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A Low-Cost RSSI-Based Localization System for Wildlife Tracking

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Abstract. This paper presents a low-cost localization system for the high-resolution tracking of bats. The system bases on a ground network consisting of multiple low-cost receiver stations, and ultra-lightweight transmitters mounted on the bats. A main challenge of the received signal strength based localization is the limited dynamic range of the employed low-cost receivers. This challenge is solved using an efficient 2-stage differential correlation concept. It significantly improves the dynamic wrt. conventional power detection methods. In addition, this concept requires low processing power and is robust wrt. frequency offsets. Finally, this paper presents a performance evaluation employing reference measurements recorded in the rain forest of Panama.

1. Introduction

Bats are important indicators for healthy natural environments. However, there is little knowledge of their behavior within their natural habitats, e.g. how they hunt or how they socially interact with other bats [1]. So far the detailed hunting behavior has only been analyzed in small areas using video cameras [2]. For monitoring significantly larger areas we have developed a new approach: The bats carry ultra-lightweight radio frequency transmitters ($< 2\,\mathrm{g}$) [3], and are then tracked by a ground network consisting of multiple receiver stations. For this purpose, the bat transmitters radiate special localization signals in the license-exempt 868 MHz band (915 MHz in the US). The ground network receiver stations, which consist only of cost-saving off-the-shelf components, are then able to localize the bat transmitters with a high temporal resolution of up to several Hz. However, the cost-saving components of this wireless sensor network (WSN) as well as the highly energy-constrained bat transmitters result in challenges. The most important challenges addressed in this paper are the limited dynamic range of the receiver and frequency offsets. Finally, the performance of our low-cost tracking system has been evaluated in a field trial in the rain forest of Panama. This paper is an extended version of the recent publication [4].

2. Wireless Sensor Network Architecture

Fig. 1 shows one possible realization of our bats tracking system. Four receiver stations are connected to a server via Ethernet cables. Each node is equipped with a directional antenna offering two patterns, a low-cost embedded processing platform (RaspberryPi B+) and two software-defined radio (SDR) capable terrestrial TV broadcast receivers. The SDR digitize the channel with a rate of 250 kS/s. Then, the digitized channel data of all receiver stations are streamed to a central server. This server uses a signal processing chain developed by ourselves that provides signal processing algorithms for the detection, the received signal strength (RSS) estimation, and finally the position estimation. This concept has the main benefit that all complex signal processing is located in a single server (e.g. a laptop computer), while the multiple receiver stations require low signal processing power.

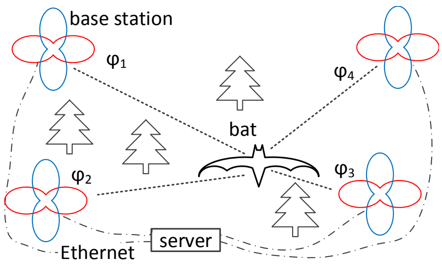

Figure 1. Bats localization system

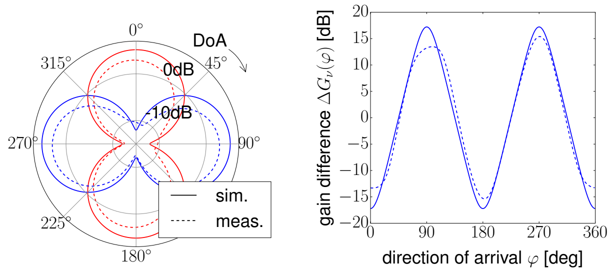

Figure 2. Simulated and measured antenna pattern and gain difference function

3. Antenna Array for RSSI-based Direction Finding

Direction finding in our system is based on the evaluation of the received signal strength indicator (RSSI) as presented in [5]. We are able to estimate the direction-of-arrival (DOA) using the RSS values of the two antenna patterns of a receiver station. The required directional antenna patterns result from a dipole array with a special feeding matrix. Details of the utilized antenna array and its optimization are discussed in [5]. Simulated and measured patterns of this antenna are presented in Fig. 2. The gain difference function, i.e. the RSS difference between the two antenna ports, $\Delta G_\nu(\varphi)$ is denoted by:

$$\Delta G_\nu(\varphi) \quad = \quad G_{RX1}(\varphi) - G_{RX2}(\varphi), \tag{1}$$

where G_{RX1} and G_{RX2} are the directional antenna gains, and φ is the DOA of the electromagnetic wave. At line-of-sight conditions with negligible multi-path the measured field strength difference is equivalent to the gain difference, i.e. $\Delta G_\nu(\varphi) \approx \Delta P_{RX}(\varphi)$. Thus, the DOA can be estimated evaluating ΔP_{RX}. As shown in Fig. 2 the measured gain difference function $\Delta G_\nu(\varphi)$ exceeds 14 dB for specific DOAs φ. This fact further increases the demands on the dynamic range: A valid estimation is only possible if the signals received via the two antenna patterns are not below the sensitivity nor exceeding the clipping level. We will discuss the impact on the localization area coverage in Sec. 5. Additionally, the RSS difference ΔP_{RX} is ambiguous with respect to the DOA as depicted in Fig. 2 (right subfigure). In our localization system we solve these ambiguities by sensor data fusion algorithms as presented in [6].

4. Signal Detection and Received Signal Strength Estimation

One main task of the central server is the detection of the bat signals within the multiple input streams digitized by the receiver stations. The dynamic range of the signal reception is limited by two bounds. The upper bound is the clipping in the ADC of the receivers. However, signals overdriving the ADC may still be decoded, but RSS measurements are not meaningful in that case. Evidently, the lower bound is the sensitivity of the receiver. Using the automatic gain control (AGC) of the SDR for extending the dynamic range is not possible, as the AGC is too slow for the short signals radiated by the bat transmitters.

Laboratory measurements indicated that simple signal detection algorithms, e.g. based on a sliding average power level detector and signal demodulation, do not lead to satisfactory results. The detection capability in combination with the 8-bit ADC leads to a dynamic range of less than 20 dB. This limited dynamic range results in a limited availability of the positioning as shown in Sec. 5. However, applying correlation-based detection overcomes this issue. According to the biologists the typical size of social groups of the Mouse-eared bat (*Myotis myotis*) is less than 12 individuals. Hence, the number of distinguishable signals is also limited by 12. Due to this reason we can correlate the received data against all possible 12 correlation sequences, resulting in excellent signal detection capabilities, even if the signal is below the noise level. For further limiting the processing load at the central server, we split this correlation into a 2-stage correlation as described in [4]. The first correlation stage detects the signals and reduces the amount of data. The second stage then provides precise RSS estimation and bat identification. Measurements show that we increase the dynamic range to 36 dB using our concept, i.e. 16 dB gain.

However, a common drawback of correlation-based signal detection algorithms is their sensitivity wrt. frequency offsets. The local oscillator (LO) of the bat transmitter has a frequency accuracy of 20 ppm, leading to a maximum frequency offset of 17.4 kHz at a carrier frequency of 868 MHz. Additionally, also the LO of the receiver shows such offset. The overall resulting frequency offset is too large for using standard correlators. In order to overcome this problem we use a correlation concept based on a differential correlator $L(\mu)$ [7]:

$$L(\mu) = \left| \sum_{k}^{L-1} r_{\mu+k} r^{*}_{\mu+k-1} s^{*}_{k} s_{k-1} \right|, \tag{2}$$

where r_μ is the complex received signal, s_k is the transmitted sequence at sample k, L is the total sequence length, and $*$ denotes the complex conjugate operator. The differential correlator $L(\mu)$ translates frequency offsets into a constant phase rotation that has no impact on the further signal processing. In addition, the overall signal-processing load is reduced, as there is no need for complex frequency estimation in the receiver.

The RSS estimation error of the proposed 2-stage differential correlation is shown in Fig. 3. The solid line represents a laboratory measurement for frequency offsets of the receiver with respect to the carrier frequency of the transmitter. The measurement shows a maximum RSS for an offset of approximately 25 kHz, which represents the total frequency offset between receiver LO and transmitter LO in this particular measurement. The dashed and dotted lines show simulation results for different frequency offsets without and with an initial frequency offset of 25 kHz. Up to a frequency offset of 40 kHz the RSS estimation error is < 1 dB, which is sufficient for our targeted application.

5. Area Coverage and Localization Results

The coverage in the presented scenario is defined by the number of receiver stations that are able to measure a valid RSS difference ΔP_{RX}. As previously mentioned, if one of the two broadcast receivers of a receiver station is clipping or receiving below its sensitivity level, no valid RSS difference can be estimated. Fig. 4 and 5 indicate how many receiver stations are able to receive a valid RSS difference in an area of 100×100 m. If we assume a dynamic range of 20 dB we only have a small part of the area where all four receiver stations are able to provide valid DOA measurements. We also have regions where only one base station is able to deliver a valid DOA, resulting in a low accuracy and potential position ambiguities. Using our 2-stage correlator concept, we are able to increase the dynamic range to 36 dB. This results in a significantly increased coverage as depicted in Fig. 5. At all positions at least three valid DOA are available. Thus, we get good localization accuracy and do not suffer position ambiguities. Fig. 6 shows

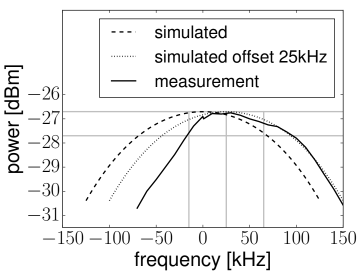

Figure 3. received signal strength estimation error

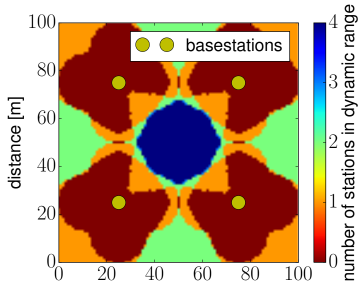

Figure 4. Coverage map at a dynamic range of 20 dB

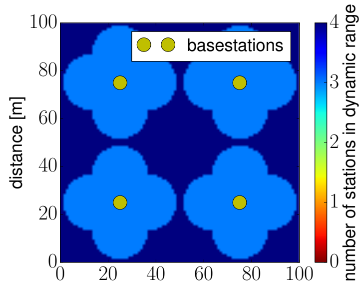

Figure 5. Coverage map at a dynamic range of 36 dB

a measurement in the rain forest of Panama with heavy multi-path effects. A bat transmitter carried by hand has been used during these measurements. The position estimation has been performed utilizing three receiver stations. The resulting average error is approx. 3.4 m.

6. Conclusion

In this paper we presented a low-cost localization system for the tracking of bats. We proved that our system applying RSS-based DOA estimation is able to cover an area of 100 × 100 m. The major challenges of our low-cost system, i.e. dynamic range and frequency offsets, have been solved by means of our 2-stage correlation concept. Results of our Panama field trial underline the performance and the precision of our system.

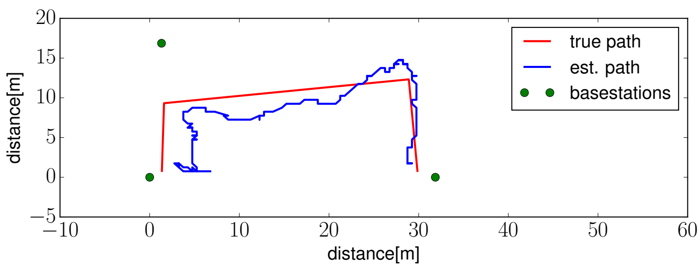

Figure 6. Estimated and true trajectory for a reference measuement in a rain forest area

Acknowledgments

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