Combined Localization and Data Transmission in Energy-Constrained Wireless Sensor Networks

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***Abstract*— Many applications demand simultaneous localization and aggregation in wireless sensor networks. For such an application, e.g. wildlife monitoring, a signaling scheme for a combined localization and communication using a common set of subcarriers is proposed. The concept is based on binary offset carrier signals. But, in contrast to Global Navigation Satellite Systems the presented approach makes use of pure subcarrier localization, and thus enables data transmission in short burst signals. The ranging performance is assessed utilizing the Cramér-Rao Lower Bound depending on the amount of data transferred and considering bit errors.**

***Index Terms*— Wireless sensor network, localization, ultra-low power communication.**

I. Introduction

Wireless sensor networks (WSN) have successfully been deployed in several application domains. One of those fields is wildlife monitoring [1]–[3]. Sensor data to be aggregated usually gets more meaningful, when it includes position information. Therefore, localization and telemetry are the most important requirements. Different localization strategies may be applied, for example relying on propagation characteristics of radio signals. In the case of telemetry, sensor data are transmitted using wireless communication from individual sensor nodes within WSNs [4].

Real-time Locating Systems (RTLSs) generally lack the possibility of data transmission or only allow a very limited amount of data to be transmitted in a rather large time-span. In contrast, in data communication focused networks large-volume data transmissions are feasible. However, as localization is rather a by-product in these networks, the signaling schemes are not optimized for the task of obtaining precise location information.

Sensor networks based wildlife monitoring have huge potentials when it comes to non-intrusive observations. Early projects relied on typical sensor platforms used in research labs [1]. In more recent activities heterogeneous sensor nodes have been used for tracking of endangered species such as Iberian lynx in order to establish safe ways for animals to cross transportation infrastructures [2]. Ultra-low power communication and tracking techniques are needed when it comes to monitoring small animals.

In the scope of the BATS[1] project, a new sensor networking technology is proposed covering localization and telemetry. Biologists are supported in their studies on habitat selection [5] and foraging behavior [6] of bats by the operation of the WSN. In order to track the movements of bats the sensors have to be miniaturized as the targeted species, the mouse-eared bat (myotis myotis), can only manage a payload of 2 g [5]. The very restricted weight is the key challenge for the transceiver design. With a very limited energy budget energy-efficiency is the dominant goal. Improving the reliability of data transmissions in a sensor network scenario with high mobility nodes has been previously studied in [3] using Erasure Codes (ECs).

With regard to power consumption, the overall energy spent on RF communication and localization signals has to be minimized. The obvious idea is to combine localization and data signals. Therefore, a signaling scheme incorporating both is proposed. However, a major question arises in this approach: Does the additional data transfer degrade the localization performance? And, if so, what is the extent of this performance degradation?

In this paper, the impact of additional data transmission on the accuracy of distance estimation in WSNs is investigated. Therefore, we refer to modern Global Navigation Satellite System (GNSS) signals in Section II, assess the range estimate limits utilizing Cramér-Rao Lower Bound (CRLB) in Section III, and present a concept for combined localization and communication in Section IV. Results for this approach are shown in Section V.

II. Reference to Modern GNSS Signals

The presented approach is similar to modern signals used in GNSSs. In [7] the range estimation error is evaluated for GNSS signals, i.e. signals with binary Phase-shift keying (BPSK) and binary offset carrier (BOC)

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

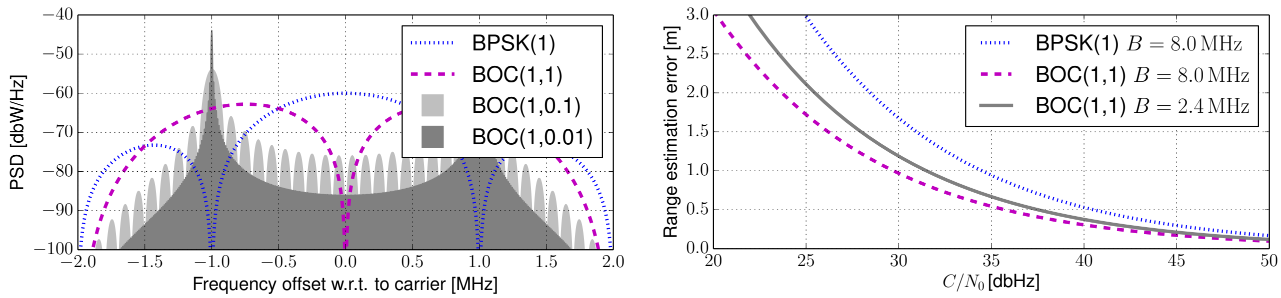

Fig. 1. Spectra and CRLB for common GNSS signals in comparison to the BATS signal.

modulation. It is shown how the ranging performance can be increased with BOC modulated signals. In the BATS system a special BOC modulation is used. However, the requirements of the bats localization system, as described above, significantly differ from those of GNSS.

Short burst signals are used due to the limited battery power for localization and communication in contrast to continuous signals in GNSS. Another reason for burst signal is to realize time-division multiplexing avoiding near-far effects. As the WSN only covers a limited area ambiguities that arise from pure subcarrier localization, which imply the use of pseudo random noise sequences in GNSSs, are not an issue for the system under consideration. Furthermore, the data rate of GNSS (1 bit per 20 ms) is far two low for a sufficient data transmission in burst signals. Moreover, the BATS system has a high subchip-to-chip ratio $f_s/f_c \gg 10$, which offers great potential in the signal design as discussed in section III.

III. Theoretical Limits in Range Estimation

A well-established measure for the estimation error is the CRLB. The accuracy of time-delay estimation in white Gaussian noise is limited by carrier-to-noise-density ratio C/N_0 and the signal duration T_s, The CRLB provides a lower bound on the error variance of the estimated range [8]. The range estimation uncertainty σ^2_{range} is given by

$$\sigma^2_{range} \geq \frac{c_0^2}{(2\pi)^2 \cdot 2T_s \cdot C/N_0 \cdot \beta^2_{rms}}, \qquad (1)$$

where c_o is the speed of light, and β_{rms} denotes the RMS bandwidth defined by

$$\beta^2_{rms} = \int_{-B/2}^{+B/2} f^2 \cdot |S(f)|^2 df, \qquad (2)$$

where $|S(f)|^2$ is the normalized power spectral density (PSD) of a signal with frequency f and bandwidth B.

As shown in [9] system bandwidth and especially RMS bandwidth have a major influence on the achievable performance of a wireless locating system, and thus RMS bandwidth is a crucial design parameter of a RTLS. For the well-known BOC signals the normalized PSD of a baseband signal with code rate f_c and subchip frequency of f_s can be derived from the autocorrelation of the time domain signal and its Fourier transform [10]:

$$\left|S_{BOC(f_s,f_c)}(f)\right|^2 = \frac{1}{f_c}\left[\mathrm{sinc}\left(\frac{\pi f}{f_c}\right)\tan\left(\frac{\pi f}{2 f_s}\right)\right]^2. \qquad (3)$$

With the PSD the RMS bandwidth β^2_{rms} of a BOC signals can be calculated, as shown in (2). It is obvious, that spreading energy to the edges of the band yields the best RMS bandwidth. The maximum RMS bandwidth is achieved for an infinite BOC modulated with no data, i.e. pure subcarrier. Every data modulation broadens the spectrum, and thus degrades the RMS bandwidth due to band limitations in the receiver, which then leads to a larger ranging error.

Fig. 1 depicts spectra for typical BPSK and BOC signals and the BATS localization signal [9]. Considering the PSD and their respective RMS bandwidth of signals on the right-hand side in Fig. 1 the CRLB is shown. The range estimation error of the BATS signal, which may be noted as a BOC(1,0.01) signal, resides well in between the BPSK(1) and BOC(1,1) signal. However, it should be pointed out that the BATS signal achieves this performance with less bandwidth, which enables the realization of low-cost narrow-band receivers.

IV. Localization Signal Design and Data Transmission Concept

A RTLS for bats comprises both functionalities of WSNs: precise trajectories have to be estimated and information gathered by the bats has to be transmitted to the ground nodes of the WSN. To fulfill low-power constraints the total time of RF activity has to be minimized. Research on habitat fragmentation of bats requires the bat sensor to be on air for at least 10 days and transmitting bursts signals at a rate of 1 to 10 Hz. Considering these requirements and meeting the energy restrictions, the nodes have to operate at a duty cycle of less than $1/1000$ [9]. The signals are limited to rather short bursts of roughly 100 μs.

The bats RTLS makes use of multiple-frequency phase-based ranging [9]. In this approach the range is estimated from the phase difference of two coherent carriers, generated by modulation (e.g. BPSK) of a single carrier. In this way a very distinct phase relation between the two carriers can be achieved. In [9] the ranging performance has been analyzed without additional data transmission.

For an additional data transmission two possibilities exist: 1) additional messages and 2) combined localization and data signals. The first increases the total time of RF communication, and thus puts strain on the power budget, the latter does not. However, the second option degrades the accuracy of the obtained location information, since the communication reduces the spectral efficiency of the signal. Therefore, the question arises to what extent is the localization accuracy impaired?

V. Impact of Data Transmission on the Ranging Performance

In the above section the CRLB has been introduced as a measure for the location error. Besides others the RMS bandwidth β^2_{rms} is one of the parameters affecting the accuracy. Assuming pseudo random and perfectly decoded data bits, considering the BATS signal as a BOC modulated signal with parameters BOC(f_s,f_c) with f_c given by the communication data rate and following equations (2) and (3) the RMS bandwidth can be calculated for different chip-to-subchip ratios. Fig. 2 shows the RMS bandwidth for given chip-to-subchip ratios and data rates, respectively. As $\sigma_{range} \propto \beta^{-1}_{rms}$ one can easily infer from Fig. 2 that moderate data transfers have a negligible influence on the distance estimation error. Moreover, the decrease in RMS bandwidth for higher data rates comes from the band limitation of the receiver.

Apart from the decrease in effective bandwidth decoding errors of data bits can further impair the localization results. Falsely detected bits lead to a mismatch in the correlated sequences, which then decreases the signal-to-noise ratio (SNR) after correlation. This SNR degradation results in a higher range estimation variance. This effect is depicted in Fig. 3. Compared to the decrease in RMS bandwidth, decoding errors have a substantial impact on the ranging accuracy.

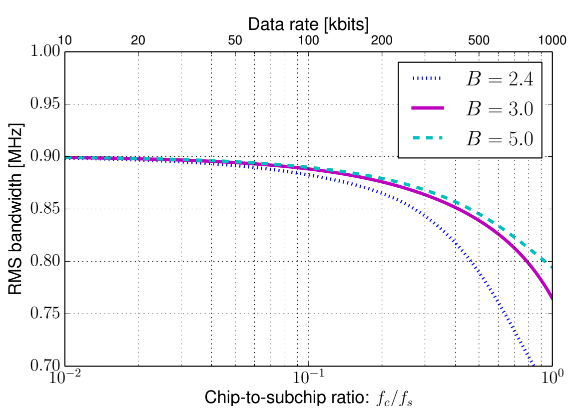

Fig. 2. Decrease in effective (RMS) bandwidth depending on the chip-to-subchip ratio and communication data rate, respectively.

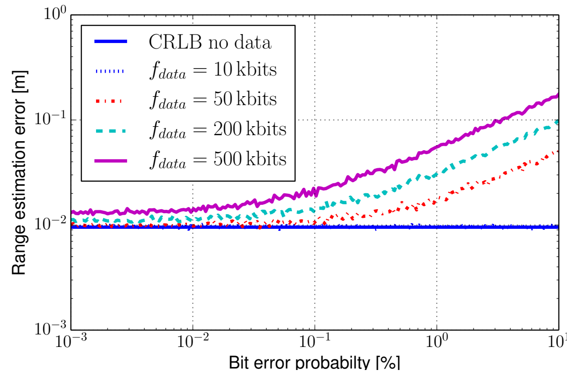

Fig. 3. Range estimation affected by data decoding errors.

VI. Conclusion

In this paper a concept for combined localization and data transmission in WSNs has been proposed. The impact of additional data modulation on the accuracy of range estimation has been analyzed. The simulation results show that the decrease in RMS bandwidth resulting from data transmissions has a negligible influence on the ranging error. However, in presence of data decoding errors the localization performance is significantly degraded.

Acknowledgments

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