Minimizing power consumption of LoRa® and LoRaWAN for low-power wireless sensor nodes

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Abstract. In this paper we show that RF transmissions using the physical layer of the "Long Range" (LoRa®) interface, and with some limitations also the data link and network layer Long Range Wide Area Network (LoRaWAN), are suitable even for extremely power-restricted devices, like energy-autonomous wireless sensor nodes (WSNs), if configured well. We analyse the most critical parameters and their influence on the power performance. This includes the outer circuitry, software and configuration of the transmitter SX1276 and the new SX1262. Based on that, we give specific advice to lower their power consumption and verify the impact of these measures with evaluations on an own build low power sensor node.

1. Introduction
The Internet of Things (IoT) is one of the terms that have gotten increasing attention during the last years. It describes the concept of having a global infrastructure with interconnected devices and services [1]. We find more and more "things" that collect and exchange data or can be remotely controlled. Well-known examples for IoT are ubiquitous sensing systems for monitoring environmental conditions in homes [2]. Many of these sensor platforms have several common requirements. They need a wireless connection, are restricted in power consumption by batteries or energy harvesting and should be producable at low costs, which limits memory and processing power capabilities of the device. With these requirements in mind, so called Low-Power Wide Area Networks (LPWANs) are being developed that should provide the capability for large concurrent transmissions over a great distance while consuming little power. The usage of standardized LPWAN technologies becomes convenient for own built low-power wireless-sensor platforms. An emerging LPWAN protocol is the LoRaWAN, which defines the data-link and network-layer based the link-layer LoRa®, patented by Semtech.

Despite the promise of a low-power wireless transmission, LoRa®-driven wireless sensor nodes (WSNs) are often not power optimized. This is a problem for extremely power-restricted devices with long lifetimes that e.g. use energy harvesting. Papers that model the energy consumption for devices using LoRaWAN report high sleep currents between 7.66 µA up to 34 mA [3]. San Cheong et. al. [4] measured sleep mode currents of 1.27 mA instead of expected 1.8 µA and a high supply current of 117 mA for the actual transmission. Semtech has published a design guide [5] for the calculation of transmission time and current consumption for various settings, but does not take into account other external circuitry and the microcontroller, necessary to run a fully active WSN. Additionally, information and experience about power
consumption of the new SX126X chip is rare. The following sections are addressing these issues, showing optimization possibilities in the outer circuitry, device configuration, software and the expected power consumption for a typical package using LoRaWAN.

2. LoRa® and LoRaWAN

This section describes the most important parameters of LoRa® and LoRaWAN that influence the power consumption of the end-device.

2.1. LoRa®

The LoRa®-protocol defines the link-layer [6], describing how the data is modulated into the transmitted signal. The protocol is proprietary, not all information is freely available. Nevertheless, it is enough to know that due to the used Chirp Spread Spectrum (CSS), the power consumption does not depend on the content of the data, as it does for modulations using e.g. On-Off Keying (OOK). The necessary energy for a transmission is therefore only dependent on the so called time on air (ToA) and the output power. The ToA for a specific payload can be calculated with formulas of the supplier’s design guide [5]. The most relevant terms, influencing the ToA of LoRa® are: (i) The Bandwidth (BW) of the transmission which can be set to 125, 250, or 500 kHz. A larger bandwidth gives better speed, but reduces the receiver sensitivity, thus the range. (ii) The spreading factor (SF) (values between 6 - 12) highly influences the bitrate, and possible range. Increasing the value by one doubles the time for a transmitted symbol, but also has a positive impact on the receiver sensitivity. (iii) The code rate (CR) parameter (ranges from 1-4) defines the additional bits added to each 4 bit package that together form a codeword. The extra are bits used for Forward Error Correction (FEC), a technique to recover partly corrupted transmissions [7]. The CR affects the ToA negatively, but makes communication more robust.

These parameters define the equivalent data-rate that can be achieved with LoRa®. It can vary from 300 bit/s up to 5.5 kbit/s. As many other link-layer protocols, LoRa® adds additional constant factors to each transmitted packet that further increase the ToA. (i) The preamble, needed for the synchronization of receiver and transmitter. The minimum length is 6+4 symbols. (ii) The optional header. It provides information about payload length, FEC-rate and whether there is a field for a Cyclic Redudancy Check (CRC) included in the package. (iii) The optional CRC at the end of each packet adds roughly 5 symbols to the transmission.

2.2. LoRaWAN

In contrast to LoRa®, the specification of the LoRaWAN-protocol is open. It defines the second and third layer in the Open System Interconnection model (OSI model). It forms a LPWAN that has a star-of-stars topology: Numerous gateways, placed all over the world relay messages between the end-devices and a given central server [8]. The protocol takes care about routing packets to the right end-device, controls access for transmissions and defines data encryption.

As end-devices have different requirements regarding power consumption, LoRaWAN specifies several classes for them. Class A has to be implemented by each end-device. The device can start a transmission to nearby gateways at any time and listens for a response afterwards during two well defined receiving-windows. A data-exchange can therefore not be started by the central server. Devices that implement Class B are also capable to receive data from the server on a periodic basis by opening a receive window at a synchronized time. Class C devices are listening continuously for incoming packets, thus are available most of the time to receive messages from the central server.

To work properly, LoRaWAN adds an overhead to each package. The raw data is being encrypted and a MAC header (1 byte), frame header (7 - 22 bytes) and a port field (1 byte) are prepended. A field for the message integrity check (4 bytes) is appended. The overhead can
vary, but is at least 13 bytes long. This is a noticeable amount as the payload length is limited first by LoRa®, that only supports maximum 254 bytes, second by regulatory restrictions that limit the ToA and third by the LPWAN itself. For example The Things Network (TTN), a provider for LoRaWAN, aims to keep the application payload below 12 bytes [9]. In this case, over 50% of the transmitted data would be just overhead.

3. Minimizing system power consumption

Not all possible settings for LoRa® and LoRaWAN are useful when applied in the field. After optimization expected results are being verified with measurements using a custom built low-power WSN. Following, the derived design strategy for running the WSN at minimum possible power is given in section 4.

3.1. Set-up and constraints

The focus on building a WSN with lowest possible power consumption while still using LoRa® or LoRaWAN implies some limitations on the application. Typically, IoT-devices have less computational power, less RAM and are in sleep mode most of the time. This is appropriate for many cases, when devices just gather and transmit data periodically or react to events. For this the system needs: A realtime clock (RTC) for triggering transmissions or measurements. A data storage for the measured values. The transmission unit, in this case explicitly LoRa®-capable chips. Otherwise connected sensors are not part of our system due to their large variety.

Our common test set-up is based on the microcontroller MSP430FR5969 (Texas Instruments). This device has 64 kB of integrated FRAM inbuilt and does therefore not loose data when powered off, with a generally lower power consumption compared to FLASH memory when writing data [10]. With the internal RTC turned on, it consumes about 250 nA in sleep mode.

All transmitter-modules that use LoRa® are based on ICs of Semtech as far as we know. Therefore only the outer circuitry affects the difference in performance between modules. To test that, we have used two modules with different outer circuitry, the inAir9 and the RFM95 which both use a SX1276 as transmitter IC. In addition, we have evaluated the performance of our WSN with the new SX1262 as a transmitter, all connected to the microcontroller. The necessary software and drivers for the modules and LoRaWAN were written based on the provided example code of Semtech [11].

The chosen settings in the test-scenario should be compatible to the popular TTN to increase comparability and realistic results. Therefore the BW has to be fixed to 125 kHz, the preamble length to 12 symbols and the transmission of the LoRa®-header has to be turned on. The WSN sticks to class A with lowest possible power consumption. Apart from the code rate, the spreading factor and the output power are the only remaining parameters influencing power consumption and range.

The payload of our standardized packet is fixed to 10 bytes, being close to the proposed 12 bytes maximum of TTN. For a package sent via the LPWAN the payload increases by at least 13 bytes to a total length of 23 bytes. Using LoRa® only, the overhead would shrink down to the preamble when everything else is configured out.

For the evaluation, the following parameters are varied and the impact on the transmission of our defined standard-packet is measured: (i) the spreading factor, (ii) output power, (iii) outer circuitry (RFM95, inAir9) and transmission chip (SX1276, SX1262). (iv) The communication overhead between MCU and transmitter, using different techniques like direct memory access (DMA), precalculated commands or avoiding unnecessary reconfiguration. (v) The switching between LoRa®-only and LoRaWAN mode for transmission.
3.2. Experimental results

First, the power consumption of the WSN and its parts in sleep mode with only the RTC active are measured with a Fluke 8845A multimeter. As shown in table 1 the supply currents for MCU and RFM95 are in the range mentioned in the datasheet (0.2 - 1 $\mu$A in sleep mode for the SX1276) but the value for the inAir9 module is significantly higher. Semtech’s reference design annotation [12] and the schematic [13] reveal the reason. Both modules use an external RF-switch that itself consumes about 8 $\mu$A. The RFM95 saves this current by turning off the RF-switch via a MOSFET mounted into its supply line.

Second, the power consumption of the WSNs is determined during a transmission for different voltages and output power. It is verified by range tests that the voltage has no impact on the transmission power. Thus it is possible to drastically reduce power consumption by decreasing the supply voltage as figure 1 states. As a result, an over 50% lower power consumption of the inAir9 is found compared to the RFM95 although both use the same chip. The reason for this is the different outer circuit. The RFM95 uses the PA boost configuration which enables higher transmission powers of up to +20 dBm with the drawback of a lower efficiency. The inAir9 can only reach a maximum RF output power of +14 dBm. The SX1262 also uses the PA boost configuration, but performs quite similar to the inAir9, and is therefore more efficient.

![Power consumption of the inAir9, RFM95 and a SX1262 at a pre-set RF output power and supply voltage. The supply voltage, the IC and its outer circuitry have a drastic impact on the needed input power.](image)

Given the optimized power consumption, the energy needed to transmit the defined standard packet can be exemplary calculated and is shown in table 2.

Finally an exemplary look was taken on the impact of the software architecture and the energy needed for communication with the transmitter. Without any optimization of the reference

| Payload: 23 bytes | 1.9 mJ | 1.3 mJ |
| Payload: 10 bytes | 3.8 mJ | 3.5 mJ |

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Table 1. Measured current drawn by the Transmitter (Tra), MCU and together of the WSN in sleep mode @3.3V. The MCU draws 250 nA more than expected, but especially the inAir9 uses a lot more.

| MCU /$\mu$A | Tra. /$\mu$A | Total /$\mu$A |
|-------------|-------------|--------------|
| inAir9      | 0.55        | 8.90         | 9.45         |
| RFM95       | 0.52        | 0.47         | 1.03         |
| SX1262      | 0.60        | 0.14         | 0.89         |

Table 2. Energy needed for the transmission of the standard data packet with 23 (LoRaWAN) or 10 bytes (LoRa® only) payload at a supply voltage of 1.9V, SF7 and 3 dBm output power.
library [11] necessary operations and the communication to the transmitter via SPI consume 34 µJ. The usage of LoRaWAN increases this value to 60 µJ due to additional overhead and encryption. After optimizing the code by removing duplicate register readings and precomputing constant values, energy consumption dropped down to 0.4 µJ resp. 26 µJ for LoRaWAN.

3.3. Efficiency for decreased transmission ranges

When higher transmission ranges are needed, either the output power or the SF can be increased. The energy needed for packet transmission will therefore increase. The possible range for a transmission is commonly expressed by the link budget which we simplify to 

$$L_B = P_{TX} + R_S.$$ 

$P_{TX}$ is the output power whereas $R_S$ is the receiver sensitivity at a given SF. Taking all possible SFs with the corresponding $R_S$ and output power combinations into account, the resulting energies for the standard packet were calculated. The results indicate that it is more efficient to increase output power rather than the SF. This is due to the significant negative impact on the transmission speed for a higher SF.

4. Summary and conclusion

We have analysed and minimized the power consumption for a typical LoRa® respectively LoRaWAN driven sensor node that uses the SX1262 or SX1276 transmitter IC. Our experimental results state that the following measures should be taken: The PA Boost configuration should not be used to save over 50% of power unless high RF output power is needed. The supply voltage can be reduced to the possible minimum, saving up to 55% additional power without affecting the RF output power. The new generation ICs, SX126x, can reduce power consumption for about 50% again compared to a similar configuration with an SX1127x. Higher transmission ranges should be primarily achieved by increasing RF output power before rising the spreading factor. When a RF switch is used in the connected circuit, it should actively be switched off during sleep mode. In contrast to that, optimization of software will be in many cases unnecessary as we have found only a low potential of about 3% for the energy needed for a packet. With this, our WSN needs only 1.0 µA in sleep mode with a running RTC and can transmit a typical LoRaWAN packet with only 1.9 mJ @ 3dBm output power, SF7. We expect to achieve even lower consumption by exchanging the transmitter with an SX1261.

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