System Design for Encounter Detection of Distributed Wireless Sensors

Martin Hierold #, Simon Ripperger *, Frieder Mayer *,
Robert Weigel #, and Alexander Koelpin #

#Institute for Electronics Engineering Friedrich-Alexander University of Erlangen-Nuremberg
Cauerstrasse 9, 91058 Erlangen, Germany
*Museum fuer Naturkunde, Leibniz Institute for Evolution and Biodiversity Science
Invalidenstrasse 43, 10115 Berlin, Germany
E-mail: martin.hierold@fau.de

***Abstract*—In this paper a system for proximity detection of small sized animals like bats is presented. The system is based on a time slotted communication between compact low weight mobile nodes. For precise time synchronization of the nodes a scalable grid of base stations is proposed that distributes a time reference signal using a time division multiple access (TDMA) scheme. The system parameters are chosen considering the timing constraints caused by the severe requirements to the mobile nodes. In a power consumption analysis the system operation time limited by the 1.8 g nodes is calculated to be 7.4 days. First field test results are shown which proof the functional capability of the system's principle.**

I. Introduction

In recent years technical advances have made great progress possible in wildlife observation. Especially the utilization of wireless sensor networks (WSNs) in field experiments enabled the collection of data which was unaccessible before. One of the first systems of this kind, presented in 2002, was Zebranet. This combination of global positioning system (GPS) receivers in a WSN offers automated recordings of animals' positions [1]. However, this early system could only be used for, e.g., larger mammal species due the high weight of its nodes. Another approach from 2012, the Encounternet system, which aimed at investigating the interactions of individuals reduced the nodes' weight to 10 g offering a two way communication between the nodes. This makes the system applicable for medium sized birds [2]. For smaller mammals, bats in particular, this is still to heavy. Therefore, relatively old fashioned radio-telemetry systems are still widely used here [3]. With these systems only one single bat at a time can be located by triangulation. To this end this a researcher has to manually detect the signals emitted by a simple transceiver that is mounted to a bat by using a directional antenna and a receiver. Approaches to improve the signal detection methods for these systems were made to avoid this tedious work [4] [5]. But these are also resulting in only coarse location information that is not sufficient to determine encounters between individuals. However, the detection of these encounters between animals in their natural environment is of great importance for studying their social behavior. For that purpose a WSN for proximity detection in an theoretical arbitrary large area is presented here. The proposed system consists of a set of mobile nodes carried by bats and base stations in their habitat. The mobile nodes have to fulfill the very severe requirements caused by the low size of the animals and must not exceed a weight of 2 g and a size of about 1 cm^3. The number of base stations determines the size of the area that can be covered with the system. To study interactions within small social groups six bat individuals should be observable during a timespan of at least one week. A field test based on the proposed system is planned at a biological research station in Central America.

II. System Architecture

For encounter detection of different tags a communication between the tags has to be established. Due to the use of a small sized battery to meet the weight and size constraints a permanent transmission and/or reception is not feasible. Therefore, the communication is performed in a time slotted manner between the mobile nodes. Each node repeatedly cycles through a pattern of transmission and reception timeslots. Fig. 1 exemplarily shows a cycle of this communication pattern for two tags. Each cycle is divided into N+1 timeslots, where N is the number of tags in the system. Every tag has a uniquely assigned slot to send out its identification (ID). It listens in N-1

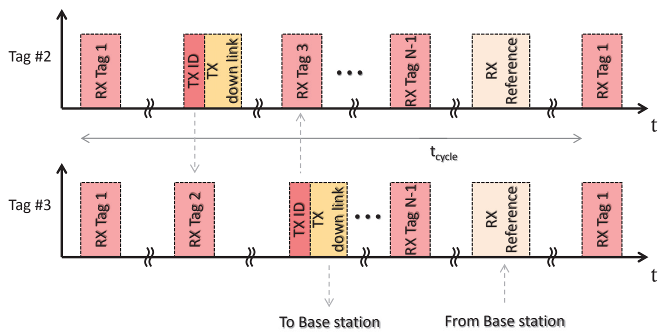

Fig. 1: Time slotted communication pattern of the mobile nodes. Exemplary for tag 2 and tag 3.

ISBN 978-3-9812668-6-3

slots to the IDs of the other tags. The remaining slot is used to receive a time reference signal provided by the base station. This signal is necessary to synchronize the tags among each other, as otherwise the tolerance of the low power oscillator would cause the time slot patterns of different tags to drift apart over time. The distance between two tags is estimated via a received signal strength indicator (RSSI) value that is stored at each meeting along with the ID of the met tag and an absolute time stamp. This information is transferred to a base station receiver directly after the transmission of each tag's ID. In each tag two timers are implemented. One timer determines the timing of the communication pattern and the other timer provides the values of the time stamps. The former is ambiguous with t_{cycle} and synchronized to the base station's reference signal, the latter is unambiguous in the whole operation time but not synchronized during operation. As the transceiver used for the base station offers no duplex capability a dedicated transmitter and a dedicated receiver form a bistatic base station. The base station receiver permanently listens for data transmitted by the tags. When receiving a packet the data is stored on a SD-card together with a time stamp of the reception. In this way it is possible in the later processing of the data to correctly assign packets received by multiple base stations. For the coverage of a wide area, e.g. the hunting grounds of the bats, a single base station would not be sufficient. Thus, multiple base stations have to be applied for the observation of bats while foraging. This means that the same time reference has to be provided by each of the base stations, so they have to be synchronized to each other. This is achieved by using the GPS reference time, which is obtained by a dedicated GPS timing module. We chose a time division multiple access (TDMA) approach to avoid interference between the time reference signals transmitted by different base stations. Each base station sends out the reference signal at a different time than its next neighbor to prevent the interferences. This is achieved by setting up the base stations in a triangle structure which is shown in Fig. 2. The coverage can be extended by repeating the marked array of bases stations. All base stations indicated with the same letter in Fig. 2 send out the time reference signal simultaneously. The TDMA pattern for the distribution of the time reference is shown in Fig. 3. The spacing between two time reference transmissions $t_{TXref,cycle}$ emitted from one base station plus the reference signal duration t_{TXref} must not exceed the receive time reference time slot length t_{RXref} of the tags to ensure the proper reception of the reference signal. Furthermore, the time reference signals transmitted by neighboring base stations must not overlap. Each base station aligns a 16 bit counter to the pulse per second signal provided by the GPS module. This timer then determines the time slot in which each base station transmits the time reference signal. This reference signal transfers the actual value of of the 16 bit counter to the tags so they can synchronize to the global relative time reference. The absolute timer on the tags that is used as a time stamp for the encounters is not synchronized and therefore suffers from the inaccuracy of the low power

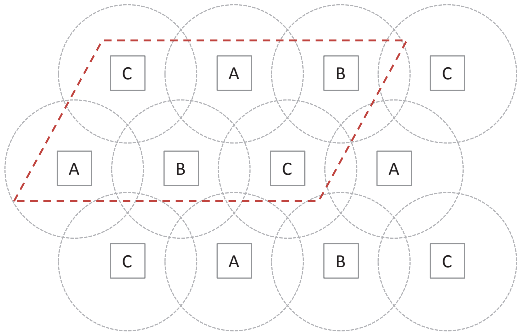

Fig. 2: Geometric arrangement of the base stations. Each circle indicates the area covered by the base station in its center.

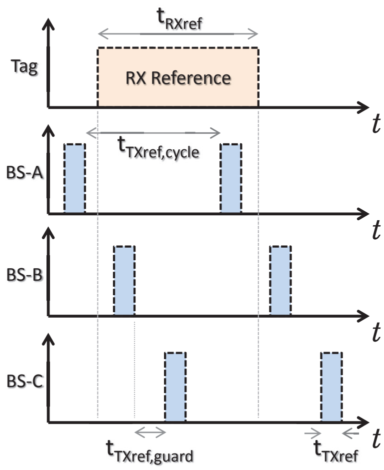

Fig. 3: TDMA pattern of the distribution of the time reference signal by the different base station (BS) instances.

oscillator. However, this is not a critical drawback as this value is to be used in the context of social behavior of the bats for which the desired accuracy is within the range of several seconds to minutes. A detailed consideration of the timings is given in section IV.

III. Hardware

The components of the system are based on the system-on-chip (SoC) solution CC430 from Texas Instruments comprising a MSP430 microcontroller and a sub gigahertz transceiver configured for the use in the 915 MHz band.

A. Mobile node

Besides the CC430 the mobile nodes' circuitry contains a 26 MHz oscillator needed for the transceiver which is connected via a balun to a 8.5 cm long wire antenna. A low power 32.768 kHz oscillator provides the clock for the timing of the mobile nodes. To buffer the high current demands from the SoC during the active phase a 330 µF input capacitor is used. The whole circuitry requires an area of only 12 x 10 mm^2. The tags are powered by a BR1225 lithium primary battery that exhibits a high energy density. The use of a secondary battery was discarded, as a wireless recharging would require additional circuitry and is hardly feasible due to the bat's high mobility. The complete node including this battery and an epoxy sealing does only weigh 1.8 g.

B. Base station

Two low cost Olimex MSP430 CCRF development boards are used as the transmitter and the receiver, respectively, to form the bistatic base station. The transmitter board is connected to the GPS timing module Resolution SMTx on a Carrier Card form Trimble plus a suitable GPS active antenna to obtain the time synchronization. The receiver board is connected via its SPI pins to a SD-card where the received data is stored. The whole bistatic base station is powered by lead-gel battery via a switching regulator. To protect the base station against environmental influences it is set up in a plastic housing.

IV. Timing Constraints

The lithium primary battery is not capable of supplying the transceiver's current demand of several mA directly. For that reason a buffer capacitor is placed between the battery and the SoC. During the inactive times of the tag the capacitance is charged via a resistor in an exponential process while it is discharged with an approximately constant current I_{act} during the active period. This obviously leads to a trade-off between the active period and the recharging time: the longer the tags stay in active mode, the longer the capacitor has to be recharged. The dependency between the maximum active period t_{act} and the minimum charging time t_{ch} can be calculated as:

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

For the values given in table I this dependency is graphically shown in Fig. 4. The tag's current consumption is in transmit (TX)-mode (10 dBm) $I_{actTX} = 32.1$ mA and in receive (RX)-mode $I_{actRX} = 16$ mA. For an intended number of six tags in the system and a cycle time of 1 second the resulting recharging time is approximately 0.14 s. Therefore, an active time in TX- and RX-mode of about 2 ms and 4 ms, respectively, must not be exceeded.

Accordingly, for the distribution of the time reference, the cycle time $t_{TXref,cycle}$ plus the length of the time reference signal t_{TXref} must also stay below 4 ms. The time reference signal consists of 2 bytes containing the timer value plus 7 bytes of overhead which results in a duration of 288 µs at a data rate of 250 kbps. Providing a guard interval $t_{TXref,guard}$ of 0.6 ms results in a cycle time $t_{TXref,cycle}$ of 2.66 ms for the proposed pattern. A slot length of 3 ms for reception of the time reference is therefore sufficient.

TABLE I: Timing constraints parameters

Property		Value
average current drawn from battery	I_{av}	0.5 mA
battery voltage	U_{bat}	2.8 V
capacitance	C	330 µF
resistance	R	200 Ω

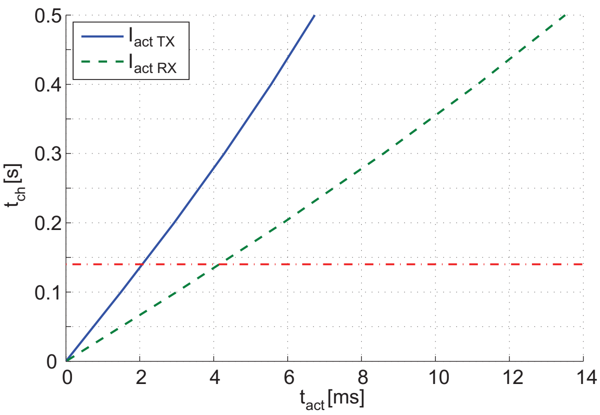

Fig. 4: Dependency of the active period and the recharging time.

V. Power Budget

For the mobile node the current consumptions in its different modes and the corresponding durations per cycle time are summarized in table II. For this values the average current consumption of the mobile node I_{avMN} can be calculated to 215 µA. This results in a total operation time of 7.4 days considering a battery capacity of 38.4 mAh (where a loss in capacity of 20 % due to a heightened current drain is already taken into account).

Table III lists the current consumptions for the base stations' different tasks. To estimate the energy demand of the base stations a worst case consideration is done by assuming a permanent transmission and reception. This leads to an energy demand of 93.2 Wh for each base station, considering an input voltage of 3.3 V. This can be covered by a 12 V lead-gel battery with a capacity of at least 7.8 Ah.

VI. Performance Verification

To verify the operational capability of the system a field test with slightly different parameters was performed in a spatially limited environment. In this field test the capability of encounter detection between different tags mounted to bats was verified. The test was performed in a bat maternity colony in an attic which could be covered by a single base station. The system was scaled to a number of five observable tags. Four of the tags were mounted to bats from this colony, the fifth tag was placed inside the attic to be able to record single bats coming to the roost. As this test was performed in Franconia, Germany the license free SRD frequency band at 868 MHz was used instead of the 915 MHz band. Additionally,

TABLE II: Current consumption of CC430 @ 3V [6] and duration per cycle

Condition	current	duration
sleep	2.2 µA	1 s
transmit ID burst (TXID)	32.1 mA	256 µs
down link transmit burst (TXDL)	32.1 mA	1.5 ms
receive ID time slot (RXID)	16 mA	1.5 ms
receive reference time slot (RXREF)	16 mA	3 ms
microcontroller active (µC)	3.45 mA	< 3 ms
crystal oscillator start up (XO)	9.5 mA	∼ 1 ms

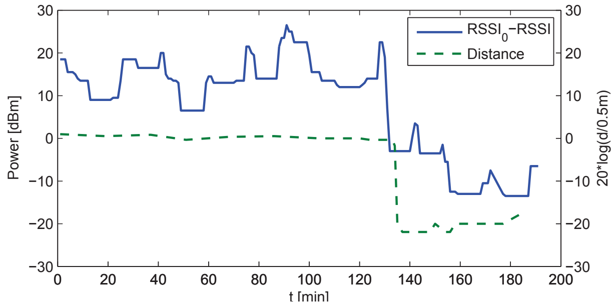

Fig. 5: Comparison of recorded RSSI value and the distance between two bats extracted from the video data. The RSSI value shown here is the maximum within a timespan of ± 3 minutes.

the radio tagged bats were marked with reflecting tape and a nightshot camcorder was placed in the roost. By this means the encounter detection data could be verified by the analysis of the video material.

With this setup encounters between 7 different tag constellations could be recorded within a time span of 3.5 days. The reduced observation time was caused by a time limited access to the roost of the bats and not by the operation time of the system. Besides the pure capability of detection of encounters between individuals the RSSI value could be successively used as a measure of the distance between the individuals. Fig. 5 shows the comparison of the recorded RSSI value and the distance between two animals extracted from the video data. For the plotted RSSI value at each point in time the maximum value within a timespan of ± 3 minutes was taken to flatten out the drops. This is considered to be reasonable, as the drops caused by misalignment of the antennas due to movements of the animals carry no useful information. The RSSI data is subtracted from a reference value $RSSI_0$ for better comparison with the distance curve which is also given in a logarithmic scale. $RSSI_0$ was determined prior to the test by reference measurements and corresponds to 0.5 m. The offset between the RSSI value and the distance results from a degradation of the antenna characteristic due to the mounting of the tags to the bats' bodies. The agreement of shape of both curves proof the applicability of the RSSI value as an estimate of the distance between the tags.

VII. Conclusion

In this paper the design of an encounter detection system for the observation of individual bats in an enlarged area was presented. A hardware setup for this system was proposed. For dimensioning the system parameters timing constraint considerations caused by the severe energy constraints on the mobile nodes have been performed. Based on this considerations the parameters were chosen and a power budget calculation proofed that the demanded operation time of the system of more than one week can be met. In a first test the capability of encounter detection of bats could successfully be shown and the RSSI value could be verified to serve as an estimate of the distance between the animals.

TABLE III: Current consumption of base station

Condition	current
transmit time reference (10 dBm)	32.1 mA
receive data	16 mA
receive GPS time reference	100 mA
active GPS antenna	11 mA

Acknowledgment

This work is funded by German Science Foundation DFG grant FOR 1508, Research Unit BATS ”Dynamic Adaptable Applications for Bats Tracking by Embedded Communicating Systems”.

References

[1] P. Juang, H. Oki, Y. Wang, M. Martonosi, L.-S. Peh, and D. Rubenstein, “Energy-Efficient Computing for Wildlife Tracking: Design Tradeoffs and Early Experiences with ZebraNet,” *ACM SIGOPS Operating Systems Review*, vol. 36, no. 5, pp. 96–107, December 2002.

[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, J. J. Millspaugh, and S. A. Wolf, *Ecological and behavioral methods for the study of bats*. Baltimore: Johns Hopkins University Press, 2009, ch. Radiotelemetry: Techniques and analysis, pp. 57 – 77.

[4] F. Korner, R. Speck, A. Goktogan, and S. Sukkarieh, “Autonomous airborne wildlife tracking using radio signal strength,” in *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*, Oct 2010, pp. 107–112.

[5] R. Kays, S. Tilak, M. Crofoot, T. Fountain, D. Obando, A. Ortega, F. Kuemmeth, J. Mandel, G. Swenson, T. Lambert, B. Hirsch, and W. M., “Tracking animal location and activity with an automated radio telemetry system in a tropical rainforest,” *The Computer Journal*, 2011.

[6] *CC430F6137, CC430F6135, CC430F6127, CC430F6126, CC430F6125 CC430F5137, CC430F5135, CC430F5133 MSP430 SoC With RF Core*, Texas Instruments Incorporated, http://www.ti.com/lit/ds/symlink/cc430f5137.pdf, 07 2014.