Ultra Low-Power Sensor Networks for Next Generation Wildlife Monitoring

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***Abstract*—We discuss challenges and solutions to enable ultra low-power communication systems. In the field of sensor networks, this question has been investigated for multiple decades now. However, only the combination of technological and algorithmic methods eventually helps designing next generation systems. Using wildlife monitoring as an application scenario, in particular monitoring the social behavior of bats, we explore novel solutions for low-power communications given the high reliability requirements and weight restrictions. We go stepwise through a series of hardware, signal processing, and coding solutions that we developed, in order to illustrate our advancements. Our concepts have been evaluated both in large-scale simulation as well as in first field experiments.**

***Index Terms*—Wildlife monitoring, sensor networks, wake-up receiver, diversity combining, forward error correction**

I. Introduction

Wireless Sensor Networks (WSNs) have become quite popular for many Internet of Things (IoT) applications because of their self-organized operation and relative ease of use [1]–[3]. One of the first applications that gained attention beyond environmental monitoring and smart home applications has been wildlife monitoring [4]–[8]. Wireless digital transceiver technology rendered even the automated mapping of social networks in wild birds possible, e.g., in the Encounternet project [9]. From these successful approaches to wildlife monitoring using sensor networks, our research community learned about hardware design issues networking questions, and application-specific challenges.

The main focus in sensor network research always has been energy. As most of the considered scenarios, including wildlife monitoring, rely on battery-powered devices, energy consumption is the key factor. Looking from a networking perspective, approaches to low-power operation range from duty cycling [10] to low-power listening [11] to wake-up receivers [12], [13]. Based on these principle concepts, many protocols have been developed over the years that also found their way into current IoT protocol standards.

Another approach to save energy is making the communication more reliable without the need of retransmissions, i.e., saving on every message that has not to be retransmitted. Most popular techniques include smart Forward Error Correction (FEC), such as erasure codes, which have been widely employed to improve the reliability in wireless transmissions in general as well as in wireless sensor networks [14], [15]. The optimal trade-off between error-correction coding within packets and erasure-correction coding across packets has been investigated for wireless transmissions without feedback channel, for example, in [16]. Similarly, receive diversity can be used to improve reception quality. In MIMO systems, algorithms such as Equal Gain Combining (EGC) or Maximum Ratio Combining (MRC) have been proposed to exploit spatial diversity of multiple receiving antennas to overcome channel impairments [17], [18]. Using the sensor network as a distributed antenna array, receive diversity can be exploited even without multiple antennas connected to a single receiver [19].

What is interesting is that very few concepts have been proposed based on combinations of the aforementioned approaches to reduce energy consumption in sensor networks. From a holistic view, the network lifetime can be used as a metric [20], which takes into consideration not only individual nodes but also the reliability of the network as a whole.

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. Until now, bat tracking is primarily based on simple radio telemetry, which requires high labour 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. We have gone one step further compared to related activities to continuously monitor contacts or *encounters* between individuals. Mouse-eared bats (*Myotis myotis*), one of the most protected species in the European Union, are our 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 [7], [21].

The main application scenario is shown in Figure 1 [7]. As depicted in this figure, 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.

In this paper, we review the core components of the developed system architecture, which we meanwhile also used for experiments in the wild [22]. The rest of this paper is structured as follows. We first introduce our protocol and

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

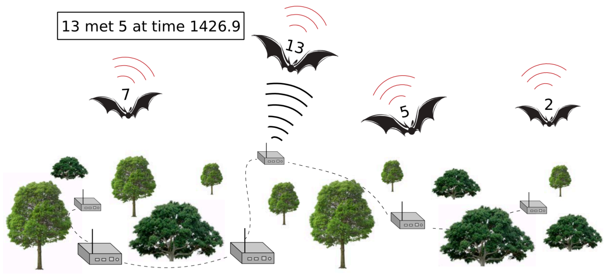

Figure 1. Conceptual scenario for bat tracking in the wild: [7].

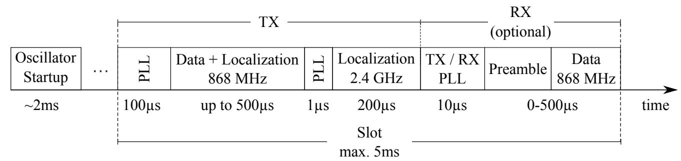

Figure 2. Communication protocol design [26].

system architecture in Section II. In Section III, we discuss our innovative wake-up receiver system, which is the basis for triggering both downloads of collected encounter information as well as software updates. Sections IV and V introduce our investigations on using coding and the use of receive diversity on signal level to improve communication reliably, respectively. We finally provide some conclusions in Section VI.

II. Protocol and System Architecture

Looking at the literature, a number of methodologies have been identified for low-power communication: (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 [23]; (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 [24]; 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 [25]).

We developed a novel approach to go one step further. Rather than using only one of these methodologies, we, for the first time, deeply integrated duty-cycling and a wake-up receiver [7], [26]. As our lightweight sensor node for bat monitoring can only make use of a very small lithium battery and as such small battery cannot provide sustainable sufficient current to power the microcontroller, we first charge a capacitor, which, in turn, can power the microcontroller for a very short time. Duty-cycling helps reducing the energy consumption (and supports recharging the capacitor). Furthermore, unnecessary transmissions need to be prevented when the bat is not in communication range to at least one ground node (or another mobile node). We use a multi-stage wake-up receiver to completely power-off both the radio transceiver and the microcontroller. When the bat is in range of a ground node, the wake-up receiver triggers the node and starts up all communication tasks.

Now, these two concepts (duty-cycling and wake-up systems) can be combined to benefit from each other. The wake-up system is used to synchronize the duty-cycle of all mobile nodes in communication range (we will discuss the need and possibility to even wake-up selected nodes in Section III). In order to support a large-scale ground network, we assume all these ground nodes to be synchronized so that mobile nodes are woken-up in perfect synchrony. 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. The entire communication slot is depicted in Figure 2 [26]. 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. Thus, multiple slots can be provided per ground node. At the moment, we assume a frequency of 10 Hz for trajectory estimation, thus, we can support about 10 nodes transmitting per wake-up pulse. Guard intervals have been introduced because the sensor nodes are not synchronized perfectly and since the oscillators might drift considerably due to temperature differences.

III. Wake-Up Receiver

Wake-up receiver have been developed to reduce (or, if possible, to eliminate) energy wastage during idle listening phases [12]. The general idea is to first send a wake-up signal that is received by a dedicated wake-up receiver. Only if such signal has been detected, the full radio transceiver and the microcontroller are powered up. Wake-up receiver only consume some nW to µW and can, therefore, be active all the time. Modern multi-stage wake-up systems furthermore support selectively waking up nodes using a node specific wake-up sequence in order to reduce false wake-ups [12], [13]. The low energy consumption however comes at the price of small data rates and low sensitivity. Therefore, they are only used to receive a short wake-up signal to turn on the microcontroller and the main transceiver to perform the actual data transmission.

In many cases, such addressing capabilities using simple pattern matching are not sufficient. These receivers can only support one wake-up scheme at the same time (unicast, multicast, or broadcast). Commercially available examples of such addressable wake-up receivers include the AS3933 from AMS, which can decode an On-Off-Keying (OOK) modulated signal and check whether this signal contains a certain predefined pattern. In order to listen to another address or to change from one scheme to another, all nodes have to be reconfigured.

We developed a new technique for what we call Selective Wake-Up Receiver (SWuRx), in which we send an address *combined* with a mask in the wake-up signal [27], [28]. This allows the *sender* of the signal to determine the wake-up scheme without reconfiguring the nodes. In essence, the mask field is used to tell the receiver, which address bits are supposed to be checked during the wake-up procedure.

Figure 3 [28] shows the basic architecture of our system. It consists of a microcontroller, a low-power OOK receiver,

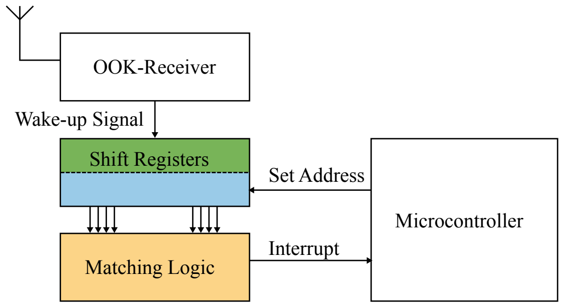

Figure 3. Basic Architecture of our SWuRx platform [28].

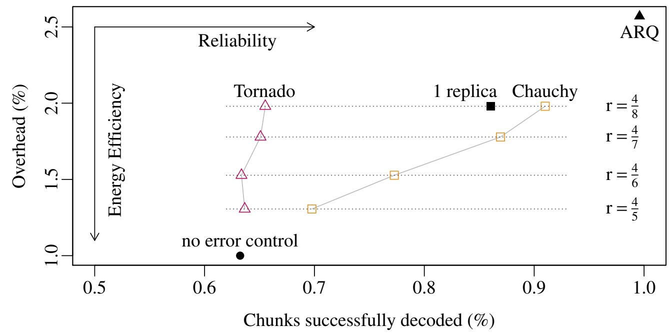

Figure 4. Reliability gain achieved by of the different error control strategies and code rates r versus energy efficiency [33].

and the wake-up logic. We introduced a quite lightweight approach using some additional shift registers and a matching logic for low-power pattern matching without powering up the microcontroller. The shift registers store the received data (green) and the predefined address of the node (blue). The logic gates (orange) check if the received data causes a wake-up for this node.

The procedure is as follows. In the initialization phase, the microcontroller configures the OOK receiver and writes the node's address into the shift register. Our new wake-up signal consists of a target address (or pattern) and a mask. When the wake-up signal is received and decoded by the OOK receiver, it is stored in a second shift register. The pattern matching logic circuit now checks for each bit in parallel. If the node's address matches the received one for all positive mask bits, an interrupt signal is raised that wakes-up the microcontroller.

Based on a prototype, we validated the feasibility of our approach and discussed the performance aspects in [27], [28].

IV. Forward Error Correction

An orthogonal approach to reduce the energy consumption in sensor networks is to improve the communication reliability without additional retransmissions. This is a particularly challenging issue in very dynamic environments, wildlife monitoring being just an example.

Due to the continuous movements of bats and the heterogeneous forest environment, the channel quality will vary massively. Usually, the simplistic approaches such as sending chunk replica together with the original data or using even sophisticated Automatic Repeat Request (ARQ) mechanisms add to the energy consumption due to additional transmissions.

Alternatively, FEC techniques can be used. The study presented in [29] includes a comprehensive comparison of ARQ and several forward error correction codes. The results indicate that Erasure Codes (ECs) are best suited for delay sensitive sensor networks since energy consumption and end-to-end latency are reduced. Meanwhile, ECs have been widely employed to improve the reliability in wireless transmissions in general as well as in wireless sensor networks [14], [15]. The key question is to whether apply FEC on the physical layer or much higher in the protocol stack. The trade-off between error-correction coding within packets and erasure-correction coding across packets has been investigated, for example, in [16].

We have explored ECs as a promising approach in our sensor networks [15], [30]. ECs offer a very good performance with reduced costs in terms of energy consumption. ECs mainly differ in the specific mathematical concepts in the encoding and decoding algorithms. Examples are Reed Solomon (RS) codes such as Cauchy [31] or Vandermonde [32].

In [33], we reported on an extensive study of using ECs for our bats monitoring scenario. For these investigations, we used a bat mobility model based on empirical observation data from field studies [15]. We were particularly interested in the impact of different code rates, which essentially define the possible error correction and the resulting overhead for additional coding data.

Of course, the coding increases the overall energy consumption, which is due to (a) the encoding algorithm and (b) the need for redundant information. This trade-off is depicted in Figure 4 [33]. We plot both the results of sending without error control and the use of ARQ as well as the results of using different ECs. 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.

We see that increased reliability comes at the cost of additional energy consumption. However, ECs like Cauchy improve the trade-off between reliability and energy consumption very effectively. Furthermore, due to the variable code rate, they can be adaptively configured depending on the scenario as well as the currently observed error rate.

V. Diversity Combining

The communication reliability can also be improved on the receiver side, so that no additional (energy) cost needs to be spend at the mobile transmitter. A well-known concept is diversity combining, which has been introduced to increase the robustness of wireless communication systems [17]. The idea is to use multiple antennas connected to the same receiver. In the best case, each antenna received an uncorrelated copy of the signal, which are aligned, co-phased, and added constructively. This way, the received Signal-to-Noise Ratio (SNR) can be improved without the need to increase the transmit power [18]. Well-known receive diversity algorithms include

Table I
POSSIBLE DIVERSITY GAIN VS. DATA RATE REQUIREMENTS [19].

Data Handling	Single Node (Mbit/s)	50 Nodes (Mbit/s)	Diversity Gain
Complete signal	64	3200	Highest
Signal samples	3.07	153.6	Highest
Soft-Bits	0.31	15.36	Medium
Hard-Bits	0.01	0.48	Very low

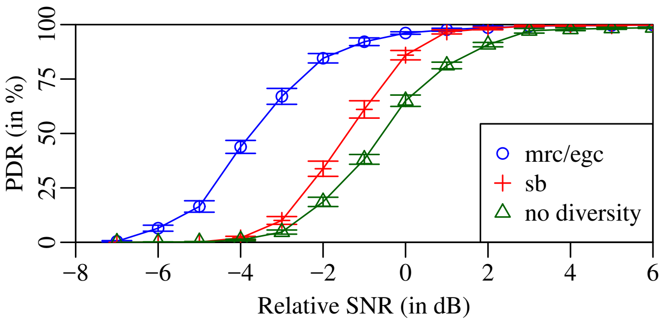

Figure 5. Experimental PDR for a two-branch diversity system [37].

EGC and MRC [17]. Modern communication systems even use distinct receivers as a distributed antenna array to not only overcome fading but also make the system more robust against interference and shadowing [34]. This, however, also opens new research challenges such as time synchronization of these receivers and data rate limitations between the systems [35].

In [36], we proposed to use the ground network of our bats system as such distributed antenna array. We explored all the possibilities of standard receive diversity algorithms, both on soft-bits as well as on the raw signal samples.

We found that converting the signal into soft-bits substantially reduces the amount of data that needs to be forwarded in the ground network, however, the diversity gain is comparatively low. Focusing on the very high data rates when transmitting raw signal samples through the ground network, we later proposed the concept of selective signal sample forwarding [37]. Here, all receivers try detecting the signal locally and forward only those signal samples that are equivalent to the packet-length.

Table I [19] shows selected results of the resulting data rates compared to the achieved diversity gain. We assume a ground network of 50 nodes and a single bat sending messages at 10 Hz. As can be seen, about a data stream of 64 Mbit/s would be generated the full signal samples compared to only 0.3 Mbit/s for softy-bits. Our selective signal forwarding positions in the middle at about 3 Mbit/s while maintaining the same diversity gain as for the full signal samples stream.

In order to also look at the diversity gain in more detail, we plot selected results from a measurement series Figure 5 [37]. We used USRP Software Defined Radios (SDRs) to collect signal samples in a lab environment (we later validated these results also in the wild [19]). These results show the baseline performance of different receive diversity techniques in a simplified scenario. SB stands for successful branch and shows the best possible reception assuming an oracle selecting the best ground node for each transmission. EGC and MRC provide an improvement of about 3 dB for a two-branch diversity system compared to no diversity and still about 2 dB compared to our oracle receiver. This diversity gain finally helps decoding even very weak messages, which, in turn, do not need to be retransmitted from the energy-constrained mobile sender.

VI. CONCLUSIONS

We reviewed approaches to improve the energy performance in sensor networks, which are, for example, used for wildlife monitoring. Quite a number of techniques have been proposed to reduce energy consumption, improve the reliability, and, eventually, the network lifetime. This includes solutions on the physical layer to improved medium access to hardware improvements. Using our bats monitoring as an example, we discuss how such mechanisms can be combined. We started with a novel combination of duty-cycling with modern wake-up receivers, which directly impact the energy performance. Indirect impact can be achieved by reducing the communication overhead that stems from unreliable wireless links. In order to reduce expensive retransmissions, Erasure Codes (ECs) can be used for error control. Turning ground nodes into a distributed antenna array, we can further make use of receive diversity techniques to improve the packet reception rate and to eventually reduce the energy footprint to finally make ultra low-power sensor networks reality.

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