A Highly Adaptable Ultra-Low Weight Wireless Sensor Network for Tracking and Monitoring of Airborne Vertebrates

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***Abstract*—This paper gives an overview of the BATS project, which aims to track the behavior of bats by developing an ultra-low power wireless sensor network. It is composed of an ultra-low weight sensor node that is attached to the animal and extensive ground infrastructure for tracking the animals as well as remote data download of locally stored sensor data from the tags. The system achieves its low power consumption by adaptively enabling certain functions based on the current situation. The mobile node, as a key component of the system, contains a variety of sensors, including an electrocardiogram (ECG) to allow precise insights in the animals' behavior while maintaining a low weight of around 1 g depending on the hardware configuration.**

***Index Terms*—wireless sensor network, low power, sensors**

I. Introduction

Wildlife monitoring with animal borne tags is motivating interdisciplinary research for more than 50 years and has been strongly technology-driven ever since. In the past, the focus was more on researching movement or migration patterns of individual animals. Due to recent development in sensor technology, the design of more advanced tags that additionally give detailed insights about the studied individual gains more and more momentum.

Simple systems, that combine tracking with other sensor data, are already available for larger animals. However, for researchers, it is still relatively complicated to get detailed information about smaller vertebrates since many available systems are too heavy. When developing animal borne sensor tags it is important to design them in a way, that they don't alter the animals behavior [1] and thus, keep the tag weight to a minimum. This leaves out a significant amount in species since light animals are a significant part of all mammal species as seen in Figure 1. Especially the research of bats has been proven challenging due to bats being not only small and light but also airborne and nocturnal. This makes e.g. visual observations not feasible. Also, this way solar-cell powered tags [2, 3] can't be used and all energy required for the tag operation has to be in the tag from the beginning.

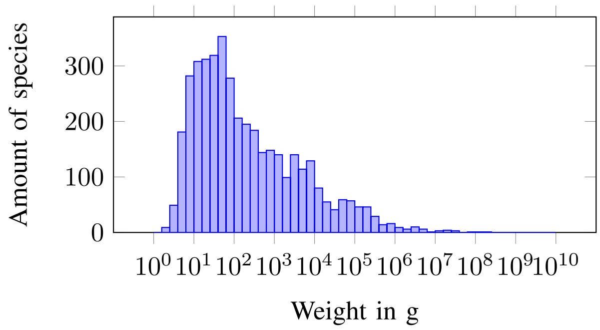

Fig. 1: Weigt distribution among mamal species (Data from [5])

In the BATS project [4], a system that is targeted on the research of bats is developed to help the studying social structures and the general behavior of bats and other small (airborne) vertebrates. The BATS system allows gathering information about the individual itself, its surrounding and its location. It is composed of a mobile tag that is attached to the animal as well as a ground station network for tracking and data transfer.

In this paper, the BATS system is described with a focus on the design and functionality of the mobile node and its newest design improvements.

II. Overall System

Figure 2 gives an overview of the BATS system architecture. The project focuses on researching bats, but it theoretically can be used on a wide variety of other animals. The strength of the system is, that it works in environments like a meadow but also in environments with heavy multi-path effects like a dense forest. To save energy and maximize the battery runtime, the different functionalities can either be completely be activated or dynamically scheduled by the system itself.

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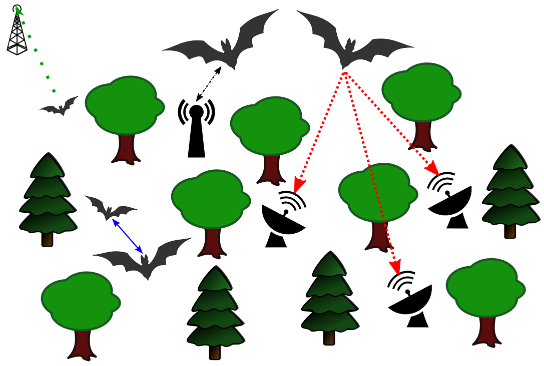

Fig. 2: Overview about the system architecture of the BATS system. Encounter detection between tags (solid blue), data download (dashed-dotted black), trajectory tracking (dotted red), long range telemetry (low density dotted green)

A. Flight Trajectory

The flight trajectories are derived from multiple location-snapshots with high temporal and spatial resolution. The locations are calculated using the Received Signal Strength Indicator (RSSI) values at each base station as well as a Direction of Arrival (DoA) estimation [6]. To increase the precision and robustness, the system uses two frequencies, one at 868 MHz/915 MHz (depending on the region) and the other at 2.4 GHz. The tracking grid is composed of multiple antennas that are placed in a grid with up to 50 m distance between each other. These base stations are designed to receive localization beacons send from the mobile nodes. To save energy these localization beacons are only transmitted by the mobile node when it is in the tracking grid. The mobile node detects this state (inside or outside of the tracking grid) by a ground node that continuously transmits a beacon to the mobile node. Since the weight of the ground node is not limited it can be equipped with a bigger battery, so that the current consumption is not as critical as on the mobile node. The localization signal is transmitted at a frequency between 1 Hz and 8 Hz. The transmission frequency can be preselected depending on the respective research question as trade-off between energy consumption and tracking precision/resolution.

B. Encounter Detection

Apart from tag-to-base station communication for localization, the tags are also able to communicate with each other for the so-called encounter detection [7] between animals. The encounter detection records meetings between animals or other tags in general. This allows researching the social structures among a group of animals or resource usage if e.g. mobile tags are attached to food sources and animals. The encounter detection works by sending an On-Off-Keying (OOK) modulated signal to other tags which can be demodulated with much lower current consumption than conventional Frequency-Shift-Keying (FSK) signals by a dedicated wake-up receiver. The detected meetings are stored in an on-board memory for future downloads.

C. Remote Data Download

While there are various data loggers for animals available, many of them require that the user retrieves the tags to get the recorded data. Since that is not always possible in the field, the BATS system includes a remote data download functionality via dedicated base stations. These allow receiving data from the mobile tag at a distance up to 200 m. In addition to the pure data download, these base stations are also used for so-called pseudo-localization. This means, that these base stations record which tags are in range to get a rough localization of the animal. While this is significantly less precise than the previously mentioned trajectory recording it allows some rough information about the movement of the animal.

D. Long Range Telemetry

While the normal base stations are able to download any locally stored data from the mobile nodes, their range of 200 m is highly limited. Thus, the BATS system includes a long-range telemetry system [8]. This allows gathering data from the tags even if the animal left the range of the normal base stations. The long range telemetry can still receive packets from the tags at a distance of 5 km. However, at this range, the data rate is significantly reduced compared to the download base stations. While the download of the stored data is not feasible anymore, the data rate is high enough to receive short beacons with the mobile node identifier number and a small payload, e.g. the activity state of the animal. The long-range data transmission comes at virtually no extra energy cost for the mobile node since it is embedded in the signal used for the encounter detection via phase jumps in the OOK signal.

III. Mobile Node

The key component of the system is the mobile node which is attached to the animal. To not affect the animal, it needs to stay lighter than 5% of the body weight [9]. This weight limitation includes the tag, the battery, the housing and material to attach the tag to the animal. The lightest version of the BATS mobile nodes (without sensors) is as light as 1 g and thus usable on a wide variety of species.

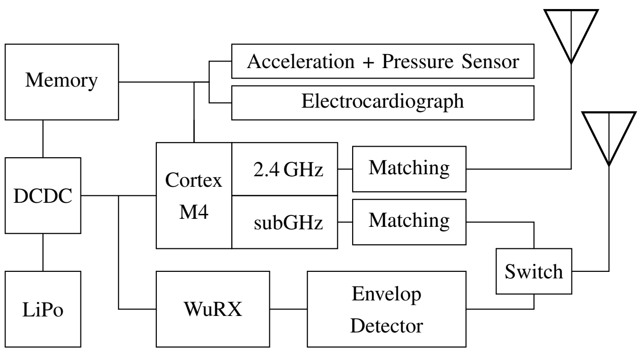

Fig. 3: Schematic of the mobile node

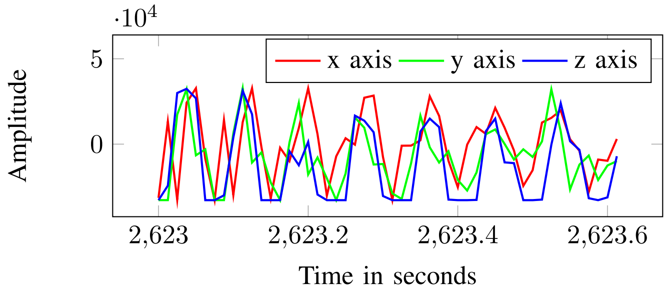

Fig. 4: Acceleration sensor data during flight with clearly visible wing beat at a frequency of 13 Hz

The full-featured mobile node is schematically shown in Figure 3. As core, it contains a Cortex-M4 processor core in a System-on-Chip (SoC) with integrated radio frontends for subGHz and 2.4 GHz data transmission. To allow energy-efficient data reception, the mobile node contains a wake-up receiver which waits on incoming OOK-modulated packages from other sensor nodes. The wake-up receiver requires a current of less than 2 µA while the conventional receiver draws up to 10 mA. In exchange for the low current consumption, the sensitivity is significantly worse than of the conventional receiver. While the conventional receiver has a sensitivity of -100 dBm, the wake-up receivers require incoming packages being stronger than -46 dBm for stable reception. Such low sensitivity could be a drawback in many applications. In the BATS system, it is actually an advantage. The wake-up receiver is used to trigger the main processor when it detects another mobile node in range. Due to the low sensitivity this detection range is limited to about 5 m. This short-range is enough for biologically relevant contacts between animals. A higher sensitivity would lead to a higher detection range and thus to more wake-ups. Since meetings at higher distance don't contain valuable information, these wake-ups would need to be assessed and filtered which requires additional energy.

To gather sensor data, the mobile node is equipped with an accelerometer and an air pressure sensor. These sensors are used to get a deeper insight into the animals' behavior. Both can be used to detect the wing beat of the bat (Accelerometer data during flight showing the wing beat is shown in Figure 4). The accelerometer can additionally detect the general activity of the bat (hanging down, crawling, flying, ...) and the air pressure sensor can, in combination with an air pressure sensor on the ground, be used to calculate the flight height of the animal.

In addition to these commercially available sensors, the mobile node contains an electrocardiogram (ECG) frontend [10], specifically developed for the use on bats, to measure the heartbeat of the animal. The ECG has been developed to work with non-invasive electrodes to reduce the impact on the animal. To keep costs down, the ECG electrodes are made of the same PCB material as the mobile node itself. In Figure 5 and exemplary ECG waveform of a greater spear-nosed bat is shown. There, the electrodes have been attached to the

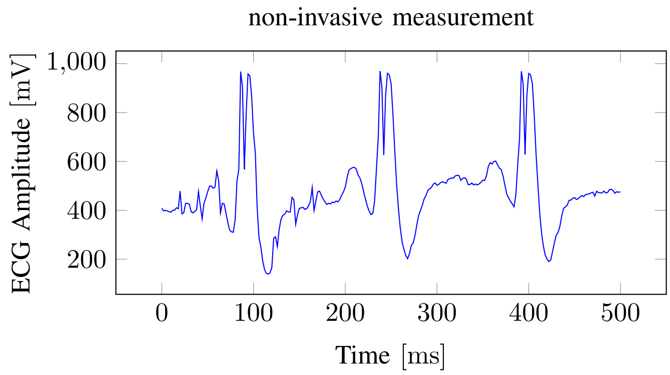

Fig. 5: ECG Signal of a free roaming greater spear-nosed bat (*Phyllostomus hastatus*) which was moving but not flying

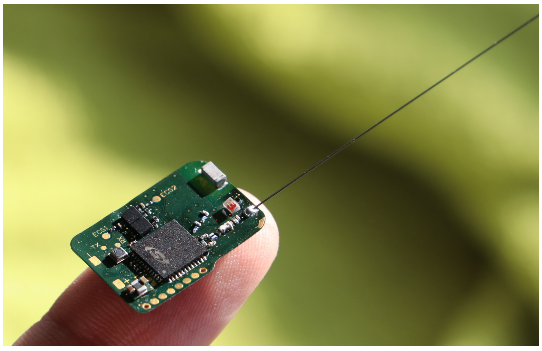

Fig. 6: Full feature node with additional sensors and ECG

depilated skin of the animal on the upper and lower back. While attaching the electrodes on top of the heart on the chest would result in better signal quality, electrodes at this position could easily be reached and removed by the animal.

The fully populated mobile node without housing can be seen in Figure 6. Since the PCB is populated on top and bottom layer, not all components are visible.

IV. Energy Consumption and Runtime

Due to the strict weight constraints, the battery of the mobile node is highly limited in weight and thus capacity. This requires the system to be highly energy efficient to still archive a long runtime.

To be able to adapt the system as good as possible on the required use-case, two hardware versions of the mobile node have been developed - one with sensors including ECG and one limited only on the encounter detection to reduce the size and weight of the PCB. This way, in combination with various battery types, the overall weight of the encounter detection only node can be as low as 1 g. The weight of this light node includes a 12 mAh battery and a housing made of the fingertip of a nitrile glove which is glued close to protect the PCB.

In encounter detection, only the overall current consumption is 55 µA at 3.7 V. When enabling all sensors with a data rate of 80 Samples per Second (sps) for accelerometer and air pressure sensor and 500 sps for the ECG as well as transmitting the data in quasi-realtime, the current consumption rises to 3 mA. Quasi-realtime means here, that the data packages are collected into burst which are then transmitted every four seconds. This bursting is implemented to reduce the energy consumption of the radio. By scheduling the sensors and other functions of the mobile node practically any value in between 55 µA and 3 mA is possible. For each use-case, the best matching trade-off between data quantity and quality and energy consumption can be set.

Figure 7 shows the runtime of the mobile node in encounter detection only mode during a field trial. With the small battery (12 mAh) a maximum runtime of 210 h and with the big battery (25 mAh) 426 h was reached. The runtime was calculated based on first and last radio contact, either between mobile nodes, with the download base station, or with the long-range telemetry network. Short runtime could, in reality, mean that the animal left the range of the base station network. Especially the tags with very short runtime are expected to be animals leaving the area shortly after tagging. Also, the intensity of contacts between bats plays a role – the more contact with other tagged animals, the more meetings are generated and thus the higher the current consumption of the tag.

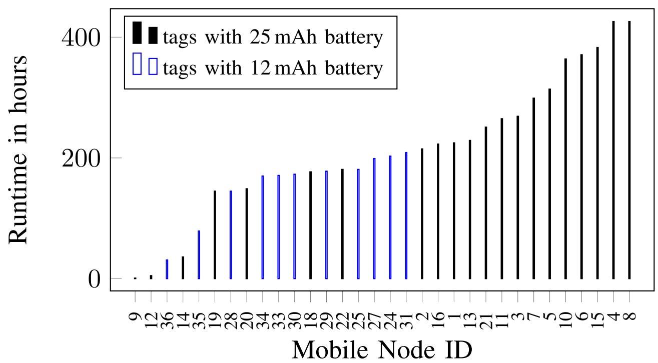

Fig. 7: Runtime of each node in hours in encounter detection only mode

V. Comparision With Other Systems

Due to combining multiple functions in one system, the BATS system can't be compared to other systems as a whole. Thus, in the following the single features are compared with other systems focusing on these aspects.

A. Tracking Systems

The tracking aspect of the BATS system can be compared best to systems like ATLAS [11], MOTUS [12] and ICARUS [13].

ATLAS uses tags with a weight of 1.5 g and a runtime of 10 days. It can track the nodes with a standard deviation of around 5 m with a ”reverse GPS” approach. This means the tag transmits a signal which gets received by multiple base stations. Based on the time of arrival difference at the base station nodes, the location is calculated.

MOTUS tags can be as light as 0.2 g with a runtime of 10 days. However, the tags are simple VHF tags that periodically transmit an analog signal without encoded data on a single frequency to be detected by the base stations. MOTUS localization works by having the tag in the range of the base station or not. Thus, it only has a limited spatial resolution. Due to the high amount of active base stations, it is used for tracking large scale migration patterns.

ICARUS uses Global Positioning System (GPS) tags with a weight of currently 5 g. The position then is uploaded to an antenna attached to the International Space Station. This way it is completely independent of any ground infrastructure. The localization precision depends on the GPS signal reception quality.

The above-mentioned systems have their strength mostly in large scale tracking, e.g. for tracking migration movements. The BATS system focuses on tracking bats with very high spatial and temporal resolution in small areas. Also, the BATS system contains a variety of advanced sensors to analyze the behavior of the animals while the other systems use no or only limited sensors for data recording.

B. Encounter Detection Systems

Another system that focuses on encounter detection is Encounternet [14]. While Encounternet also has mobile nodes as light as 1.3 g their biggest drawback compared to BATS is a limited runtime of just 21 hours. This is around 5% of the runtime that the BATS system achieves with a comparable tag weight. The Encounternet runtime can be extended to 7.5 days when setting the nodes to transmit only. In that configuration, they are unable to detect nearby nodes themselves but only can be detected by other nodes or base stations. When using tags with a weight of 10 g, a runtime of 2 month is possible with Encounternet. Similar to the BATS system, Encounternet also includes a remote data download function.

C. Sensor Systems

While there are multiple mobile nodes with sensors like accelerometer available, ECG sensor tags are relatively uncommon. One comparable system that can record ECG data is, for example, the SP2000 HR Sparrow Systems [15]. The SP2000 uses invasive electrodes which are transmitted via an analog modulated radio wave. This way a receiver always has to be in range and the transmission is prone to errors. The ECG included in the BATS mobile node has the advantages of using non-invasive electrodes. This way the impact on the animal is significantly reduced and the application in the field is simplified. Also, the BATS mobile node digitizes the ECG data directly after the ECG frontend. This allows easy onboard storage of the ECG data in case a receiver is not in range.

VI. Conclusion

With the BATS system researchers have a powerful tool for researching the behavior of bats more detailed than it was possible before. It was shown that due to being highly flexible the BATS system can be tailored to each use-case and that it can even schedule functions itself based on the situation to use the available energy in the battery as efficiently as possible. While especially in the tracking area, other systems are available, the BATS system meets simultaneously the needs for proximity sensing and local high-resolution tracking in a single system with ultra-low weight mobile nodes.

The BATS system is already actively used in multiple biological studies with bats [16, 17] and other animals and has proven to generate precise and valuable results.

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