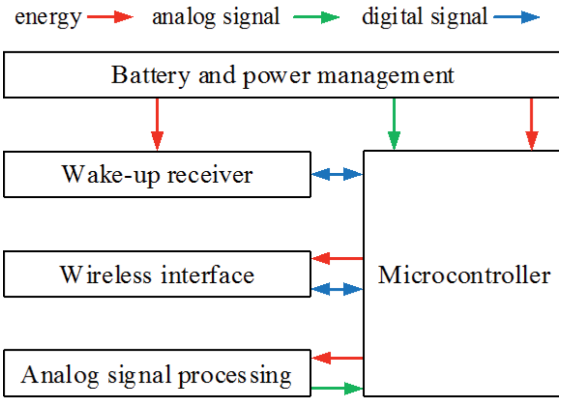

Figure 1. Block diagram of the data logger.

In the experiment planned here, the aim is to determine the temperature gradient over the skull bone of a sheep to evaluate the usage of thermoelectric generators as a power source for implants. In expectation of very small temperature differences a very precise measurement with a high resolution is required. Due to the limited space in the skull a very small sensor element is needed, therefore miniaturized platinum thermistors are suited best for the application. Attention has to be paid to the readout of the sensor. As it is placed into a body, voltages above the hydrolysis decomposition voltage of water have to be avoided, respectively may only be exceeded for a very short time, which on the other hand also helps to avoid self-heating of the sensor.

3 Circuit Design

3.1 Digital circuit and power management

The core of the system is a low power microcontroller (MSP430FR5949, *TI*) responsible for the power management, the recording and the storage of the measurement data, as well as for the communication. In active mode the power consumption is 100 µA/MHz, which can be decreased to 0.4 µA in sleep mode[1]. The microcontroller has an internal ADC (analog to digital converter) with a resolution of 12 bit.

To store an adequate number of measurement data an external memory chip is used. To ensure a low power consumption, an SRAM (23A1024, *Microchip*) with a standby current of 4 µA, controlled over the SPI-interface of the microcontroller is chosen. The memory size is 1 Mbit allowing the storage of 262 144 values per channel, which corresponds to a logging time of 72 days at a sample rate of 1 sample/min.

For the power supply a lithium battery with a capacity of 330 mAh is used. The voltage of a fully charged battery exceeds the maximum supply voltage of the microcontroller, therefore a linear voltage regulator is used to generate a stable voltage of 3.3 V. The efficiency of a linear regulator is typically worse compared to step-down converters, respectively buck-converters. On the other hand a linear regulator does not use an external coil which creates electromagnetic stray fields at a relatively high switching frequency of DC-DC converters. Experiments have shown, that these stray fields can interfere with the wake-up receiver. As this component is very sensitive by design, unintentional wake-up events of the system were triggered by the operation of the nearby DC-DC converter. Taking into account an average voltage of the battery of 3.6 V, an energy efficiency of 91 % is achieved with a low dropout regulator, comparable to the performance of a buck-converter. By choosing a voltage regulator with a very low quiescent current (STLQ015, *ST*) of only 1 µA, the losses can be limited further.

3.2 Wake-up receiver and wireless interface

The wake-up receiver is based on the low-frequency wake-up receiver ATA5283 from *ATMEL*. The main function of the IC is the regulated amplification and the demodulation of a carrier signal with a nominal frequency of 125 kHz. However, the receiver will also accept signals in a range between 30 kHz and 180 kHz. A wake-up is generated when a signal burst containing more than 704 oscillation periods is detected. After that, a digital wake-up output is set from high to low level. If desired, it is possible to transfer data over an amplitude modulated signal after the wake-up event, which are available at a data output. For this application this feature is not needed. To set the data and wake-up pin to high level again and to enable the detection of a new wake-up burst, a reset pin of the IC has to be set to a high level. A separate circuit has been designed using four Schmitt-trigger NAND gates (74LV132, *NXP*) to perform this task in an automatic way, a short period of time after the end of every detection burst, see figure 2. This autonomous reset circuit does not only allow the reset of the wake-up IC, but also a reset of the microcontroller if it is irresponsive to wake-up signals. It will also avoid that the microcontroller freezes and stays blocked in its program execution during a wake-up or during normal operation, as every wake-up that is not handled correctly leads to an automatic reset of the whole data logger. Under normal operation the microcontroller will inhibit this automatic system reset. The function of this circuit is as follows:

Under normal operation capacitor C7 is kept charged to supply voltage level. The output of IC1A is in a low state through the resistor R5, as well as the signal at the reset pin of the ATA5283. Also the output of the Schmitt trigger inverter IC2C is low, reflecting the high voltage level at C15.

When a wake-up signal is present, the ATA5283 sets its wake-up pin from high level to ground potential. Now, C7 is discharged via resistor R4, until its voltage has dropped below the logic level of the inverter IC2C, which then toggles its output to a logic one. By capacitor C8, working as a high pass filter, a short voltage pulse is formed at the reset pin of the ATA5283, thus resetting the IC and re-enabling wake-up. This voltage pulse is also present at the output of IC2A and will recharge C7 quickly through diode D2. As the wake-up pin has been set to a logic one by the ATA5283, as a reaction to the positive pulse at its reset pin, the system is in a stable logic condition again, and prepared for the occurrence of the next wake-up event. The delay time between the detection of a wake-up event and the reset of the wake-up receiver is determined by the time constant of the RC tank C7-R4.

To reset the microcontroller a fourth NAND gate IC2D is used. One input is connected to an output of the microcontroller (RST_INH) and pulled up to VDD under normal operation. This signal serves as a reset inhibitor for the microcontroller. When the microcontroller detects a wake-up the RST_INH signal is set low as a correct reaction. Thus, independent of the level of the second input at gate IC2D, the output of the NAND gate stays high. When the microcontroller freezes it cannot set the RST_INH to low level, which leads to a low output at IC2D, respectively to a reset of the microcontroller when the output of IC2A is providing its short high reset pulse.

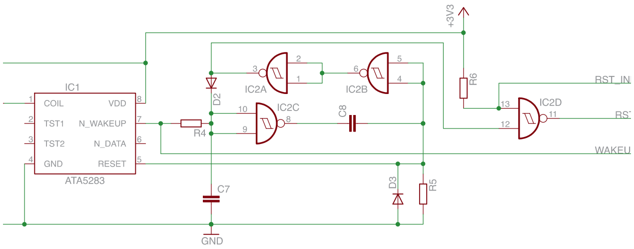

Figure 2. Schematic of the analog circuit for reset of the wake-up IC and the microcontroller.

To further increase the sensitivity of the wake-up receiver IC a diode detector with an amplifier is implemented at the input of the wake-up IC (see figure 3). The gain of the AC-coupled transistor amplifier is about 40 at a frequency around 32 kHz, with a supply current of only 1 µA at 3.3 V. The RF sensitivity can thereby theoretically be increased from 1 mV_{rms} to 25 μV_{rms}[2].

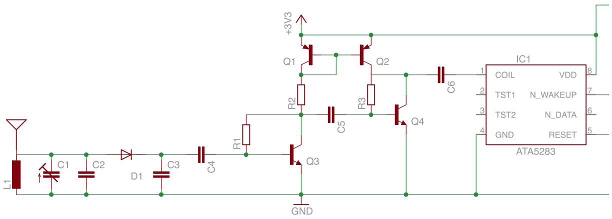

Figure 3. Schematic of the diode detector receiver and the low power transistor amplifier.

For the wireless interface a commercial chip based on the CC1101 from *TI* communicating with the microcontroller over the UART module is used. The carrier frequency is 433 MHz not to interfere with the wake-up signal which works with a carrier frequency of 315 MHz. The transmission rate is set low (9600 baud) to minimize the number of incorrect transfers.

3.3 Analog Circuit for temperature sensors readout

To achieve a maximal resolution, PT1000 thermistors of class DIN 1/3 showing a precision of 0,13°C are used. For the readout the sensors are placed in a Wheatstone bridge. The value of the resistors in the bridge is equal to the resistance of the PT1000 at the middle temperature of the desired temperature range to achieve a symmetric output characteristic, neglecting the small nonlinearity of the PT1000. For a temperature range from 5°C to 45°C the middle temperature is 25°C where a PT1000 shows a resistance of 1097 Ω whereas resistors of 1100 Ω are chosen for the bridge. The differential signal is amplified by an instrumentation amplifier (INA333, *TI*) with a gain of 60, to match the input voltage range of the microcontroller's ADC from 0 V to 2,5 V. To achieve a symmetric transfer function the output of the amplifier is shifted by half of the ADC's reference voltage. With the microcontroller's 12bit ADC a theoretical resolution of 9.77 mK can be achieved.

Due to limited space available in the animal skull, the data logger is placed in the neck of the animal and the temperature sensors are connected by wires. To ensure the mobility of the animal's head and to lower the risk of inflammations caused by stiff wires, very flexible and elastic wires are used. The drawback of these wires is a high serial resistance of approx. 300 Ω/m which leads to the fact that the sensor cannot be directly connected to the device. In fact the whole Wheatstone bridge has to be integrated in the sensor head. Otherwise, the resistance of the wire has to be well known and constant over the temperature range to not cause any measurement error. Thus the Wheatstone bridge is integrated in the sensor head by combining three SMD resistors with 0,1% precision and the PT1000 sensor on a support structure.

To really get independent of the wire resistance, the supply of the Wheatstone bridge should be carefully considered. A simple voltage feed would lead to an undefined voltage drop over the bridge, leading to an undefined sensitivity. This behavior can be avoided by a current feed of the bridge. By the imprint of a constant current the voltage drop and thereby the output signal only depend on the resistors of the bridge.

Solely the voltage drop over the wire should be considered to ensure a proper function of the current source. By reducing the current also the sensitivity decreases. With a voltage drop of 1 V and with an accuracy of 1% the current source LT3092 from *Linear Technology* is well suited for the application. A further improvement is achieved by connecting 4 grains of the wire in parallel leading to a wire resistance of 80 Ω.

4 Measurement results

4.1 Power consumption and lifetime

To calculate the expected lifetime of the data logger the power consumption during wireless communication and during a measurement was measured. For a transmitting power of 0 dBm a power consumption of 92 mW was measured, during the temperature logging the power consumption decreases to 43 µW (see table 1.)

Table 1. Power consumption of the different modules.

Module	Power [µW]
Wake-up receiver	13,2
SRAM	15,0
LDOs	7,3
Microcontroller	1,0
1 sample/min/channel (10µJ)	6,4
Wireless interface	92 000

Neglecting the self-discharge rate of the battery the theoretical lifetime of the data logger can be determined from these data. Lifetime will depends mainly on the sampling rate and on the number of wireless data readouts. Assuming a sample rate of 1 sample/min for both channels and a readout once per week, taking 3 min of readout time, a weekly capacity of 11.8 As is required. With a battery capacity of 330 mAh the data logger has a lifetime of 101 weeks.

4.2 Temperature measurement

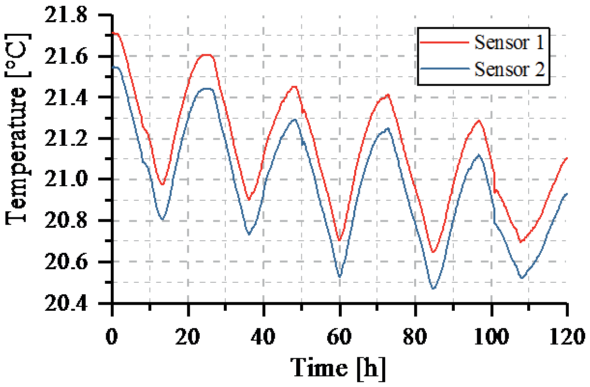

Figure 4. Recorded ambient temperature with the data logger in the laboratory for two weeks.

The theoretical resolution of the temperature measurement is 10 mK. Due to thermal noise such a high resolution cannot be achieved in practice. To determine the resolution, different constant temperatures within the temperature range were generated with the help of a peltier element and a copper block stabilizing the temperature. 100 values per temperature were recorded. The maximum difference from the digitized values was calculated to 7 representing a resolution of 70 mK which is still sufficient for the measurement of the temperature gradient in the brain where a difference of 1-2 K is expected. To test the temperature measurement over a longer time period the data logger was placed in the laboratory to log the ambient temperature once per minute for five days (see figure 4). The difference between the two sensors can be explained by different common mode voltages in the Wheatstone bridges induced by different wire resistances. With a calibration of the sensors this error can easily be compensated in a digital post processing step.

4.3 Performance of the wake-up receiver and the wireless interface

To characterize the wake-up receiver first the sensitivity was measured. The test signal was a 315 MHz carrier signal amplitude-modulated with a 32 768 Hz sinusoidal signal. The sensitivity was defined as the minimal transmission power needed to trigger a wake-up and was measured as -51 dBm.

To measure the transmission range of the wireless interface and the wake-up receiver the data logger was placed in the laboratory together with the transmitter. To take into account the shielding of animal tissue, the data logger was enclosed with four pork cutlets with a thickness of 15 mm. Subsequently the distance between transmitter and receiver was increased successively and the data logger was woken up and read out every 50 cm. With a transmission power of 10 dBm a maximum distance of 6 m was achieved for the wake-up receiver until a wake-up could not be guaranteed anymore. With the wireless interface an uninterrupted transmission up to a distance of 9 m was achieved at a transmission power of 1 dBm.

5 Conclusion and outlook

In this work an implantable data logger with a wireless interface has been developed. The wireless link allows the readout and the programming of new measurement tasks with different sampling rates during the measurement phase as well as a live monitoring of sensors. To achieve a long lifetime the data logger is set in a sleep mode and only woken up for the recording of a measurement value or from the wake-up receiver. This receiver is required to turn on and off the wireless interface, in order to achieve a low average power consumption of only 43 µW during a typical measurement. During data transmission the power consumption is increased to 92 mW. Nevertheless an implantation of 101 weeks is possible with a readout once a week at a sample rate of 1 sample/min. The range of the wireless interface is guaranteed up to 6 m, thus the free movement of the experimental animal is not restricted. The temperature measurement shows a resolution of 70 mK. First in vivo measurement results will be available from October 2017 on when the device is implanted in a sheep.

6 Acknowledgment

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7 References

[1] Texas Instruments, *MSP430FR59xx Mixed-Signal Microcontrollers*, Data sheet, 2015.

[2] ATMEL, *Interface IC for 125 kHz Wake-up Function*, Data sheet, 2004.