Robust Multi-Carrier Frame Synchronization for Localization Systems with Ultrasound

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***Abstract*—Time of arrival (TOA) based localization extracts the positions from the signal delay between senders and receivers in a network and puts high requirements on synchronization, in particular synchronization on the line-of-sight (LOS) signal. We propose an ultrasound based system with pure LOS synchronization and data transmission for sender identification. We use two carriers with 38 respectively 40 kHz in a baseband OFDM scheme and by comparison of the phase shift of both carriers we estimate with the Cramér-Rao lower bound a distance error between sender and receiver of 0.047 mm for a transmission range of 20 m. We transmit 8 bit in 1.5 ms where no inter-symbol interferences are expected in most practical scenarios for robust localization.**

When transmitting data in a communication system, the properties transmission delay and signal attenuation available as RSSI values can additionally be used for distance measurements between sender and receiver, which is the input for a localization system. However, the measured distance can be imprecise due to multipath propagation, since the signal strength has strong local fluctuations due to the wave characteristics and the reception time of the multipath signal is a mixture of all paths. In contrast, the line-of-sight (LOS) signal only represents the shortest path between sender and receiver where the signal attenuation and signal delay can be uniquely mapped onto the distance between sender and receiver. Thus, separating the LOS signal from the remaining signal paths can drastically improve the localization accuracy.

We present a novel data transmission system for localization which transmits a short message in such a short time (1.5 ms) that the LOS path and the other paths do not overlap in time in practical scenarios. Thus, we can process the pure LOS signal at the receiver and ignore the signal of the remaining paths giving false information. Our ultrasound system uses two carriers in a baseband OFDM scheme to increase the data rate and keep the transmission time short. We focus additionally in this paper on precise frame synchronization at the receiver not only for a low bit error rate (BER) at low signal-to-noise ratio (SNR) and long transmission ranges but also to measure a precise signal delay[1].

Table I shows a comparison of related and this work.

Table I
COMPARISON OF ULTRASOUND LOCALIZATION SYSTEMS. (NOT AVAILABLE DATA IS DENOTED WITH NA)

Range [m]	Precision [mm]	Bandw. [kHz]	Pulse [ms]	Modulation	Data [bit]	Ref
4	NA	47-52	5.10	BPSK, CDMA	-	[?]
4	10	35-65	0.87	Chirp	-	[?]
4	7	32-48	20.46	BPSK, CDMA	64	[?]
3	70	35-45	0.18	BPSK, CDMA	-	[?]
5	0.62	39-41	1.00	NA	-	[?]
10	0.4	38-42	1.50	$\pi/4$-DQPSK	8	this

Our system can outperform other systems in transmission range, and precision for localization whereas providing data transmission for sender identification at the same time. Our sender consumes 2.4 mW with sending rate 1 Hz compared to 360 mW in [?].

I. SYSTEM

Figure 1 shows the ultrasound baseband transmission system with the two carrier frequencies 38.8 kHz and 40.8 kHz. On both, we use $\pi/4$-DQPSK modulation for data transmission. The low power design of the sender enables photovoltaic powering. Further, the communication works with acceptable bit error rate up to 20 m.

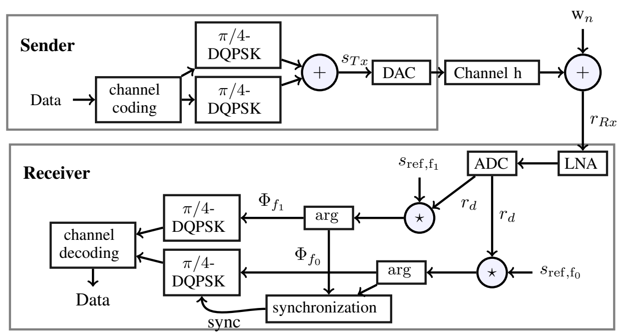
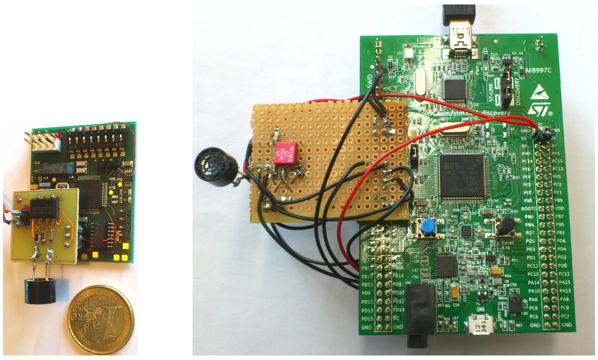


Figure 1. Schematic diagram of the transmission.

The environment for the data transmission is designed to be echo free. Figure 3 shows the transmission path for line of sight (LOS) and multipath. The receiver are mobile and have the distance $d_{\mathrm{Rx,W}}$ to the next wall. Whereas, the senders

[1]The signal delay can be computed with the sending and receiving time of the message and clock synchronization between sender and receiver. For localization systems based on Time Difference of arrival (TDOA), the reception times of several transmissions without sending time are sufficient and clock synchronization can also be determined with enough transmissions.



sender receiver

Figure 2. Photo of the sender and receiver of the transmission system.

are mounted on the ceiling with a height of h_{Mon} and distance $d_{Tx,w}$ to the same wall. The time between the signal and echos is than for the speed of sound v_s

$$\tau_{ef} = v_s\left(d_{Rx,w}+d_{Tx,w}\right)\sqrt{1+\frac{h_{\text{Mon}}}{d_{Rx,w}+d_{Tx,w}}} - v_s\sqrt{h_{\text{Mon}}^2+\left(d_{Tx,w}-d_{Rx,w}\right)^2}\,.$$

This is guaranted by the short pulse of only 1.5 ms and a minimum distance of the sender to the wall of 2 m. Figure 4 shows the limits of echo free transmission for a 2 ms packet length. Points above the lines guaranted to be echo free, whereas points below the line indicate a distortion by multipath transmission.

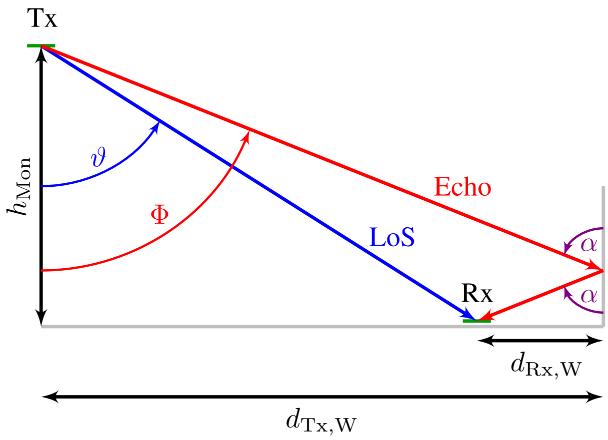


Figure 3. Graph of the line of sight and the multipath propagation.

II. Synchronization

Localization systems rely on precise distance measurements. When using the signal propagation delay τ of a transmission from sender to receiver to determine the distance $d = v\tau$ for signal speed v, a high precision of the reception time and the synchronization of the clocks of sender and receiver are necessary. In the following, we analyze the accuracy of the reception time given by the frame synchronization of an

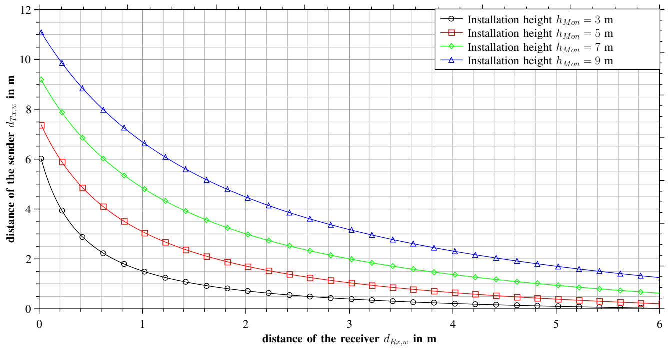


Figure 4. Figure for minimum distance for echo-free reception of 2 ms packet length.

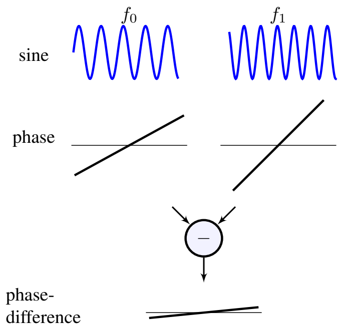


Figure 5. Phase difference synchronization

ultrasound transmission[2]. For carrier $k \in 1,2$ with frequency f_k the phase at sample position n with a correlation of N samples and sampling frequency f_{sample} is

$$\phi_k\left(n\right) = \arg\left[\sum_{x=1}^{N} r_d\left(x+n\right)\cdot \mathrm{e}^{j2\pi\cdot f_k\cdot x/f_{\text{sample}}}\right] \,. \qquad (1)$$

Then we compute the difference of the angles of both frequencies $\phi_D\left(n\right) = \phi_1\left(n\right) - \phi_2\left(n\right)$ which is a linear function in n. The synchronization can be determined by the angle difference with two methods. The first is to search a zero of $\phi_D\left(n\right)$. Therefore, we compute the absolute of the angle difference and search for the minimum

$$n_{\text{sync}} = \arg\min_n\left[\left|\phi_D\left(n\right)\right|\right] \,. \qquad (2)$$

Another option is to correlate the calculated phase difference with a linear reference function $\phi_{Dr}\left(x\right)$ for the phase difference and search the maximum of the correlation

$$n'_{\text{sync}} = \arg\max_{n'}\left[\sum_{x=1}^{M}\left(\phi_D\left(x+n'\right)-\bar{\phi}_D\left(n'\right)\right)\phi_{Dr}\left(x\right)\right] \quad (3)$$

whereby the mean of the measured angle is

$$\bar{\phi}_D\left(n'\right) = \frac{1}{N}\sum_{m=1}^{M}\phi_D\left(n'+m\right) \,. \qquad (4)$$

The point of maximum correlation is also the point for minimal error between the reference and the calculated phase. While the second method requires more processing power it proves to be more stable against outliers of phases errors.

[2]Proofs are omitted due to space constraints of the extended abstract.

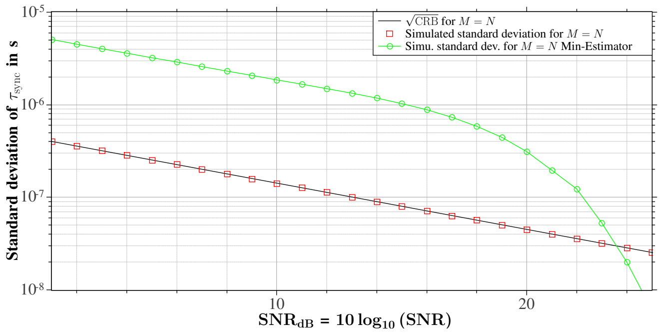


Figure 6. CRLB for phase difference synchronization of two carriers.

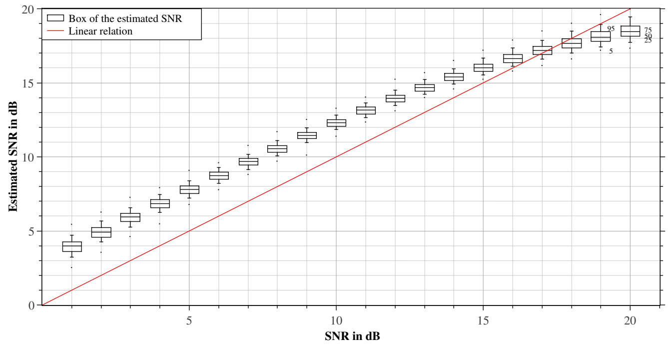


Figure 7. Graph of the adjusted SNR versus the estimated SNR.

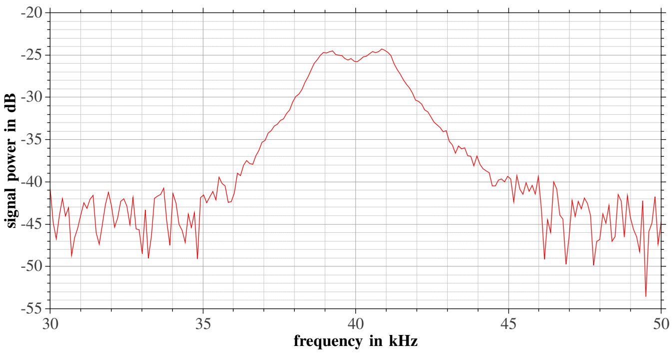


Figure 8. Spectrum of the used ultrasound devices.

A. Cramér-Rao Lower Bound

The Cramér-Rao Lower Bound (CRLB) specifies the minimum variance for an unbiased estimator. We use the CRLB to determine the precision of the synchronization.

Theorem 1. *Our ultrasound transmission system reaches a synchronization that estimates the distance d between sender and receiver with variance*

$$\text{Var}(d) \geq \frac{v^2}{2\pi^2 \cdot \text{SNR} \cdot f_{\text{sample}}^2} \tag{5}$$

for a given signal speed v, sampling frequency f_{sample}, SNR value and synchronized clocks of sender and receiver.

The correlation between the signal r_d and both reference signals $s_{\text{ref,f}_\text{k}}$ must have length $\tau_{\text{sym}} = 1/f_{\text{Diff}}$ respectively $N = f_{\text{sample}}/f_{\text{Diff}}$ to be orthogonal. The general CRLB for the variance of the frame synchronization $\hat{\tau}$ is:

$$\text{Var}(\hat{\tau}) \geq \frac{1}{2\pi^2 \cdot \text{SNR} \cdot f_{\text{Diff}}^2 \cdot M \cdot N} . \tag{6}$$

Figure 6 shows the standard deviation for frame synchronization $\hat{\tau}$ over the SNR for both synchronization methods. The non linear estimator in equation 2 outperforms the maximum likelihood estimator (Eq. 3) for high SNR. For a range of 20 meters we estimate the SNR with 10 dB resulting in the standard deviation of the distance $\sqrt{\text{Var}(d)} \approx 4.7 \cdot 10^{-5}\,\text{m}$.

Corollary 2. *Radio transmission needs a sampling frequency of* 454 GHz *at carrier frequency* 2.4 *GHz to attain same synchronization precision as ultrasound with a difference frequency of* 2 kHz *at carrier frequency* 38.8 *kHz.*

III. SNR Calculation

For communications systems it is necessary to know the SNR to estimate the bit error rate (BER). The SNR calculation is motivated by the single carrier SNR estimation from Pauluzzi [**?**]. We determine for every symbol the SNR. The MLE for the SNR is

$$\text{SNR}_{f_k} = \frac{2\rho\left(s_{Tx,\,f_k},\, r_{Rx}\right)^2}{1 - \rho\left(s_{Tx,\,f_0},\, r_{Rx}\right)^2 - \rho\left(s_{Tx,\,f_1},\, r_{Rx}\right)^2} \tag{7}$$

with the cross correlation

$$\rho\left(s_{Tx,\,f_k},\, r_{Rx}\right) = \frac{E\left[s_{Tx,\,f_k},\, r_{Rx}\right]}{\sqrt{\sigma_{s,\,f_k}^2 \sigma_r^2}} \tag{8}$$

where $E\left[\cdot\right]$ denotes the expectation value, the signal power of the transmitted signal $\sigma_{s,\,f_k}^2$ and the received signal power

$$\sigma_r^2 = E\left[r_{Rx}^2\right] \tag{9}$$

Figure 7 shows the simulation results of the SNR estimation algorithm. The center of the box represents the mean, the upper and lower bounds are 75 and 25 %. The whiskers represents the range from 5 to 95 % of the values. The points indicate the maximum and the minimum for the SNR simulation.

IV. Measurements

Spectrum

The sender sends with a constant interval the same data. The receiver estimate the TOA with the proposed synchronization method. Further, the sampling frequncy at the receiver is 500 kHz, which correspends to a time resolution of 2 μs.

Figure ... shows the synchronization error in μs.

Figure ... shows the histogramm of the unbiased error. Thus, the error is normal distributed with the variance ...

The variance is about $1.43 \cdot 10^{-12}\,\text{s}$ and the standard deviation is about $1.19\,\mu$s. Which results in an distance error at a velocity of 340 m/s of 0.4 mm.

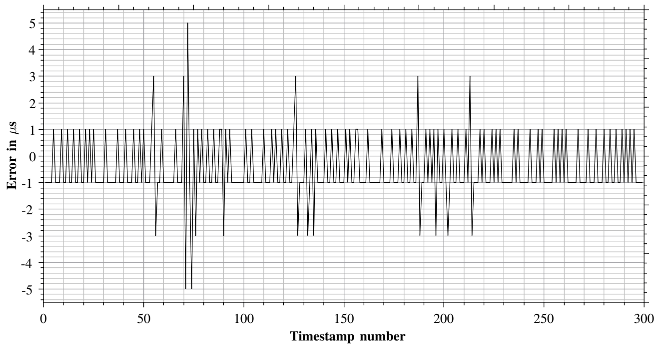


Figure 9. Graph of the synchronization errors at 10 dB SNR.

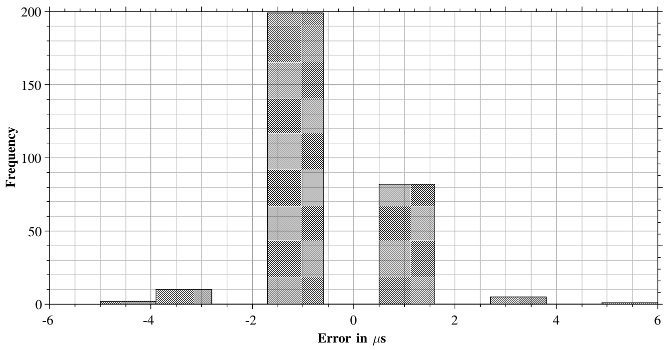


Figure 10. Histogramm of the unbiased synchronization errors at 10 dB SNR.

V. Conclusion

We present two novel frame synchronization schemes which are specialized on TDoA localization and uses ultrasound. It uses multiple carrier frequencies to resolve the ambiguity of frame synchronization of only one carrier frequency.

Acknowledgement

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