From Radio Telemetry to Ultra-Low Power Sensor Networks – Tracking Bats in the Wild

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***Abstract*—Sensor networks have successfully been used for wildlife monitoring and tracking of different species. When it comes to small animals such as smaller birds, mammals, or even insects, the current approach is to use extremely lightweight RF tags to be located using radio telemetry. A new quantum leap in technology is needed to overcome these limitations and to enable new ways for observations of larger numbers of small animals. In an interdisciplinary team, we are working on the different aspects of such a new technology. In particular, we report on our findings on a sensor network based tracking solution for bats. Our system is based on integrated localization and wireless communication protocols for ultra-low power systems. This requires coding techniques for improved reliability as well as ranging solutions for tracking hunting bats. We address the technological and methodical problems related to system design, software support, and protocol design. First field experiments have been conducted that showcase the capabilities of our system.**

I. Introduction

Wildlife tracking has been one of the early applications in Wireless Sensor Networks (WSNs) and remained, among a few others, one of the most successful ones [1], [2]. Sensor-networking-based wildlife monitoring provides more sophisticated methods for biologists to study individuals of a specific species, in terms of gathering a huge amount of data by long-term observations. When it comes to tracking smaller animals like very small mammals or birds, radio telemetry is still considered state of the art [3]. This means that for localizing a single individual, at least two radio receivers operated by biologists in the field are needed to obtain a single position sample per triangulation. Here, both the rate of localization samples is very low – too low for continuous tracking, and the observation is usually restricted to very few individuals.

In the scope of the BATS[1] project, we are developing a new sensor network based system for monitoring group dynamics of bats in their natural habitat. In particular, we go one step further compared to related activities and investigate potentials of ultra-low power sensor systems carried by the bats to monitor contacts or *encounters* between individuals and to track their routes at high spatial and temporal resolution. Tracking bats is especially challenging because direct observations on flying bats are almost impossible due to their nocturnal activity and high mobility. Mouse-eared bats (*Myotis myotis*), one of the most protected species in the European Union, are the main study target. The key challenge is that the animals with an average body weight of about 20 g can carry sensors of at most 2 g (including a 1 g battery), which is even less weight than a sheet of paper in A5 format. Comparable sensors published in the literature typically weigh more than 100 g, with the Encounternet tags being outstanding with a weight of only 10 g – which is one order of magnitude higher compared to our requirements [2]. This poses a series of fundamental research questions that need to be addressed from a multi-disciplinary perspective ranging from hardware design, system support, and communication protocol engineering.

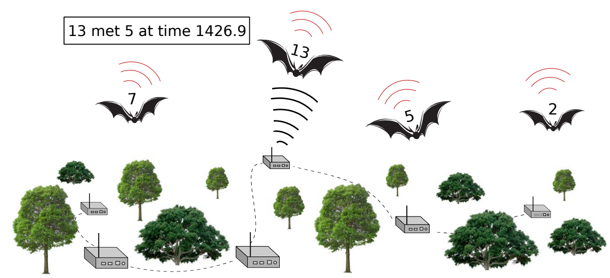

Figure 1. Conceptual scenario for bat tracking in the wild: stationary ground nodes are used to localize and to track bats based on emitted beacon messages. The mobile nodes are also used to monitor encounters and to download this data to the ground network to increase the observation range beyond the ground station area.

Our bat tracking scenario involves a variety of functions that need to be integrated with a main focus on energy efficiency. In a first stage, we aim at tracking flying bats using a stationary ground network. The concept is outlined in Figure 1. The ground stations localize and track the bats using a combination of Received Signal Strength (RSS) and phase-based localization techniques. Given the energy constraints of the mobile nodes, special modulation schemes are needed. When talking about the mobile nodes, we need to emphasize that a 1 g battery cannot directly power the microcontroller and the radio transceiver for a longer time period – in particular, we have to charge a capacitor first to provide peak operating current for the system. We investigated a combination of Wake-Up

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

Receiver (WuRx) and carefully controlled duty cycling to recharge the capacitor.

In a second stage, the system is also used to exchange contact information among the mobile nodes to increase the observation range beyond the ground-station area. The encounter information is then downloaded to the ground network when in communication range – as determined by the WuRx. In the following, we will refer to this data as *chunks* representing sets of contact information collected by a mobile node on the bat. The download follows the same power constraints and needs to be integrated with the localization signal. As the channel quality varies quickly in the given environment, additional error control mechanisms need to be integrated. We explored the capabilities of Erasure Codes (ECs) and were able to show that substantial improvements are possible.

Right now, the project goes beyond initial fundamental research on all the different aspects mentioned: First field experiments have been completed in Germany as well as Panama showcasing the capabilities of the envisioned architecture. In this article, we summarize all the related inherently inter-disciplinary research challenges and outline conceptual approaches solving the problems – towards a novel ultra-low power sensor networking solution for tracking bats in the wild.

Our main contributions can be summarized as follows:

- We report on first field tests using our $2\,\mathrm{g}$ sensor platform enabling, for the first time, tracking of animals weighing as few as $20\,\mathrm{g}$.
- We developed a novel system architecture supporting precise localization and tracking.
- We summarize system design aspects from the operating system to wake-up receiver design.
- We finally outline the novel integrated wireless communication and localization protocols from PHY to forward error control using erasure codes.
- We briefly report about first successful outdoor experiments in Germany and Panama.

II. Related Work: Studying Bats in the Wild

First projects relied on typical sensor platforms as used in academic research labs, e.g., the Great Duck Island project, or on special hardware that is even robust enough to be carried by larger animals, e.g., the ZebraNet project. More recently, tracking has become a major application besides the collection of several sensor readings. Also, the technological advances enabled new generations of sensor nodes that can be used to track much smaller animals such as the Iberian lynx [1]. Wireless digital transceiver technology rendered even the automated mapping of social networks in wild birds possible, e.g., in the Encounternet project [2]. From these successful approaches to wildlife monitoring using sensor networks, we learned about hardware design issues, network management, and data collection techniques.

State of the art technology for bat tracking is still radio telemetry. However, this method requires high labor costs since two or more persons must manually observe one or a few individuals at a time. The reward for this high effort is a minimal number of animal positions that are separated by several minutes and usually contain localization errors of tens of meters.

Observing the movements of individual animals in their natural habitat is one of the most difficult tasks in the field of behavioral biology; however, it is the key to understand complex biological processes such as foraging, social interactions, migration, and gene flow. Recent technological advances in satellite based animal localization and automatized data acquisition are restricted to medium sized to large mammals and birds due to the considerable weight of available transmitters [4]. The most promising approach for tracking large-scale movements of small animals from space is represented by the ICARUS initiative. It is expected to start in 2016 and tags will initially weigh $5\,\mathrm{g}$ but should become considerably lighter within a couple of years [5]. Until ICARUS will finally launch and tags underwent further miniaturization, traditional radio telemetry still represents the state of the art of bat tracking as radio transmitters are available with a weight down to $0.2\,\mathrm{g}$. However, this technique can only provide a rough estimate of foraging movements based on animal positions that are separated by several minutes and that contain localization errors of at least tens of meters. However, the identity of the individuals remains unknown when such experiments are used to study bats in the wild and the observable area is limited.

The study of social interactions among individually identifiable bats is especially challenging in the wild. To date, the only option to automate this is to use extremely light passive integrated transponder tags (PIT-tags), which can be identified within known roosting sites that are equipped with PIT-tag readers [6]. The only possibility to document group dynamics while foraging is again radio telemetry [7].

The BATS sensor network aims at implementing both automated high-precision positioning of many individuals at a time and documenting interactions of the observed bats. The high temporal and spatial resolution of data will render the reconstruction of individual flight trajectories possible. Communication among mobile nodes will shed light on interactions among individual bats at the individual level during the nightly activity phase, which were impossible to study until now. The advances of the BATS system holds the potential to gain a deeper understanding of bat behavior, e.g., habitat use, analysis of flight maneuvers, and group dynamics.

III. The BATS Ground Network

A. Experiment Management

Many projects on wildlife tracking mentioned in the introduction have used a Data-Stream Management System (DSMS) to collect the data. This has the advantage of processing the data early, i.e., selecting and aggregating them, which has proven to reduce power requirements for WSNs. This in general is favorable, as battery lifespans increase and maintenance costs are reduced. Queries are deployed to the ground network and later even to the mobile nodes on the bats to define the early processing. The stream operators invoked by the queries can be adjusted or even replaced in case the biologists want to tweak resolution to support their experiments. It is still a research issue to conduct dynamic stream operator replacement efficiently in sensor networks.

Due to technical restrictions, especially the communication data rate between mobile nodes and ground nodes, not all acquired data can be sent. For example, providing a time stamp and duration of a meeting, which is mandatory for further analysis, uses almost $70\,\%$ of the available data rate. Other data like different Received Signal Strength Indicator (RSSI) values cannot be sent without any violation against data rate requirements. Therefore, only a subset of acquired data can be sent to the base station network. Thus, a decision has to be made to select the most suitable data to be sent. Depending on the current research focus, the system will be adapted to increase the quality of the relevant data while balancing the other goals: Providing additional data for later offline analysis and increasing node lifespans.

B. Ground Nodes

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 as we assume no tight energy constraints for the ground nodes. This versatile SDR platform allows to exploit the localization methods described above. Comprising an FPGA and a dual ARM core, the ground nodes feature enough processing power to enable complex range estimation and direction finding algorithms.

The ground nodes also have to wake up the mobile nodes in order to initiate and to coordinate the transmissions when the mobile nodes that are in range of the network. Periodic beacon signals allow to loosely synchronize the mobile nodes to the ground stations. Using this beacon signals, mobile nodes can decide whether to transmit localization signals or to save energy.

C. Ground Network

In order to support both localization as well as data collection from the mobile nodes, an efficient and decentralized distributed data storage and lookup is needed. A promising concept is a Distributed Hash Table (DHT) integrated with ground network routing capabilities. There exist various protocols for sensor networks providing standard DHT functionalities [8], however, most of them rely on globally valid topology information, need geographic location information, or do not take into consideration the physical position of nodes, which leads to increased routing paths. We selected the Virtual Cord Protocol (VCP) [8], which overcomes many of these shortcomings. VCP supports routing in the ground network topology using a virtual cord based on neighborhood information. For data management, each node is then responsible for data with a hash value that matches its virtual node identifier.

IV. Mobile Node Design

A. Hardware Design

The building blocks of the mobile node and a successfully used prototype are depicted in Figure 2. Due to its high energy density, a lithium primary coin cell battery is used to power the tag. Caused by the maximum current of lithium cell supply capability, a buffer capacitance is applied. A DC/DC switching converter down converts the variable capacitor voltage to a constant system-on-chip input voltage of $1.8\,\mathrm{V}$. The system on chip (SoC), which is the key component of the tag, comprises a microcontroller, a dual-band frontend for transmission and reception in the $868\,\mathrm{MHz}$ and the $2.45\,\mathrm{GHz}$ band, and a WuRx operating in the $868\,\mathrm{MHz}$ band. First prototypes containing a Cortex-M0+, an Si4460, and an AT86RF233 are built to set up a system demonstrator. Besides the SoC an accelerometer is placed on the tag to facilitate a motion detection. A dual-band antenna is shared by the regular transceiver and the WuRx. The whole hardware assembly is protected against physical influences (e.g., humidity or the attempt of the bat to scratch it off) by an epoxy sealing.

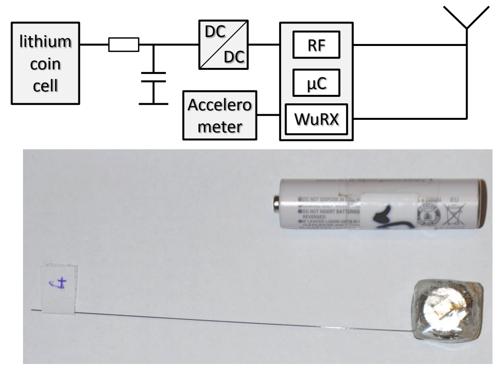

Figure 2. Hardware architecture and assembly of the mobile node.

The WuRx must be suitable for two different operating conditions: the communication between mobile nodes and the communication between ground node and mobile node. Defined by the spacing of ground nodes the maximum distance for ground node to mobile node communication is approximately $50\,\mathrm{m}$. According to the communication channel this corresponds to an attenuation of $65\,\mathrm{dB}$ (free space path loss) to $78\,\mathrm{dB}$ (free space plus linear fading with $0.25\,\mathrm{dB/m}$) at $868\,\mathrm{MHz}$. Given a transmission power of $10\,\mathrm{dBm}$, this leads to a minimum required sensitivity of $-55\,\mathrm{dBm}$ and $-68\,\mathrm{dBm}$, respectively. We rely on the concept described in [9], which is suitable for both operating conditions.

B. Power Management

The lithium primary battery offers a high capacitance, but still the current that can be drawn is limited to $\sim 0.5\,\mathrm{mA}$. However, the SoC, especially the transceiver, demands several mA when active. To satisfy this demand a buffer capacitance is integrated, that has to be charged by the battery before it is being discharged by the SoC. Hence, a continuous operation of the transceiver is not feasible. Furthermore a trade off between active period and recharging time exists: the longer the transceiver is active the longer the capacitor has to be recharged. With the assumption that the current drain during the sleeping phase of the tag and the recharging during the active period is negligible the dependency between the maximum active period t_{act} and the minimum recharging time

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

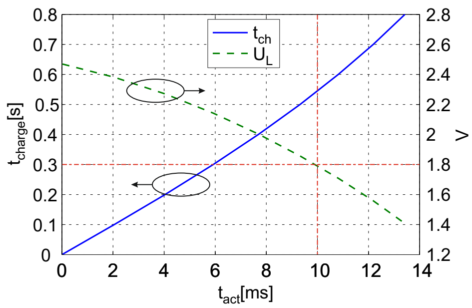

Figure 3. Dependency of the active period and the recharging time.

t_{ch} is visualized in Figure 3. The fact that the capacitor's voltage decreases during its discharge leads to the existence of an absolute maximum time limit of the active period. Namely when the voltage of the capacitor at the end of the active period U_L falls below the $1.8\,\mathrm{V}$ input voltage of the SoC. The value of U_L is also given in Figure 3 and determines the limit of the active period to be about $10\,\mathrm{ms}$. The resulting protocol design challenges are discussed in Section V.

C. System Support

Hardware limitations inevitably have an effect on the resources that are available to the software components running on top. In the BATS project, this limitation is even more difficult to manage as we have to assume a deeply embedded system with a microcontroller and available memory that are considerably more limited than, for example, common embedded devices such as smart phones or lab-style sensor nodes. This demands for a common software infrastructure to efficiently use underlying hardware components and render resource efficient applications possible. Yet, these applications still need to meet certain other criteria apart from pure energy efficiency, for example, complying to certain deadlines such as soft and hard real time. For tiny embedded systems, a multitude of different operating systems exist, each may having divergent approaches since they are geared towards different use cases. Yet, most of these operating systems still aim to be general purpose, which results in a certain degree of potential efficiency losses. Alternatives are real-time operating systems such as SLOTH [10]. This particular system allows making full use of the available hardware support, which leads to smaller program code and space that the operating system allocates in memory.

To address the requirement of having an operating system and applications that also need to be optimized regarding energy efficiency, we rely on both the SEEP energy estimation framework developed by Hönig et al. [11] and energy measurements from our self-developed measurement device. Furthermore, this gives us the possibility to write predictable code in terms of its expected lifetime on the actual hardware. By following the framework's profile-driven approach, we have created an energy profile for our target platform, and therefore, are able to retrieve estimated, expected energy consumption values for a SLOTH application under test (e.g., with CPU-intensive code such as erasure encoding processing, described in Section V-C). This enables us to pro-actively develop program code and make energy optimizations before the actual system is deployed and field tests are being conducted.

We further extended SLOTH with support of dynamic program code reconfiguration; that is, the possibility to efficiently switch between different code parts that already reside on the platform at run time. With this mechanism, we can either react to a query that was sent by the front-end user (i.e., a biologist) or to predictions automatically derived from ongoing data stream analyses. By way of example, we are able to alter the bit fields of the meeting, which consists of a meeting's duration, starting time, and RSSI values.

V. COMMUNICATION PROTOCOLS

A. Protocol Design

When it comes to the design of low energy communication protocols in sensor networks, three main approaches have been identified in the literature: (a) duty cycling, i.e., periodically switching between active and passive state to power off main components in the passive stage – synchronization is explicitly required; (b) low power listening, i.e., "waking up" the receiver node using multiple transmission attempts (either full messages or wake-up preambles) to dismiss the synchronization requirement; and (c) wake-up MAC protocols, i.e., using dedicated hardware to wake-up the node in case of an upcoming transmission (e.g., PW-MAC [12]).

Given the discussed energy constraints, the communication protocol for mobile to ground communication needs to be designed in a completely novel way. First of all, duty cycling is an inherent feature given the recharging cycles of the capacitor that powers the radio transceiver. Furthermore, unnecessary transmissions need to be prevented when the bat is not in communication range to at least one ground node. Here, a multi-stage WuRx is used to completely power-off both the radio transceiver and the microcontroller.

These two concepts can be combined to benefit from both advantages. Duty-cycling helps reducing the energy consumption (and supports recharging the capacitor) when the bat is in range of a ground node and the multi-stage WuRx triggers the initiation of this duty cycling and turns off all digital components if not needed. The entire cycle is controlled by the ground network, i.e., all ground nodes are assumed to be synchronized. We assume a frequency of wake-up pulses of up to $10\,\mathrm{Hz}$ for trajectory estimation.

In each cycle, a wake-up pulse disseminated by the ground nodes wakes up the mobile nodes. In a second phase of the project, we aim to even encode data on the wake-up 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. Obviously, more than a single mobile node needs to be supported by the mobile to ground communication protocol and to track multiple individuals at the same time. Timing is controlled by the base station. We picked this approach to increase the robustness of the protocol even though (without an uplink signal) this limits the number of mobile nodes to the number of available time slots. Furthermore, guard intervals have been introduced because the sensor nodes are not synchronized perfectly and since the oscillators might drift considerably.

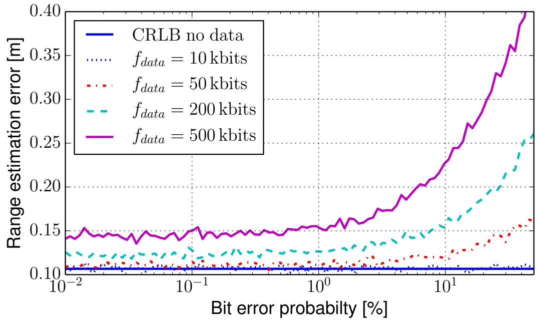

Figure 4. Impact of data transmissions on the maximum achievable range estimation performance.

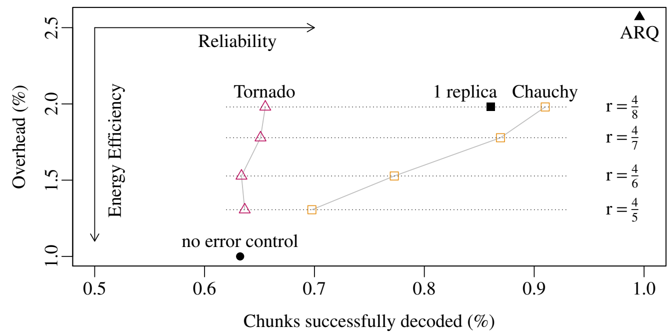

Figure 5. Reliability gain achieved by of the different error control strategies and code rates r versus their energy efficiency in terms of the necessary number of packet transmissions.

B. Encoding and Modulation for Combined Localization and Data Communication

As energy awareness is one of the most crucial aspect for our system, the energy spent on RF activity for localization and communication has to be minimized. We recently proposed a signaling scheme that combines localization and data signals [13]. In the presented approach Binary Offset Carrier (BOC) modulation is used to simultaneously transmit data and provide accurate range measurements. BOC modulation is well-known in the field of Global Navigation Satellite Systems (GNSSs). In contrast to GNSS and due to the limited energy, very short burst signals are used for communication and localization instead of continuous signals. A further motivation for burst signals is to avoid near-far effects in local Real-Time Locating Systems (RTLSs) by time division multiplexing.

Due to limited observation area pure subcarrier tracking is applied in the BATS system as this approach maximizes Root Mean Square (RMS) bandwidth and thus leads to a minimum range estimation variance. Data transmission is realized by modulation of the subcarriers. This modulation broadens the subcarriers and also decreases the RMS bandwidth, but still has only a negligible impact on the range estimation accuracy. Yet, data decoding errors have a rather substantial influence on the distance estimation as they result in a mismatch of the correlated sequences, which then lead to a Signal-to-Noise Ratio (SNR) degradation. This significant increase in the range estimation variance is shown in Figure 4.

C. Improving Communication Reliability

The channel quality may vary quickly due to the continuous movements of bats and the heterogeneous forest environment, thus, the communication is in general assumed to be highly unreliable and error control techniques have to be applied. We consider ECs as a specific class of forward error correction codes as a promising approach in our BATS scenario. ECs are widely employed to improve the reliability in wireless transmissions [14]. Compared to the simplistic approach to send chunk replica together with the original data as well as to the classic Automatic Repeat Request (ARQ) mechanism, ECs offer a better performance with reduced costs in terms of energy consumption. Likewise, ECs show a better efficiency than on demand chunk retransmissions realized by acknowledging successfully transmitted chunks.

The significant difference between the various ECs is the mathematical background of the encoding and decoding algorithms. Reed Solomon (RS) codes such as Cauchy and Vandermonde share the same algorithms, however, they work on different kinds of matrices, whereas codes like Tornado vary significantly in the algorithm itself. We investigated the mentioned codes for their applicability in our scenario [15]. These codes support different code rates that essentially define the possible error correction vs. the overhead for additional coding data. To the best of our knowledge, there exists no study on the feasibility of ECs for scenarios with spontaneous connectivity such as the scenario we are investigating with its specific channel properties.

The usage of ECs and replicated sending inevitably increases energy consumption. Primarily the sending of redundant chunks drains energy, however, in the former case the execution of the encoding algorithm has to be taken into consideration as well. This trade-off between the improved reliability and the overhead caused by redundant chunks is outlined in Figure 5. The graph illustrates the gain in reliability for the different error control techniques in comparison to the energy efficiency. The plotted results have been collected in a series of simulations based on the discussed mobile to ground communication protocol and assuming a typical packet error rate of about $20\,\%$ in addition to the used two-ray path loss model to resemble multipath fading effects in the simulation.

As we move from left to right in the graphs, reliability measured against the amount of recovered data increases, whereas moving from bottom to top the energy efficiency decreases with an increasing overhead. For reference, also the non-replicated sending is indicated, obviously not inducing any overhead but at the cost of very low reliability.

As we can see, ARQ as well as Tornado-based ECs either significantly increase the overhead or lead to only marginal reliability improvements. However, combining the wireless communication with a chunk-based RS code, we observe substantial improvements at acceptable energy costs. This especially holds for code rates of $r = \frac{4}{7}$ to $r = \frac{4}{8}$.

VI. First Experiments on Wild Bats

The basic functionality of the BATS concept has been validated on the target species *Myotis myotis*, the greater mouse-eared bat, and on the tropical fringe-lipped bat, *Trachops*

Figure 6. Individuals of the focus species *Myotis myotis* (left) and *Trachops cirrhosus* (right) carrying prototypes of mobile nodes that are attached between the shoulder blades with surgical cement.

cirrhosus, in Panama. In order to demonstrate the technical feasibility to build an energy efficient proximity sensor node of less than $2\,\mathrm{g}$ with a theoretical battery life of at least one week, we performed a field test on four bat individuals in a maternity colony of mouse-eared bats in Upper Franconia. Presence and absence of the tagged individuals in the colony has been documented and interactions among the tagged individuals have been surveyed. Communication of mobile nodes with the base station served as an indicator of presence in the colony, while RSSI measurements were used to estimate the distance between two bats. During a second field experiment conducted in Gamboa, Panama, we successfully documented encounters among members of a social group of the fringe-lipped bat outside the roost while hunting. Furthermore, we tracked foraging movements of individual bats on a small area of about $20\,\mathrm{m}$ by $25\,\mathrm{m}$ based on field strength measurements. Tagged animals of the focus species *Myotis myotis* and *Trachops cirrhosus* are shown in Figure 6.

VII. Conclusion and Future Work

We reported on our findings towards a new era of ultra-low power sensor systems used for tracking bats in the wild. Even though the BATS sensor network has been designed to observe bats, i.e., small animals that are moving in three dimensions at high speed, it will also be applicable to a wide range of vertebrates including mammals, birds and reptiles, and even certain invertebrates as, e.g., large beetles. In first field tests, we succeeded collecting contact information of bats in their natural environment and documented foraging movements. These very promising early results encourage further investigations and research in this inherently interdisciplinary project. Many of the scientific findings can be adapted to other application fields – we believe that our technical solutions will substantially impact research on ultra-low power sensor networks in general.

Certainly, there are still many open research questions and big challenges to be addressed. This particularly includes the option to provide even more reliable wireless communication without increasing the energy budget. Such functionality is needed, for example, for online reconfiguration and even software updates of the mobile nodes. We also think about integrating sensors to combine physiological and environmental data with tracking data. The applicability to a wide species spectrum across taxa (not only bats) may even be increased by further miniaturization.

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References

[1] A.-J. Garcia-Sanchez, F. Garcia-Sanchez, F. Losilla, P. Kulakowski, J. Garcia-Haro, A. Rodriguez, J.-V. Lopez-Bao, and F. Palomares, "Wireless Sensor Network Deployment for Monitoring Wildlife Passages," *Sensors*, vol. 10, no. 8, pp. 7236–7262, 2010.

[2] C. Rutz, Z. T. Burns, R. James, S. M. Ismar, J. Burt, B. Otis, J. Bowen, and J. J. S. Clair, "Automated mapping of social networks in wild birds," *Current Biology*, vol. 22, no. 17, pp. R669–R671, 2012.

[3] S. K. Amelon, D. C. Dalton, and S. A. Millspaugh, Joshua J.and Wolf, "Ecological and Behavioral Methods for the Study of Bats," T. H. Kunz and S. Parson, Eds. Baltimore, MD: John Hopkins University Press, October 2009, pp. 57–71.

[4] M. Hebblewhite and D. T. Haydon, "Distinguishing technology from biology: a critical review of the use of GPS telemetry data in ecology," *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 365, no. 1550, pp. 2303–2312, June 2010.

[5] E. Pennisi, "Global Tracking of Small Animals Gains Momentum," *Science*, vol. 334, no. 6059, p. 1042, November 2011.

[6] G. Kerth, N. Perony, and F. Schweitzer, "Bats are able to maintain long-term social relationships despite the high fission-fusion dynamics of their groups," *Proceedings of the Royal Society of London B: Biological Sciences*, vol. 278, no. 1719, pp. 2761–2767, September 2011.

[7] D. K. N. Dechmann, B. Kranstauber, D. Gibbs, and M. Wikelski, "Group Hunting - A Reason for Sociality in Molossid Bats?" *PLoS ONE*, vol. 5, no. 2, p. e9012, February 2010.

[8] A. Awad, R. German, and F. Dressler, "Exploiting Virtual Coordinates for Improved Routing Performance in Sensor Networks," *IEEE Transactions on Mobile Computing*, vol. 10, no. 9, pp. 1214–1226, September 2011.

[9] N. Pletcher, S. Gambini, and J. Rabaey, "A 2GHz 52 μW Wake-Up Receiver with -72dBm Sensitivity Using Uncertain-IF Architecture," *IEEE Journal of Solid-State Circuits*, vol. 44, no. 1, pp. 269–280, January 2009.

[10] W. Hofer, D. Lohmann, F. Scheler, and W. Schröder-Preikschat, "Sloth: Threads as Interrupts," in *30th IEEE Real-Time Systems Symposium (RTSS 2009)*. Washington, DC: IEEE, December 2009, pp. 204–213.

[11] T. Hönig, C. Eibel, R. Kapitza, and W. Schröder-Preikschat, "SEEP: Exploiting Symbolic Execution for Energy-aware Programming," in *23nd ACM Symposium on Operating Systems Principles (SOSP 2011), 4th Workshop on Power-Aware Computing and Systems (HotPower 2011)*. Cascais, Portugal: ACM, October 2011, pp. 4:1–4:5.

[12] L. Tang, Y. Sun, O. Gurewitz, and D. Johnson, "PW-MAC: An energy-efficient predictive-wakeup MAC protocol for wireless sensor networks," in *30th IEEE Conference on Computer Communications (INFOCOM 2011)*. Shanghai, China: IEEE, April 2011, pp. 1305–1313.

[13] T. Nowak, A. Koelpin, F. Dressler, M. Hartmann, L. Patino, and J. Thielecke, "Combined Localization and Data Transmission in Energy-Constrained Wireless Sensor Networks," in *IEEE Radio Wireless Week (RWW 2015), IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet 2015)*. San Diego, CA: IEEE, January 2015.

[14] C. R. Berger, S. Zhou, Y. Wen, P. Willett, and K. Pattipati, "Optimizing Joint Erasure- and Error-Correction Coding for Wireless Packet Transmissions," *IEEE Transactions on Wireless Communications*, vol. 7, no. 11, pp. 4586–4595, November 2008.

[15] M. Mutschlechner, B. Li, R. Kapitza, and F. Dressler, "Using Erasure Codes to Overcome Reliability Issues in Energy-Constrained Sensor Networks," in *11th IEEE/IFIP Conference on Wireless On demand Network Systems and Services (WONS 2014)*. Obergurgl, Austria: IEEE, April 2014, pp. 41–48.

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