Design of Autonomous Base Stations for Low Power Wide Area (LPWA) Communication

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***Abstract*—The *Internet of Things (IoT)*, *Machine-to-Machine-Communication (M2M)* and *Industry 4.0* are keywords arousing great research interest in recent years. All these terms incorporate the idea of data exchange among diverse objects in wireless sensor networks. In a previous paper, we extended the domain of sensor-based applications to the scope of wildlife tracking, in particular the tracking of bats. The concept of a *Low Power Wide Area (LPWA)* sensor network was introduced, built up by lightweight *Ultra Low Power (ULP)* nodes attached to the back of the animals, transmitting sensor data via long range telemetry over a distance of several kilometers. The network architecture was discussed and suitable transmission schemes meeting the harsh energy and weight restrictions were evaluated. For an optimal system performance, however, it is also essential that the receiving network is properly designed. In this paper, we elaborate the development of a LPWA reception network of telemetry-related base stations, tackling the highly demanding requirements for mobility, energy efficiency and remote maintainability. Both, hardware as well as software components are addressed and their interactions are illustrated. The energetically self-sustaining base stations are equipped with directional and omni-directional antennas in a MIMO-like fashion. A Software Defined Radio (SDR) controlled frontend allows for a flexible reception and fast data processing. The operation performance toward the stated requirements is evaluated. Finally, initial results of field trials in Berlin (Germany) are presented, proofing the successful recording of actual bat signals.**

***Index Terms*—Low Power Wide Area (LPWA) communications, Ultra Low Power (ULP) wireless sensor network, long range telemetry, base station design.**

I. Introduction

Concepts like Machine-to-Machine-Communication or the Internet of Things share the common objective to endow numerous heterogeneous objects with sensors and thus, enable them to exchange data among each other or with a central hub. The collectivity of connected nodes forms sensor networks whose field of applications range from communicating workpieces in industry to infrastructure monitoring and countless other scenarios. We extended this range of usage by deploying a sensor network for wildlife tracking, in particular the tracking of bats. Conventional tracking approaches incorporate rather bulky antennas and manual handling, resulting in high costs and effort, yet not providing satisfactorily accurate data [1], [2]. Furthermore, the amount of tagged animals is restricted as transmitters are expensive and limited in number. These drawbacks let sensor networks appear to be advantageous over regular tracking methods, especially when it comes to the tracking of an extensive amount of individuals as well as extremely lightweight animals like bats, only capable of carrying a tag of few grams [3]. In an interdisciplinary project, the so called *BATS*[1] project, funded by the German Research Foundation (*Deutsche Forschungsgemeinschaft, DFG*), we equip numerous bats with Ultra Low Power (ULP) sensors, thus forming a Low Power Wide Area (LPWA) [4] telemetry sensor network. These bat nodes not only facilitate the communication among each other, exchanging their unique identification (ID) to generate so-called *meetings*, but also allow for collecting sensor data like air pressure or acceleration. These data sets are then forwarded wirelessly via high rate modulation to a system of ground stations, when in range. Hereby, the aim is to perform a long-term monitoring of a multitude of individuals and thus, enable the identification of collectives among animals, as well as a better understanding of social interactions, hunting behavior and group dynamics. The *BATS* project is divided into two phases. In the first phase, that has already been completed, the aforementioned system of distributed ground stations was developed, positioned in a dense structure around the assumed roost of the bats in the forest. They are serving the purpose of the localization of bat nodes and act as a communication hub for the short range communication when gathered sensor data and generated meetings are downloaded to the ground network. With the current system proofing its functionality, the trackable range is yet limited, as the deployment of additional stations is costly and the bats are not capable to carry bigger batteries. In addition, the system shall still enable a long-term observation, lasting for up to nine days [3]. Enlarging the range of transmissions under the harsh restrictions of weight and energy efficiency is thereby imposing rather contradictory requirements. In the second phase of the project, we tackle these challenges proposing an adaptive transmission scheme subject to the distance of the nearest station and the channel characteristics at hand, as presented in our previous paper [5]. To expand the tracking range even far beyond the area covered by the ground stations, we alter the transmission mode switching rate and modulation dynamically. The so-called *Telegram Splitting (TS)* technique is utilized for the newly introduced long range telemetry, allowing for robust transmissions for up

[1] http://www.for-bats.org/

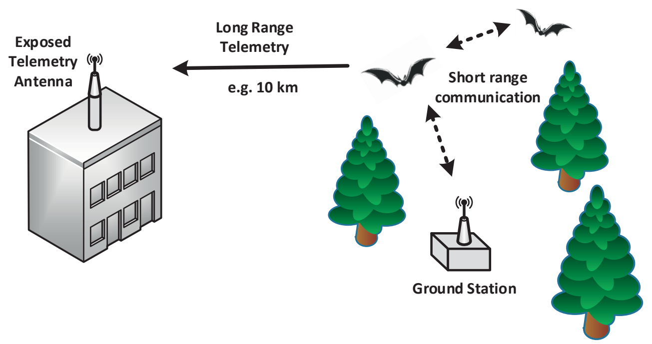

Fig. 1. Newly introduced long range telemetry base stations extending the existing ground network.

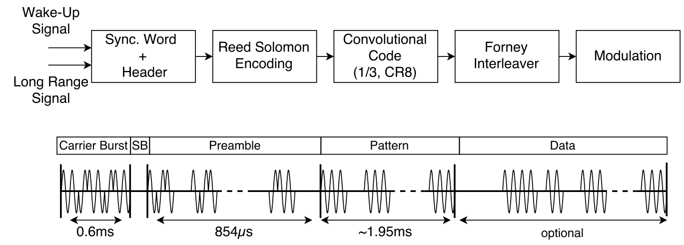

Fig. 2. Encoding chain and waveform of the bat signals.

to $10\,\mathrm{km}$ at reduced data rate in narrowband communication [6], [7]. In dependence of the inferred scenario, the sending behavior along with its corresponding data rate is adopted, aiming at an optimal balance between data volume and energy efficiency. To support the usage of long range telemetry within the existing system, we introduce new telemetry-related base station types, extending the existing ground station network. Fig. 1 shows an illustration of the ground network extended by the additional long range telemetry base stations.

In this paper, design considerations for these new telemetry stations are presented. At first, a short introduction to the encoding scheme of the bat signals is given in Section II. Furthermore, an estimate for the minimal reception power and the resulting transmission range is given, based on the minimal Signal-to-Noise-Ration (SNR) for error-free reception and the system's noise figure that is derived in Section V. Subsequently, Section III states requirements for the developed base stations that receive these signals, comprising the needs for mobility, energy efficiency and maintainability. Section IV addresses the software framework hosted by the frontend. Initial results of a first field trial conducted in Berlin (Germany) are depicted in Section V. The evaluation of the reception chain regarding its noise figure, energy efficiency and operation performance is also subject to this section. Finally, Section VI summarizes the system layout along with the test results and concludes this paper by illustrating ongoing work for a further system enhancement.

II. Encoding Scheme of Bat Signals

This section shortly illustrates the encoding scheme of the signals sent out by the bats, as these explanations make up the basis for the system evaluation in Section V. A block diagram of the encoding chain along with a stylized depiction of the resulting waveform is shown in Fig. 2, where SB denotes the term separation bit.

The bat nodes broadcast the so-called wake-up beacons (compare [5]) in periods of several seconds, using an On-Off-Keying (OOK). These signals trigger other nodes to generate meeting data as described in Section I. Since no information is carried within the phase of these signals, they can efficiently be exploited for the purpose of the long range telemetry transmissions without any additional expenditure of energy. Therefore, a combined modulation is performed, applying an additional Binary Phase Shift Keying (BPSK) on the OOK sequence that encodes the telemetry data. Following Fig. 2, both streams, the wake-up and telemetry signal are extended by a synchronization word and header information. The Forward Error Correction (FEC) is implemented by a shortened Reed Solomon Code (RS(253,255)) for error detection combined with a convolutional code (0255,0331,0367) with a code rate of $\frac{1}{3}$ and a constraint length of 8. A subsequent Fourney interleaver exhibits 24 branches. It is spreading one payload byte over 24 wake-up bursts, resulting in a time interleaving of approximately one minute and thus ensuring an ultra-robust transmission. Subsequently, the OOK modulation is performed with the telemetry data being encoded by alternated phases of the OOK sequence. The phase modulation is performed within the carrier burst and the preamble as these are fixed in length and shape, so the on-times are known (*cf.* Fig. 2). The pulses are Manchester-coded to extinguish any dependency between the number of on-times and the data that is being transmitted.

An interesting research aspect is the investigation of the minimum reception power needed for a certain tolerated error probability. For this purpose, the error rate was simulated, provided the parameters for the applied forward error correction scheme just presented (*cf.* Fig. 2). Fig. 3 shows the results on the bit as well as the packet level in dependency of different Signal-to-Noise (SNR) values besides the curve for the uncoded transmission for comparison.

For a packet error rate of $20\,\%$, with a packet consisting of 5 bytes, one obtains a minimal SNR value of about $-5\,\mathrm{dB}$. Providing this value along with the base stations' noise figure of $6\,\mathrm{dB}$ (see Section V), one is able to calculate the absolute minimal signal strength needed for a successful decoding. Given a nominal payload data rate of $11.363\,\mathrm{kbit/s}$ for the long range telemetry signal as well as the presented values for the noise figure and the thermal noise floor, the equivalent noise power computes to $-127.4\,\mathrm{dBm}$. With Fig. 3 showing the case for a regular BPSK modulation, one has also to correct the minimal SNR needed by an offset of $3\,\mathrm{dB}$, accounting for the energy loss due to the carrier. Consequently, a minimal theoretical reception strength of $-129.4\,\mathrm{dBm}$ is obtained for the discussed scenario. Assuming an equivalent radiated power (EIRP) of the bat node of $5\,\mathrm{dBm}$ and an antenna gain of $17\,\mathrm{dB}$, a overall path loss of $151.4\,\mathrm{dB}$ can be overcome, while still providing a successful packet decoding rate of $80\,\%$. These

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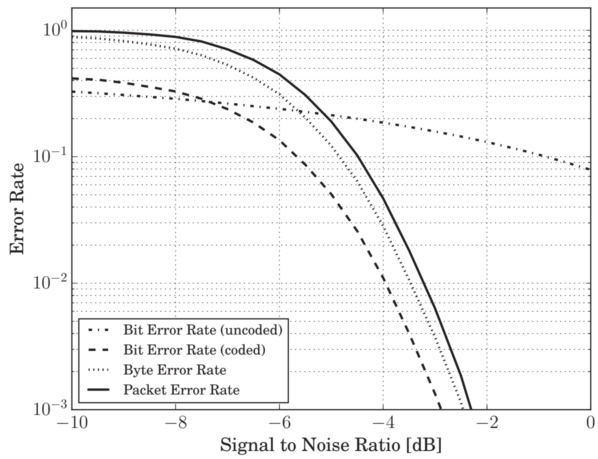

Fig. 3. Bit Error Rate and Packet Error Rate for the presented encoding scheme in dependency of different SNR values.

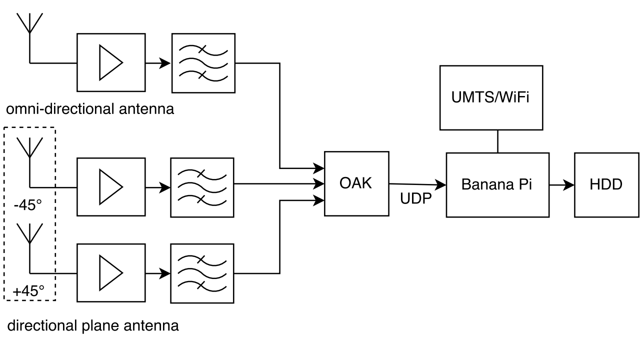

Fig. 4. Schematic representation of the essential hardware components.

findings show that a transmission over several kilometers is possible, even under the unfavorable circumstances of a bat flying at low altitude and a base station having a minor height (compare Fig. 5 in [5]).

In Section III the design of appropriate long range telemetry base stations is addressed, capable to receive and process the bat signals just presented.

III. System Components

Aiming at an ideal base station design, a deliberate selection of components is essential. In this section an overview over the whole structure of the base station is given, illustrating its components based on the station's needs. Fig. 4 shows a simplified diagram of the main hardware components, serving as a reference for the following explanations.

Power Supply

For the application of wildlife monitoring the new stations have to meet certain requirements. One is mobility, as several stations shall be deployed at various locations, so an architecture as small as possible is preferable. Furthermore, the energy efficiency is another design aspect, since a continuous power supply might not be available on-site and a strict separation of power supply lines is beneficial for insurance reasons. A battery powered operation shall still be possible for several days though. Consequentially, we supply the complete station just with a solar battery providing $150\,\mathrm{Ah}$ of energy. This setup also allows for an extension by a solar panel and thus enables a self-sufficient operation even for weeks. The voltage of $12\,\mathrm{V}$ supplied by the battery is down-converted to $5\,\mathrm{V}$ by a converter circuitry and distributed within the system.

Antennas

At first, the choice of antennas has to be considered. In contrast to the ground stations, the newly introduced telemetry stations are sited at exposed positions, preferably on top of high buildings, thus, assuring an approximate line of sight when the bats rest in trees or fly while hunting. For a signal detection in distances of up to ten kilometers with a maximum equivalent isotrophic power (EIRP) of just about $5\,\mathrm{dBm}$ [5], dual polarized panel antennas with an average gain of $14\,\mathrm{dBi}$ and a half-power beam width of $66°$ were chosen. They cover the desired Short Range Devices (SRD) frequency band around $869\,\mathrm{MHz}$ allocated by the bat nodes. Internally they consist of two antenna arrays mounted in a cross-like fashion with an angle of $\pm 45°$ respectively (*cf.* Fig. 4) [8]. These antennas exhibit a directional radio pattern and are thus arranged facing in a direction towards the forest. There might be some situations in which the bats fly around the station and therefore, are not trackable in the dead zone of the directional antennas. To mitigate that, each base station is also equipped with an omni-directional antenna with $0\,\mathrm{dBi}$, yet a $360°$ beam width. Thus, a MIMO-like system is established, enabling techniques of stream combining for improved reception.

Signal Processing

As the signal is received by one or more antennas, it is subsequently fed into a Low Noise Amplifier (LNA). This LNA is characterized by a low noise figure of just about $0.5\,\mathrm{dB}$ and a high gain of approximately $17\,\mathrm{dB}$ at the center frequency of $869\,\mathrm{MHz}$ [9]. The LNAs are highly sensitive to deviations imposed on the supply path, involving the danger to harm their linearity. Therefore, unlike the rest of the components, they are powered by a separate dedicated power supply that assures a smooth progression. Subsequent to the amplifier, the signal is filtered by a bandpass filter covering the SDR band between $863\,\mathrm{MHz}$ and $870\,\mathrm{MHz}$. Within this band, the bat nodes transmit data according to the Telegram Splitting technique with varying center frequencies [5], [6]. The filtering serves the purpose of a channel preselection and is needed, since other strong interfering signals present on these unlicensed bands might otherwise impair the reception of the rather weak bat signals. The next component of the signal processing chain is the so-called OAK board, a self-developed receiver frontend board that samples the scanned spectrum and generates complex IQ samples. The RF-frontend comprises the Analog Devices AD9361 transceiver module endowed with $12\,\mathrm{bit}$ ADCs and supporting bandwidths of several MHz [10]. The plug-in MicroZed card [11] extends the frontend by additional programmable logic. After the digitalization of the spectrum, the IQ samples are processed by a Banana Pi M3 single board computer. For a mobile base station a lightweight setup is needed that is as energy-efficient as possible but is powerful enough to handle the tremendous data rate caused by the streams of all three antennas at a certain bandwidth. The Banana Pi is therefore ideal for the application, as it exhibits just a small scale, yet provides eight processing cores for pure multi-threading, sufficient RAM and a dedicated floating point unit [12]. Furthermore, it is capable of running various operating systems as a basis for hosting our self-developed SDR signal processing framework (see Section IV). Following to the signal processing, the data is stored on an external hard drive disk (HDD) of several terabytes connected to the Banana Pi via USB 2.0. A stand-alone USB driver ensures access compatibility and data integrity between different systems when the recorded data sets are read out again.

Remote Access

With the measuring sites being far off in the woods, a maintenance of the system is not easy to provide. For the purpose of an operation monitoring and the control of the stations, a remote access was implemented by the means of a mobile UMTS modem serving also as a local WiFi router (*cf.* Fig. 4). A model supporting only UMTS connections was deliberately chosen because the uplink of the LTE standard occupies frequencies close to the SDR band from 863 MHz to 870 MHz that the base stations are scanning for bat signals, whereas UMTS uses frequency bands at 1900 MHz and above. Thus, the danger of masking comparatively weak reception signals can be avoided when the modem transmits. A minor transfer rate is unproblematic as just the stations' control and configurations are carried out over the connection and a streaming of data is not needed. The modem's local WiFi network serves as an entry point for the Banana Pi to connect to. Subsequently, a virtual private network (VPN) is established with a VPN server hosted at the chair or control facility. The manipulation of base stations is then performed via remote access using SSH (Secure Shell), regulating process execution and manipulating configuration files.

Within this section an overview of all system components was given. They are arranged on two levels within a waterproof enclosure for long-term outdoor measurements. Fig. 5 shows a picture of the whole circuitry, whereas Fig. 6 depicts the complete developed base station (solar panels are not shown). Section IV briefly introduces the software framework hosted by the OAK board and Banana Pi for data handling and manipulation.

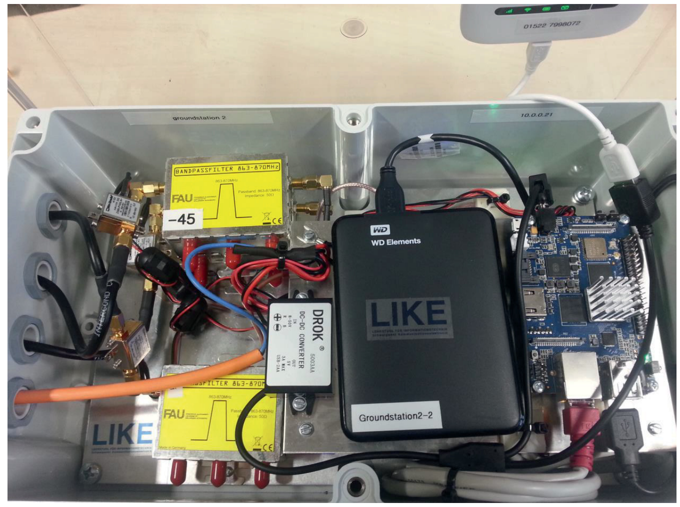

Fig. 5. Picture of the hardware setup showing the LNA, filter, HDD, Banana Pi and UMTS modem (OAK underneath).

Fig. 6. Picture of the complete base station on a rooftop facing the forest. The omni-directional antenna is mounted on top, followed by the directional sector antenna array, battery and circuitry.

IV. Software Framework

The software running the base stations should be maximally flexible and generic to allow for the reception of different signals with various frequency, bandwidth, rate and modulation. Moreover, speed concerns are of interest, since the data handling has to cope with high data rates of several streams and a loss of samples must be avoided. Aiming at these requirements, a SDR signal framework, the so-called *Data Flow Control for C++ (DFC++)*, has been developed by the chair in cooperation with the Fraunhofer Institute of Integrated Circuits (Fraunhofer IIS[2]) [13]. The framework offers an efficient operation on different platforms such as PCs, ARM chips or DSPs. A module-based structure and a common interface definition ease the integration and portability of various software components. Additionally, the acceleration of execution is an important design aspect. The usage of modern programming techniques and flow control mechanisms for multi-threading allow for dynamic signal paths as well

[2]https://www.iis.fraunhofer.de/

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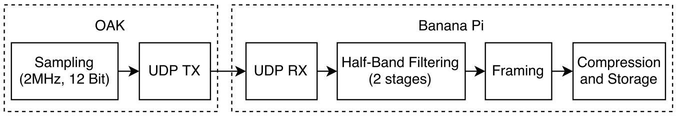

Fig. 7. Software modules for data processing.

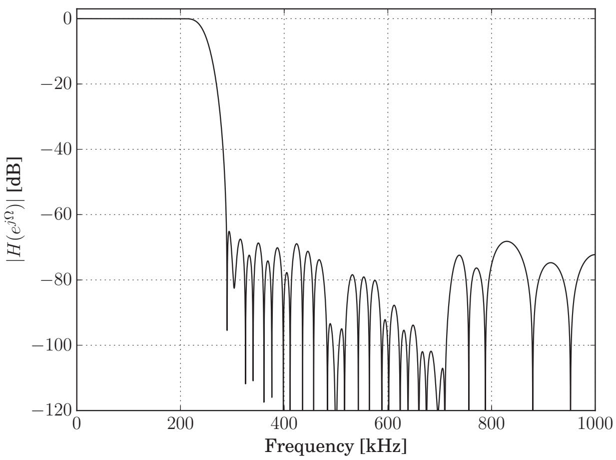

Fig. 8. Combined transfer function of the consecutive half-band filters in dB.

as variable data rates and enable an in place post-processing of gathered complex IQ data. Fig. 7 illustrates the simplified data processing scheme and the software modules involved, implemented in DFC++ for the recording of bat signals. The OAK Board (see Section III) samples the spectrum at a rate of $2\,\mathrm{MHz}$ with a resolution of $12\,\mathrm{bit}$. Data sets of several thousand complex IQ samples are encapsulated in UDP packets and sent to the Banana Pi via Ethernet. A cascade of two subsequent half-band filters reduce the rate to about $500\,\mathrm{kHz}$ per individual stream. The combined transfer function of both consecutive half-band filters applied for the overall sampling rate reduction by 4 is shown in Fig. 8. It provides a stopband attenuation of about $70\,\mathrm{dB}$ with just 9 non-zero coefficients in the first and 27 non-zero coefficients in the second filtering stage, thus keeping the balance between the suppression of aliasing and execution time. The prior oversampling and later downsampling is needed to avoid any spectral impairments within the desired frequency bands caused by non-ideal filter slopes. Next, some meta information is added in the module denoted by the term framing in Fig. 7. The data is thus provided with an index and a time stamp assuring a correct time mapping and synchronization of the different streams afterwards. Finally, the header information and the streams are compressed and jointly stored on the connected hard drive for later analysis.

Beside the actual data processing, a control mechanism was implemented. If the hard disk did not boot properly, data buffers would face an overflow and samples would get lost. Likewise, the inability to connect to the UMTS modem would make a remote maintenance impossible. Therefore, a software-implemented daemon checks for the accessibility of both and triggers a system restart to prevent deadlocks, data loss and continuing communication outage. Logfiles serve for process monitoring and debugging.

V. Initial Results

In July 2016, the developed setup was tested in a first field trial lasting for two weeks in Berlin, Germany. This section briefly presents the initial results and evaluates the proposed base station system regarding its functionality, operation stability, noise figure and power consumption. Based on these findings, means for a further system enhancement are illustrated in Section VI.

For the field trial several bats were equipped with sensor nodes transmitting their unique identification number via long range telemetry according to the modulation scheme presented in [5], [6] and the encoding scheme described in Section II. Fig. 9 shows the location of two base stations utilized for the measurements. They were built up at exposed sites on the roof of tall buildings, facing the adjacent forests. During the test it was possible to gain about 8 terabytes of IQ data that can be used for an offline processing and demodulation later on. An example of a signal spectogram that was recorded at 00:45 am at night is shown in Fig 10.

At about $0.26\,\mathrm{s}$ close to the middle of the depicted stream section one can clearly see a strong signal exhibiting a central carrier and several side lobes, marked by the white arrows. With the bats transmitting on the unlicensed frequency bands around $869\,\mathrm{MHz}$, other interfering signals are also present and visible within the spectrum. In Fig. 11 the according samples regarding the assumed bat signal at about $0.26\,\mathrm{s}$ are cut out and the normalized absolute values are plotted. One can clearly see the wake-up beacon as described in Section II (compare Fig. 2). The initial burst is followed by the specific on-off-pattern that can be used to address individual as well as all nodes in range. Thereby, Fig. 11 shows that the developed base station setup could successfully record bat signals, proofing both, the basic functionalities of the newly introduced long range telemetry base stations and the signal modulation by the bat nodes. The actual decoding of detected signals is part of a subsequent post-processing and subject to current work.

As described in Section III, a remote access to the base stations using a VPN connection was established. Throughout the field trial a continuous process monitoring was performed and a remote system control was possible.

Beside a remote access to the stations an energy efficient design was pursued, as a frequent maintenance and exchange of batteries is costly. Therefore, the power consumption of the system's individual components was investigated, identifying the energetically most critical elements. Table I shows a listing of components, their operating voltage and peak current consumption as well as the corresponding power dissipation. With a value of $5.04\,\mathrm{W}$ the OAK board handling the high frequency sampling and preprocessing shows the highest consumption. The power dissipation caused by the UMTS modem used for the base stations' network connections is highly dependent on

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Fig. 9. Test site in Berlin with two exposed base stations, covering the forests of *Treptower Park*, *Plänterwald* and *Königsheide*. "©OpenStreetMap contributors"

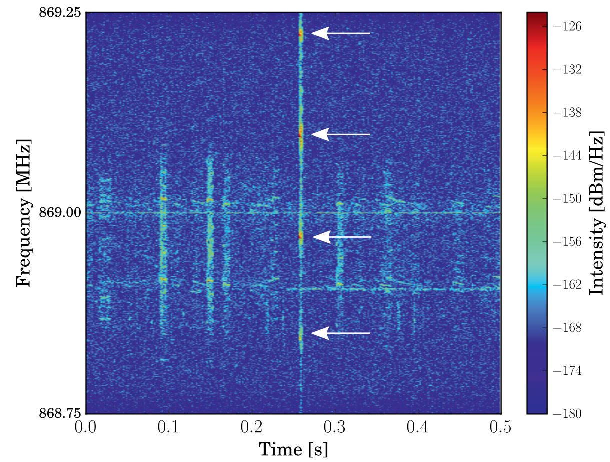

Fig. 10. Spectogram of a bat signal recorded at 00:45 at night on the 20th of July 2016.

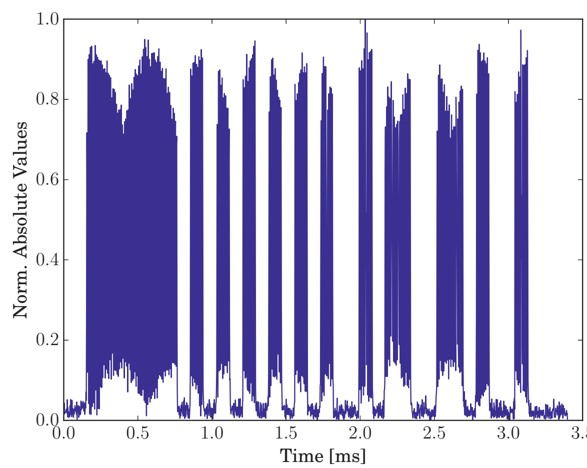

Fig. 11. Normalized absolute values of signal section at about 0.26 s as seen in Fig. 10, constituting the OOK-based wake-up beacon of a bat node.

the current mode of operation. Table I gives a value of 3.5 W for this component. For a worst-case assumption this value originates from the initial start and dial-up process constituting the most consuming mode. These measurement results are the basis for an upper-bound estimation of the overall system's consumption. Accounting for the three LNAs built into one single base station and the efficiency coefficient of the 12V-5V-converter one obtains a power consumption for the base station of about 21.3 W in total, where all contributions are also given in Watts. This result is consistent with the measurements of the whole system in operation, showing a peak current of 1.8 A and thus, an overall consumption of 21.6 W. One has to notice again, that these values are valid for the worst case scenario with the modem dialing up and charging its battery.

During the field trial a battery holding a capacity of 150 Ah with a voltage of 12 V was provided. Therefore, the system should theoretically be able to run for about 3.5 days. However, the actual operation time was limited to about two days before a recharge or exchange was needed which can be attributed to the batteries' numerous discharging cycles in prior usage. These findings indicate that future improvements concerning the power supply might be beneficial to allow for a reduced maintenance effort and and enlarged system operation.

The dissipation of several Watts is always associated with a certain heat development. This can be quite critical especially when the system is mounted within a waterproof and thus almost airtight enclosure. For an outdoor operation, however, the usage of a closed cover was unavoidable and a direct heat exchange is not feasible. Without any cooling some components like the OAK board reach notable temperatures of 78 °C during operation such that a reliable long-term usage can not be guaranteed. To mitigate the heat development, the base station circuitry is equipped with a fan that ensures an air circulation within the enclosure. Additionally, the system was protected from direct sunlight when mounted. The evaluation

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TABLE I
PEAK POWER CONSUMPTION OF THE INDIVIDUAL COMPONENTS

Component	Voltage	Curr. Cons.	Power Cons.
OAK Board	12 V	0.42 A	5.04 W
UMTS Modem	5 V	0.70 A	3.50 W
HDD	5 V	0.47 A	2.35 W
Banana Pi	5 V	0.42 A	2.10 W
LNA	6 V	0.30 A	1.80 W
Fan	12 V	0.05 A	0.60 W

of logfiles showed that no temperature-induced system throttling or shutdowns occurred during the field trial even with high ambient temperature in summer time.

While power consumption and heat dissipation are critical factors for operation, the noise figure of the whole signal processing chain constitutes the decisive aspect concerning signal quality and reception sensitivity. As described earlier, the base station comprises three different reception antennas (*cf.* Fig. 4), so the noise figure was measured for each of the corresponding signal paths independently. Therefor, each of the three inputs was stimulated with a pulse signal of defined level, varying its frequency over the sampling range of $500\,\mathrm{kHz}$ around the center frequency of $869\,\mathrm{MHz}$. The gathered IQ data served as reference points for the power calibration. Subsequently, the resulting noise floor and its offset to the minimal power spectral density of thermal noise given by $-174\,\mathrm{dBm/Hz}$ [14] at a reference temperature of $290\,\mathrm{K}$ were determined, correcting also for the equivalent noise bandwidths of the applied analysis filters. Hence, noise figures between $6\,\mathrm{dB}$ and $7.2\,\mathrm{dB}$ were determined for the input paths. The deviations in between the signal paths may be ascribed to the diverse amplifiers exhibiting not quite uniform gain characteristics and also the custom made filters' manufactoring tolerances in each path.

This section proofed the system's functionality and showed its mobile long-term usage by its energy-aware design. Investigations concerning power consumption, noise figure and minimal reception level characterize the base station's operation behavior. A first field trial was conducted, successfully recording bat signals while an automated decoding is part of current work.

VI. CONCLUSIONS AND FUTURE WORK

In this paper a base station prototype for the long range telemetry within a Low Power Wide Area (LPWA) sensor network was presented, extending an existing near field communication network. The overall system setup was shown, illustrating the basic hardware components coping with requirements of a small size factor for mobility and energy efficiency. The self-developed software framework was introduced as well as the modules running the digital signal processing.

In a first field trial the proposed base station showed its functionality, yet there are still possibilities for a further system enhancement. The operating time shall be enlarged, spanning also the complete duration of a long-term measurement without a direct power connection. Therefore, the extension of the station by solar panels and a charging circuitry is planned. The energetic analysis of the system architecture indicates that the OAK board constitutes a key component both in consumption and heat development. Here, alternative RF-frontends can be evaluated to alleviate these challenges. To separate the software-based signal processing from controlling tasks, an additional board driven by a microcontroller will be implemented that monitors the supply voltage. If it drops too low, an automated notification shall be issued and a safe shutdown must be triggered, assuring that no data or storage medium is being corrupted. With the bats being nocturnal animals, their activity is assumed to be rather restricted to night time. Hence, the microcontroller board might also infer the time and deactivate the whole base station during daytime to save power and recharge the batteries.

Another point of ongoing work is the extended utilization of antenna diversity to make use of the MIMO-like architecture. Techniques for the synchronization and combination of the three different antenna streams are currently evaluated as a means to further increase the rate of successful signal detection and subsequent demodulation even under the presence of strong interfering signals.

The development of a bat signal dedicated decoder is also subject of current work. Detection algorithms and stream manipulation techniques shall thereby allow for an efficient preprocessing and a simplified handling of the tremendous data rates.

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