System and Signal Design for an Energy-efficient Multi-frequency Localization System

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***Abstract*— In this paper a concept for an energy-efficient multi-frequency localization system is proposed. The system design aims at extremely light-weight, and thus energy-efficient tags. The localization system is realized by a Wireless Sensor Network comprising signal strength and phase measurements. The concept is based on signals for phase-based ranging. The proposed signals have to meet several constraints: low-power signal generation, efficient signal processing, and, most important, precise range estimation. The performance of the range estimation is assessed utilizing the Cramér-Rao Lower Bound.**

***Index Terms*— Wireless sensor network, localization, multi-frequency, phase-based ranging.**

I. Introduction

Real-time locating systems (RTLS) are well established in several fields of application, and also tracking of animals is gaining attention. Biologists are interested for instance in the social behavior of bats [1]. To get an insight into the bat's life, the animals have to be tracked continuously in certain areas, e.g. their hunting grounds.

This problem can be solved by putting up a Wireless Sensor Network (WSN) and equipping the bats with very light-weight tags. Restricted by the bat's maximum payload the tag is supposed to weigh less than 2 g [1]. This yields to hard constraints for the transmitter in terms of power. In this paper a new concept for a localization system is proposed, especially addressing precise ranging for low-power tags. Its performance is assessed applying the Cramér-Rao Lower Bound (CRLB).

There are several methods to estimated the range between a tag and a receiver. The most popular are time-of-arrival (TOA) estimation using pseudo noise (PN) codes and tracking of the carrier phase. However, either of them has significant drawbacks. Precise TOA estimation demands a direct-sequence spread spectrum system with high bandwidth, which in this case is not feasible due to low-power requirements.

Since code tracking of narrow-band signals does not allow for precise range measurements, phase-based ranging techniques have to be applied. Unfortunately, tracking the carrier phase is not reasonable due to inaccurate clocks and short signals. Furthermore, carrier phase tracking leads to ambiguities in the range estimation [2]. These drawbacks can be circumvented by transmitting multiple phase-coherent carriers, which leads to the approach presented here.

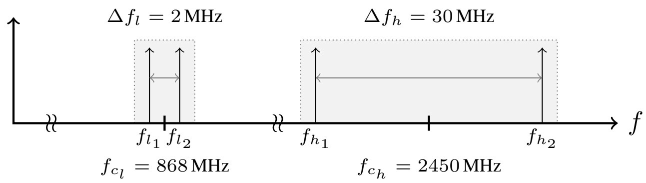

Fig. 1. Signal design with multiple coherent carriers

II. Multi-frequency phase-based ranging

The approach presented here makes use of multiple phase-coherent carriers in several frequency bands. Fig. 1 depicts how the coherent carriers can be organized in the corresponding frequency bands. Since the phase of each signal is affected by wave propagation over the distance R, the range $\hat{R}$, similar as in RFID approaches e.g. [3], can be estimated from the phase difference $\Delta\phi$ of the two corresponding frequencies Δf as expressed by

$$\hat{R} = \frac{c_o \cdot \Delta\phi}{2\pi \cdot \Delta f}. \tag{1}$$

As phase observations are wrapped within the interval of 2π, an ambiguity problem arises. However, phase measurements are unambiguous up to a maximum range of $R_{max} = c_0 \cdot f^{-1}$. The resulting unambiguous ranges for the proposed carrier spacings are shown in Table I. The range estimation in the 868 MHz band can be used to resolve the ambiguities of the beat phase signal in the 2.4 GHz band.

Coherent carriers from a single band are transmitted simultaneously while carriers from different bands are transmitted successively (Fig. 2). In order to minimize the power consumption, a duty cycle of approximately 1/1000

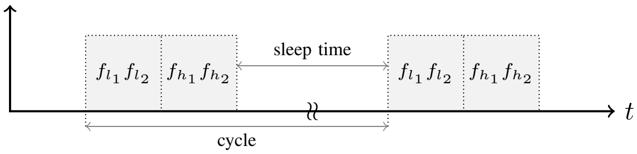

Fig. 2. Pulse structure for transmission of multi-carrier signals

is used. This leads to constraints of signal duration and measurement rate of the system, respectively.

III. Assessment of Ranging Performance

The CRLB provides a lower bound on the error variance of an unbiased estimator [4]. The ranging performance for time-delay estimation in additive white Gaussian noise is limited by signal-to-noise ratio (SNR) and the signal bandwidth. For one-way ranging, which is in general a problem of parameter estimation, the CRLB gives a lower limit for the ranging precision [5]. The ranging uncertainty σ^2_{range} is given by

$$\sigma^2_{range} \geq \frac{c_0^2}{(2\pi)^2 \cdot T_s \cdot B \cdot SNR \cdot \beta^2_{rms}}, \quad (2)$$

where c_o is the speed of light, T_s is the time duration of the burst signal, B is the signal bandwidth, and β_{rms} the RMS bandwidth defined by

$$\beta^2_{rms} = \int_{-\frac{B}{2}}^{+\frac{B}{2}} f^2 \cdot |S(f)|^2 df, \quad (3)$$

where $|S(f)|^2$ denotes the power spectral density (PSD) of a baseband signal with frequency f. It can be easily seen from (2) that, apart from SNR and signal length, signal bandwidth and signal shape, which determines the PSD in (3), are the only limiting factors for precise distance measurements. As signal bandwidth in many cases is strictly limited by regulatory authorities, the actual parameters for range estimation are the PSD and SNR. These parameters are covered below.

A. Power Spectral Density of Proposed Signals

A possible approach generating two coherent carriers is to modulate a single continuous wave carrier. In this way the two subcarriers (e.g. generated by BPSK modulation) have a very distinct phase relation. Using burst signals with a fixed modulation pattern (e.g., symbol rate: 2 MHz and pattern $[1, -1]$) this signal can be thought of as a Binary Offset Carrier (BOC) signal with a low chip frequency and a subchip frequency being half the symbol rate.

Such BOC signals are very well known and studied in the field of Global Navigation Satellite Systems. The normalized PSD of a baseband signal for a code rate f_c and a subchip frequency of f_s can be derived from the autocorrelation of the time domain signal and its Fourier transform [6]

$$\left|S_{BOC(f_s,f_c)}(f)\right|^2 = f_c \cdot \left[\frac{\sin\left(\frac{\pi f}{f_c}\right)\sin\left(\frac{\pi f}{2f_s}\right)}{(\pi f)\cos\left(\frac{\pi f}{2f_s}\right)}\right]^2. \quad (4)$$

With the PSD the RMS bandwidth β^2_{rms} of the proposed signal is calculated, as shown in (3).

B. Power Budget

As the transmit power is an essential parameter for the SNR calculation, the power budget is discussed in this section. A 0.8 g lithium coin cell with a capacity of 48 mAh at 3 V is supposed as energy source of the tag. Its 144 mWh must supply signal generation at 868 MHz and 2.4 GHz, the operation of a micro-controller, and transceiver for an intended operating time of 14 days. As bats are only active for about 6 hours per day, full tag activity is required for 84 hours to meet this time span.

Exemplary values for the power consumption of the required components are shown in Table II, referring to commercial RF transceivers CC430 [7] and CC2590 [8] from Texas Instruments. Considering these values, the transmission duty cycle of 1/1000 and an assumed micro-controller active duty cycle of 2.5% results in an overall demand of energy of 26.5 mWh. Simulations of a modified monopole antenna for double band operation have shown that signal transmission can be achieved with high efficiency of over 90% and a realized gain of 1.7 dB and 2.5 dB in the 868 MHz band and the 2.4 GHz band, respectively. Even if the antenna's gain being compensated by the losses between the RF frontend and the antenna, the power budget still proves the feasibility of the proposed tag even if its circuitry efficiency is as low as 19%.

TABLE I
Coherent carriers in multiple bands

Carrier frequency		**868 MHz**	**2.4 GHz**
Carrier frequency	f_c	868 MHz	2450 MHz
Carrier spacing	Δf	2 MHz	30 MHz
Unambiguous range	r_{max}	$\sim$ 150 m	$\sim$ 10 m
SNR simulation parameters			
Transmitted power	$P_{tx,dB}$	10 dBm	
Noise figure	NF	8 dB	
Fade margin (linear)	FC_1	0.25 dB/m	0.40 dB/m

TABLE II
Power consumption of different tag functionalities

Functionality	**Condition**	**Power**	**Time span**
Total circuitry	Power down	3 μW	252 h
Micro-controller	Low power mode	7 μW	84 h
	Active mode	10.5 mW	$\sim$ 1 h
Transmission	2.4 GHz (10 dBm)	51 mW	$\sim$ 5 m
	868 MHz (10 dBm)	99 mW	$\sim$ 5 m
Reception	868 MHz	45 mW	$\sim$ 5 m

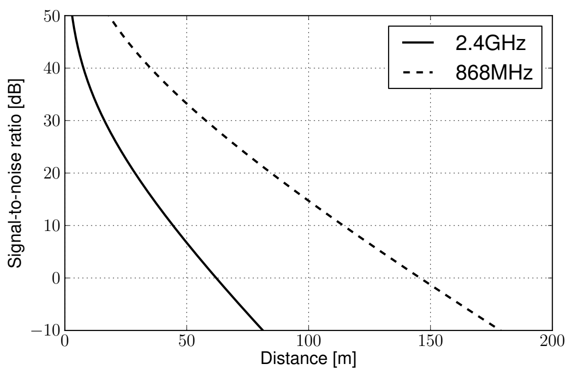

Fig. 3. Signal-to-noise ratio

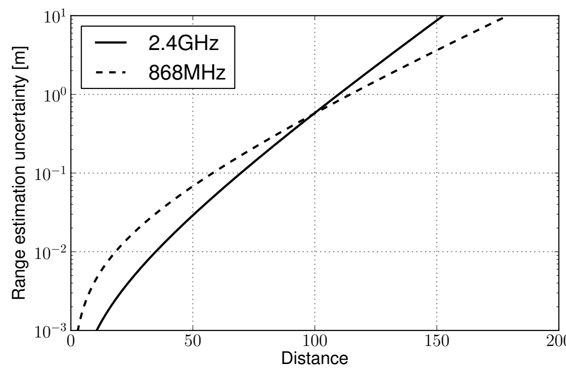

Fig. 4. CRLB for one-way ranging

C. Signal-to-Noise Ratio

On the receiver side the SNR limits the accuracy of range estimation. Thus, the SNR is of special interest for any ranging system. The power at the receiver P_{rx} can be expressed as

$$P_{rx,dB}(R) = P_{tx,dB} - FSL_{dB}(R) - R \cdot FC_1, \qquad (5)$$

with FC_1 being the linear fading coefficient for attenuation in vegetation [9], P_{tx} the transmit power, and $FSL_{dB}(R)$ is the free-space path loss for a given distance R with

$$FSL_{dB}(R) = 20\, lg\left(\frac{4\pi R f_c}{c_0}\right). \qquad (6)$$

The SNR ratio at the receiver is

$$SNR_{dB}(R) = P_{rx,dB}(R) - NF - N_{dB} \qquad (7)$$

incorporating the receiver's noise figure NF and the influence of thermal noise N_{dB}. The thermal noise N is expressed by

$$N = k \cdot T_n \cdot B_n, \qquad (8)$$

with $k = 1.38 \cdot 10^{-23}$ Ws/K being the Boltzmann constant, temperature $T_n = 290\,°$K, and the noise bandwidth B_n.

Fig. 3 shows the results of the expected SNR according to the distance between transmitter and receiver for 868 MHz and 2450 MHz with the simulation parameters given in Table I.

D. Simulation Results

The ranging performance was assessed with the simulation parameters shown in Table I. Fig. 4 clearly shows the superior performance of the two-tone signal centered at 2.4 GHz compared to 868 MHz for smaller distances. Due to the higher linear fading coefficient this behavior changes for distances over 100 m. Combining phase measurements in both frequency bands, the simulations show a promising performance for an unambiguous range estimation. The simulation result show a performance which by far outperforms the well-known approaches for the localization of bats, like homing or triangulation [1].

IV. Conclusion

In this paper a new concept for an energy-efficient multi-frequency localization system has been introduced. An approach for the generation of phase-coherent carriers has been proposed. Furthermore, the power budget of such a system and its constraints to signal power, burst length, and duty cycle have been investigated. The theoretical limits of range estimation has been assessed by SNR simulation and calculation of the CRLB. The results show that with different carrier spacings we are capable to resolve the ambiguities in phase-based measurements and provide an accurate range estimation for energy-efficient tags.

Acknowledgment

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