Protocol Design for Ultra-Low Power Wake-Up Systems for Tracking Bats in the Wild

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***Abstract*—We present a novel concept for a wake-up system based ultra-low power communication protocol for sensor networks. The main application field is monitoring contacts and even tracks of bats in the wild. Our sensor nodes can weigh at most 2 g out of which 1 g remains for the battery. We investigate a novel communication protocol design applicable to these systems and also showing great potentials for other ultra-low power sensor networks. In particular, we investigate the bat to ground communication by combining duty cycling with a multi-stage wake-up receiver. We employ Binary Offset Carrier (BOC) modulated signals that allow to accurately localize and track the bats while transmitting data in parallel. In a first step, we evaluated the conceptual design using a software-defined radio system to demonstrate the feasibility of the protocol design.**

I. Introduction

Sensor networking technology has successfully been used in many application domains ranging from structural health monitoring [1] to water quality measurements [2] and to habitat monitoring [3]. A major challenge and technical constraint has always been the limited energy budget [4] and, therefore, the overall network lifetime [5]. We are focusing on wildlife monitoring, one of the first applications of Wireless Sensor Networks (WSNs). Years after early projects such as Great Duck Island or ZebraNet, we aim for a next generation of sensor networking technology allowing to observe the hunting and social behavior of bats in the wild.

In the scope of the BATS[1] project, we go one step further and investigate potentials of ultra-low power sensor systems carried by the bats to monitor contacts between individual bats and to track their routes. The aim of the project is to support biologists with their study on bats, one of the most protected species in European Union, to track their living habitats and social behaviors. Mouse-eared bats (*Myotis myotis*) are the main study target of this project [6]. The key challenge is that the animals with a typical weight of about 20 g can carry sensors of at most 2 g, which strongly limits the available energy budget as well as the computational power and storage capabilities.

Communication from the mobile (bat) nodes is constrained by the hardware components. Given the weight limit of 2 g, only 1 g can be spent for the microcontroller plus radio transceiver and the battery, respectively. Thus, ultra-low power communication is needed in order to monitor contacts between the bats and to track the flight path during the hunting process. The general principle is to deploy ground nodes in the hunting area providing precise localization capabilities at a frequency of about 10 Hz for continuous tracking. In this paper, we concentrate on the downlink from the bats to these ground stations and explore the design space for potential communication protocols. The protocol must be able to suite both the localization and the data communication requirements.

The ground nodes consist of MicroZed boards[2] equipped with a custom Software Defined Radio (SDR) RF frontend based on the Analog Devices AD9361 transceiver chip – we assume no tight energy constraints for these ground nodes. The mobile nodes, on the other hand, must operate on a low duty cycle to save energy. We employ a multi-stage Wake-Up Receiver (WuRx) to initiate and to coordinate the transmissions when being in communication range of the ground nodes. Conceptually, the ground node sends a simple radio signal to wake up the first stage at the mobile node. In a second step, the mobile node tries to receive a digital signal to loosely synchronize to the base station and to power up the digital radio transceiver and, eventually, the microcontroller.

Most critical is the embedded battery, which is not able to power the radio transceiver and the microcontroller directly. Instead, it is used to charge a capacitor, which then provides sufficient current to power the system for a very short time. Thus, novel concepts are needed for the communication protocols, especially when considering the need for data communication and ranging. In this paper, we present a first step towards ultra-low power wake-up protocols for use in wildlife monitoring applications and discuss potential protocol designs.

Our main contributions can be summarized as follows:

- We study the design of an ultra-low power sensor node to be used for monitoring bats in the wild (Section III).
- We analyze potential communication protocol designs considering all the given hardware constraints and combine

[1] Dynamically adaptive applications for bat localization using embedded communicating sensor systems, http://www.for-bats.org/

[2] http://www.zedboard.org/

Table I
COMPARISON OF TYPICAL WAKE-UP RECEIVERS

	[8]	[9]	[10]	[11]
power consump.	28.3 µW	8.4 µW	52 µW	0.27 µW
data rate	1.024 kbps	1 kbps	100 kbps	10 kbps
sensitivity	−83 dBm	−73 dBm	−72 dBm	−46 dBm

duty cycling with a multi-stage WuRx (Section IV).

- We prototyped the developed protocol on a SDR and conducted a set of performance measurements. The results demonstrate the feasibility of our approach (Section V).

II. RELATED WORK

For WSN applications, duty cycling and WuRxs represent the most promising technical solutions. These systems monitor the channel continuously, trigger an event by identifying a particular wake-up signal, and most importantly, consume very little energy so that the system can run from several weeks to years. We concentrate on hardware based WuRx that are more suited to the application scenario. Predictive solutions have been studied in the literature and show promising results when it comes to data communication patterns instead of physical contacts [7].

WuRx can be grouped into different categories based on their characteristics. First, by the requirement of DC supply, it can be classified into passive and active. The former can be powered up by transforming the RF input signal into DC supply with a rectifier circuit. While this architecture consumes zero power, it also suffers from poor sensitivity.

The active WuRx, in turn, can provide higher sensitivity, but is challenged by higher power consumption. One of the strategies to decrease the power consumption is duty cycling, which activates the circuitry periodically [12]. Here, the system benefits in terms of power consumption of the receiver, but increases the latency of detection and also implies higher energy consumption of the transmitter. To solve the latency issue, an ultra-low power WuRx, which can listen continuously, has been proposed in [10]. It consists of a filter, an amplifier, a detector, and a mixer with LO signal generator for down conversion of higher operation frequency. However, while it solves the latency problem and achieves higher sensitivity, the power consumption of the receiver still suffers by the always-on WuRx.

To further reduce the power consumption of the receiver, a 2-stage duty cycled WuRx has been introduced [9]. At the first stage, a duty cycling scheme is applied on the ultra-low power WuRx, which can only process the input signal with low data rate. To obviate the condition that the WuRx miss the detection from the wake-up signal, the sampling rate of the WuRx should be aligned to the wake-up signal from the transmitter. As the wake-up signal is confirmed, the second stage is activated which turns on the WuRx permanently in order to process additional information, such as ID and data, with higher data rate. The topology is similar to the continuous-listen WuRx, except the digital control circuit for duty cycling. This approach consumes less power at the receiver while maintaining the sensitivity.

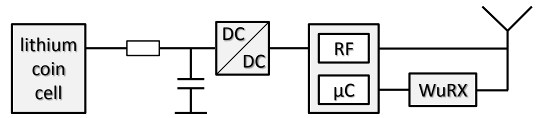


Figure 1. Hardware architecture of the mobile node.

The low data rate at the first stage still incur latency problems, which means the power consumption of the transmitter would be increased. Table I summarizes the performances of different WuRx systems. We notice that there is a trade-off between power consumption of the receiver as well as the transmitter and sensitivity.

III. SYSTEM DESIGN

Coming up with a system design that meets all the requirements of the BATS project is very challenging. Considering the communication from mobile nodes to ground nodes, the 2-stage WuRx is the best option since it has relative low power demands while providing high sensitivity. The slight increase in power consumption of the transmitter is not a problem since the power limitations are not so strict.

In contrast to that, the continuous-listen WuRx, which guarantees low power consumption at both the receiver and transmitter is a better choice for the communication between mobile nodes. In this paper, however, we concentrate on the mobile to ground communication and select a multi-stage WuRx design.

A. Hardware

Figure 1 depicts the block diagram of the mobile node. Its key component is a System on Chip (SoC) comprising a microcontroller and a dual band RF frontend capable of transmitting and receiving in the 868 MHz and the 2.45 GHz band. The transceiver is used for both bidirectional communication and the transmission of localization signals. The power source is a lithium coin cell battery, which offers a very high energy density. Unfortunately, the small battery does not allow to drain currents of several mA, which are needed for powering the SoC. Therefore, we have to employ a buffer capacitor, which is charged during the inactive phases of the SoC. A DC-DC-converter is used to down convert the battery's output voltage to the input voltage of the SoC. The antenna is shared by the RF-frontend and the WuRx, which allows the module to stay in sleep mode until it is woken up by an external signal.

B. Constraints for the Wake-Up Receiver

For the proposed system the WuRx must be suitable for two different operating conditions: the communication between mobile nodes and the communication between ground node and mobile node. In this paper, We concentrate on the mobile to ground communication.

Defined by the spacing of ground nodes the maximum distance for ground node to mobile node communication is approximately 50 m. According to the communication channel this corresponds to an attenuation of 65 dB (free space loss

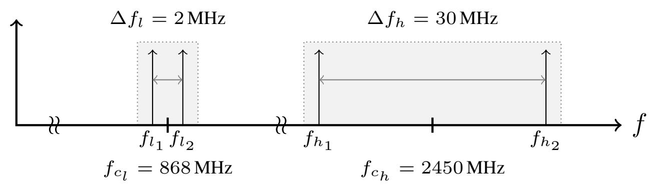


Figure 2. Signal design with multiple coherent carriers.

Table II
COHERENT CARRIERS IN MULTIPLE BANDS

Frequency band		868 MHz	2.4 GHz
Carrier frequency	f_c	868 MHz	2450 MHz
Carrier spacing	Δf	2 MHz	30 MHz
Unambiguous range	r_{max}	$\sim$ 150 m	$\sim$ 10 m

(FSL)) to 78 dB (FSL + linar fading with 0.25 dB/m) at 868 MHz. Given a transmission power of 10 dBm, this leads to a minimum required sensitivity of -55 dBm and -68 dBm respectively. The WuRx described in [10] seems perfectly suitable for both operating conditions.

C. Localization Signal Design

The localization concept is based on multi-carrier signals in two frequency bands. Figure 2 depicts how the carriers are organized: We use two carriers that are spaced by 2 MHz in the 868 MHz band and two 30 MHz spaced carriers in the 2.4 GHz band.

With the signals propagating through space, the carrier phase changes according to the distance travelled R and the frequency f of the corresponding carrier.

Similar to [13], a range estimate $\hat{R}$ can be calculated based on the phase difference $\Delta\phi$ and the spacing Δf of the two carriers:

$$\hat{R} = \frac{c_o \cdot \Delta\phi}{2\pi \cdot \Delta f} \ . \quad (1)$$

Since phase observations wrap within an interval of 2π, an ambiguity problem arises. Yet, phase measurements are unambiguous up to a maximum range of $R_{max} = c_0 \cdot f^{-1}$. Table II shows the resulting unambiguous ranges for the proposed carrier spacings. Measuring the signal strength may be used to resolve the ambiguities in the 868 MHz band and the range estimation in the 868 MHz band enables resolving the ambiguities of the signal's phase in the 2.4 GHz band.

D. Localization and Data Transmission Concept

The considered WSN features two of the most common functionalities: communication and localization. Due to the strictly limited power budget the total RF time has to be minimized. The most obvious idea is to combine the communication and localization signals. Therefore, a signaling scheme is used that incorporates data transmission and localization.

The proposed signaling scheme is related to signals utilized in modern Global Navigation Satellite Systems (GNSSs). In particular, a special type of Binary Offset Carrier (BOC) modulation is used [14]. However, it must be noted, that the requirements of the BATS system differ significantly from the ones of GNSS.

In contrast to GNSS short burst signal are used due to the limited energy amount instead of continuous signal. The most essential difference to GNSS is the limited area that is covered by the WSN. Ambiguities that arise from pure subcarrier localization, are not an issue for the bat tracking WSN. This fact makes the use of a pseudo random noise sequence unnecessary and enables the transmission of data bits within the localization signal. The potential of this approach and its theoretic limitations in range estimation have been discussed in [15].

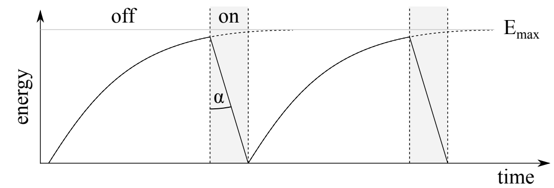


Figure 3. Qualitative overview of the charging and discharging process of the capacitor and the duty cycle of the transceiver.

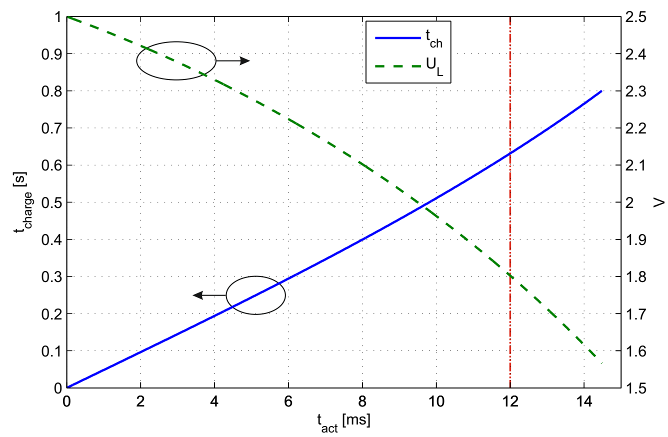
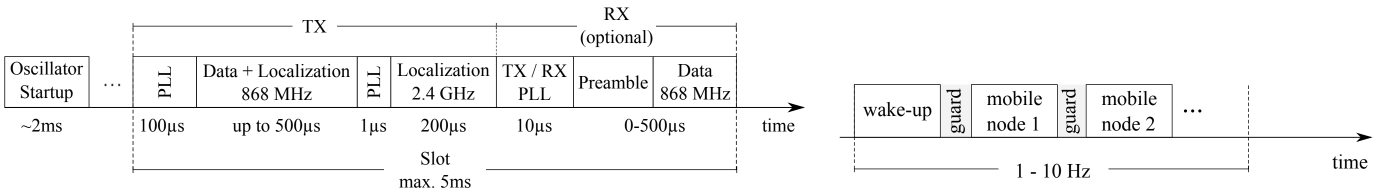


Figure 4. Dependency of the active period and the recharging time.

E. Timing Constraints

The applied type of battery is not capable of delivering the current of several mA demanded by the transceiver directly. Instead, the battery is used to charge a capacitor, which is then drained by the communication module. As a direct consequence, the communication module cannot be activated permanently but a duty cycle has to be applied. A qualitative overview of the duty cycle and the charging process is depicted in Figure 3 (we will discuss the duty cycle in mode detail in Section IV). Obviously, there is a trade-off between the charging interval and the active period: a longer active period requires more energy and, thus, leads to a longer charging period. While discharging of the capacitor through the communication module is approximately linear (assuming a constant power demand $U_{SoC} \cdot I_{act}$), charging is an exponential process depending on the output voltage of the battery U_{bat}, the capacitance C, and



(a) Sequence during a single communication slot

(b) TDMA-like communication slots with guard intervals

Figure 5. Communication protocol design.

the resistance R. The slope of the linear decrease (denoted as α) is defined by the power consumption of the device.

The energy that is drawn by the communication module and the upper voltage U_U of the capacitance at the end of the charging process lead to a lower voltage U_L at the end of the active period. While recharging, the current drawn from the battery can not exceed an upper limit I_{av} due to constraints of the battery.

With these relations the dependency between the maximum active period t_{act} and the minimum charging time t_{ch} can be calculated as

$$t_{act} = \frac{C \cdot \eta_{DCDC}}{2U_{SoC} \cdot I_{act}} \cdot \tag{2}$$

$$\left[\left(\frac{I_{av} \cdot t_{ch}}{C} \right)^2 \cdot \left(1 - \frac{2}{1 - e^{-\frac{t_{ch}}{RC}}} \right) + \frac{2U_{bat} \cdot I_{av} \cdot t_{ch}}{C} \right],$$

considering a fixed efficiency η_{DCDC} of the DC-DC-converter.

The dependency is shown in Figure 4 for the parameters given in Table III. For small values of t_{ch} the linear term is dominant in the equation. For higher values the nonlinear term gains influence which additionally limits the active period.

The corresponding values of U_L are also given in the graph to illustrate that the maximum active period is about 12 ms. At this point U_L falls below the input voltage of the SoC. Furthermore, the plot shows that for the desired wake-up cycle of 10 Hz the maximum active period is only 2 ms.

IV. Protocol Design

The protocol design is mainly motivated by the discussed constraints posed by the hardware platform. In the following, we explore the design space and propose a new protocol that combines duty cycling for re-charging the capacitor with a multi-stage wake-up receiver. We also show how multiple mobile nodes can be supported in a coordinated Time Division Multiple Access (TDMA) scheme.

Table III
Energy management constraints

Property		Value
average current drawn from battery	I_{av}	0.5 mA
battery voltage	U_{bat}	2.8 V
Soc voltage	U_{SoC}	1.8 V
DC-DC efficiency	η_{DCDC}	90 %
capacitance	C	330 µF
resistance	R	600 Ω
current consumption (TX/RX)	I_{act}	$<$ 30 mA

A. Duty Cycling and Wake-Up Receiver

The duty cycle is controlled by the ground network. During the inactive period, the device is completely shut down and is only switched on by a wake-up signal emitted by one of the ground nodes. This duty cycle is depicted in Figure 3. Besides the discussed system limitations (in particular the need to re-charge the capacitor for the next transmission cycle) the duty cycle has to be selected in a way to obtain a sufficient number of position samples for continuous tracking. We currently assume that a frequency of up to 10 Hz is required to calculate the trajectory of the bats.

The wake-up signal is detected by a multistage wake-up receiver, where the first stage is handled by an analog circuit that consumes only a negligible amount of energy. If energy has been detected, a second stage is activated, which already allows to process simple digital information without completely powering up the microcontroller. In a second phase of the project, we aim to use this phase to start receiving and decoding a simple on-off keying modulated signal. This information can be used to coordinate channel access in order to avoid collisions if multiple bats are within the range of a ground node.

B. Design of the Communication Slot

During a communication slot, the mobile node sends ranging signals and optionally sends and receives data. The sequence of operations during a communication slot and its associated timings can be seen in Figure 5a. When the wake-up signal is received the mobile node chooses a time slot and starts its quartz oscillator, which takes about 2 ms. The oscillator is needed in order to count down a timer that notifies the node about the start of the communication slot. Shortly before the slot starts, the node synthesizes a 868 MHz carrier with the oscillator and a Phase Locked Loop (PLL), which takes $T_{\text{PLL}} = 100\,\mu\text{s}$. At the start of the slot, the node sends a BOC modulated ranging signal. We require $T_{\text{TX}} \leq 500\,\mu\text{s}$ in order to provide a stable localization signal. This signal can be modulated with a low-rate data signal to allow communication from the bat to the ground network [15]. In particular, we use a data rate of 200 kbit/s. Thus, a time slot of 500 µs translates to a frame length of 12 B. Alternatively, a time slot of 200 µs translates to a frame length of only 5 B.

Ranging in the 868 MHz band uses a small bandwidth of 2 MHz that allows for a large unambiguous range, but low spatial resolution. Therefore, another ranging signal with a larger bandwidth is sent in the 2.4 GHz band. In this case, frequency synthesis is really fast since the PLL is already locked, so that only the frequency divider has to be changed ($T_{\text{PLL short}} = 1\,\mu\text{s}$). After the second ranging signal is sent, the node may optionally receive a signal from the ground node. For this, it retunes to the 868 MHz band. Again, the PLL is already locked but the system must switch from TX to RX, i.e., requiring $T_{\text{TX/RX}} = 10\,\mu\text{s}$. Then, the node checks for a preamble, indicating an optional data transmission from the ground network to the bat ($T_{\text{preamble}} + T_{\text{RX}} = 0\,\mu s to 500\,\mu\text{s}$.

Overall, the following timings must be obeyed:

$$T_{\text{active}} = \underbrace{T_{\text{PLL}} + T_{\text{TX}}^{868\,\text{MHz}} + T_{\text{PLL short}} + T_{\text{TX}}^{2.4\,\text{GHz}}}_{\text{mandatory for downlink}} + \underbrace{\left[T_{\text{TX/RX}} + T_{\text{preamble}} + T_{\text{RX}}^{868\,\text{MHz}}\right]}_{\text{optional for uplink}} . \quad (3)$$

Hence, T_{active} sums up to 801 µs to 1311 µs. Thus, we can support the needed 2 ms duty cycle discussed in Section III-E.

C. TDMA Scheme for Supporting Multiple Nodes

The protocol discussed so far supports the downlink for contact information (and optionally uplink for control data) to the ground nodes for a single mobile node. We have not yet discussed how to operate multiple nodes, i.e., to support tracking of multiple bats in the same setup. Consider using the prosed approach without further changes. After a bat arrives in the communication range, the ground node initiates the transfer by waking up the WuRx on the mobile node. We have two options to realize this: (a) Timing is not controlled by the base station, thus, the start of the sequence is initiated by the time the mobile node first receives a wake-up signal. If two bats arrive at roughly the same time, or at least in the repeated time slot, they will always cause a collision for the downlink. (b) Timing is controlled by the base station, in this case, all mobile nodes will automatically be synchronized – and cause collisions for each downlink transmission.

We solve this dilemma by relying on a ground station controlled TDMA schedule supporting multiple bats in the same collision domain. A mobile node does not access the channel immediately after it is woken up, but chooses a fixed-length time slot that is either pre-programmed or based on the data encoded in the wake-up signal. Since the sensor nodes are not synchronized perfectly and since the oscillators might drift considerably, the use of guard intervals between slots is crucial.

An overview of this slotted TDMA scheme is shown in Figure 5b. The wake-up signal initiates the transmission but first starts a timer implemented in the wake-up receiver counting down towards the bat's time slot. Due to hardware constraints posed by the battery and the charging of the capacitor the wake-up cycle will not be faster than 10 Hz. For a 10 Hz cycle, this system can support up to about 10 bats (downlink only). If more individuals are to be tracked, the frequency needs to be reduced, which also reduces the tracking granularity.

V. Performance Evaluation

The feasibility of the system in terms of timings has already been shown. Yet, we lack the proof that a combined ranging and data signal is indeed possible and can be run in a reasonable signal-to-noise ratio (SNR) environment.

Table IV
Power consumption of different tag functionalities

Functionality	Condition	Power
Total circuitry	Power down	0.003 mW
Microcontroller	Low power mode	0.007 mW
—	Active mode	10.5 mW
Transmission	2.4 GHz (10 dBm)	81 mW
—	868 MHz (10 dBm)	99 mW
Reception	868 MHz	45 mW
PLL		28.5 mW
XO start up		3.3 mW

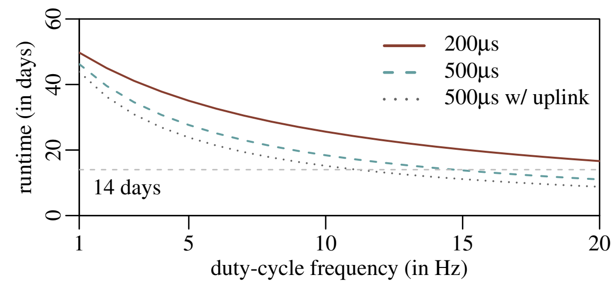


Figure 6. System runtime dependent on duty cycle and burst configuration.

A. Power Budget

For the mobile node, we selected the battery model BR1125, a lithium coin cell that provides a capacity of 144 mWh. This battery provides a stable voltage until 90 % of its capacity has been used. The goal is to power the node for two weeks with this extremely limited energy budget. Considering the worst case scenario, i.e., when the bat stays within range of ground nodes all the time, the total energy demand can be calculated using the exemplary values given in Table IV. Power consumptions are taken from data sheets of the CC430 and the CC2590 from Texas Instruments, as well as Atmels AT86RF233, while the timings are extracted from Figure 5a. Furthermore, the power demand of the WuRxfrom [10] is considered.

We made the following assumptions for calculating the power budget: The power demand of the mobile node is higher when the bat is within the range of ground nodes. The main reason is the need for more frequent transmissions of localization signals, resulting in a microcontroller duty cycle with 1 % active time. As the bats are only active for about six hours a day, the high node activity is only required for less than 6 h in communication range of the ground network.

Based on these data, we can calculate the lifetime of a sensor node in our scenario. Figure 6 shows the results. We plot the possible runtime as a function of the duty cycle frequency, i.e., the number of communication slots per second. Furthermore, we plot the results for three protocol options: 1) 200 µs downlink slot, equal to a frame length of 5 B, 2) 500 µs downlink slot, equal to a frame length of 12 B, and 3) 500 µs downlink plus the optional 500 µs uplink slot.

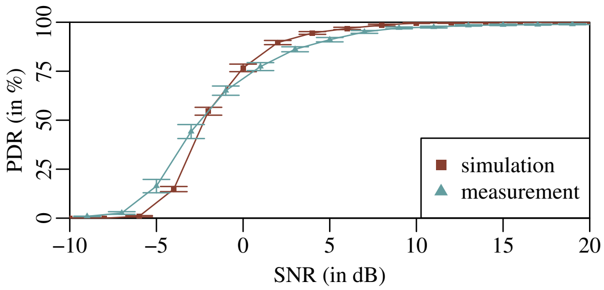


Figure 7. Simulated packet delivery ratio at different SNR levels.

As can be seen, we can support a lifetime of two weeks for the fully functional sensor node (downlink and uplink channel) at 10 Hz. This frequency is needed for obtaining accurate trajectories of the mobile node. We also see that by reducing the frequency and limiting the length of the transmission slot and/or disabling the uplink, we can easily achieve prolonged lifetimes of more than seven weeks. This proofs the feasibility of the investigated protocol design.

B. Packet Delivery Ratio

To understand the performance of the data communication, we implemented a BOC(1, 0.2)-based transceiver with a chip rate of 2 Mc/s and a data rate of 200 kbit/s. The implementation is based on GNU Radio, a real-time signal processing framework for use in SDR platforms. The transceiver sends bursts of 12 B, where 1 B is used for both preamble and start of frame delimiter and 2 B are used for a CRC, leaving 8 B per frame for data. Such a burst takes 480 µs and fits within the time slot reserved for downlink data communication. On the receiving side, we despread the signal and use the start of frame delimiter to synchronize.

With this implementation, we simulate transmissions over an AWGN channel and conduct real over the air transmissions. The real transmissions are performed with Ettus N210 USRPs in an office environment. The resulting packet delivery ratio is depicted in Figure 7. Note that we can not measure absolute power values in the proposed setup. Therefore, the SNR levels of the measurements were shifted to fit the simulated ones. This potential offset and the fact the Packet Delivery Ratio (PDR) of the measurements is less steep can well be explained by effects of the wireless channel and hardware impairments like frequency offset and non-linearities of the analog frontend. Even though these measurements present the best case, they clearly underline the feasibility of the approach. The final transceivers that are deployed in the woods will suffer from more complex channel effects potentially reducing the SNR.

VI. Conclusion

In this paper, we discussed the communication technologies needed for ultra-low power sensor nodes used for monitoring bats in their natural habitat. The system design is particularly challenging due to the strict weight limits of 2 g of which 1 g is used for the battery. As a novel concept, we integrated duty cycling with a multi-stage wake-up receiver, which only activates the mobile node when in communication range to the ground nodes. The bat-mounted system then starts transmitting contact information to the ground node. The same signal is also used for localization and tracking of the bats while hunting. In this paper, we explored the design space for the respective protocols. According to the available energy, we show that this ultra-low power node can be operated for a period of two to six weeks depending on the configuration and the needed localization accuracy. The proof of concept study has been evaluated using a GNU Radio based transceiver implementation.

Acknowledgements

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