Performance Analysis of Communication Signals for Localisation in Underwater Sensor Networks

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I. Abstract

This study evaluates the localization performance of polar-coded multiple frequency shift keying (MFSK) signals in a bistatic active sonar system under low signal-to-noise ratio (SNR) conditions. The objective is to assess the effectiveness of communication signals in estimating the position of a moving underwater target. The Cramér-Rao Bound (CRB) analysis is performed to evaluate the theoretical lower limit for the localization error. The simulation results present localization error contours with different measurements, providing insights into system performance. The findings demonstrate the effectiveness of the MFSK signal, highlighting its potential for efficient underwater sensing applications.

II. Background

Underwater target localisation is of significant importance for situational awareness, particularly in protecting critical infrastructure from foreign submarines and autonomous underwater vehicles (AUVs). For moving targets with low signal signatures, achieving accurate localisation becomes challenging [1]. This task is addressed by deploying wireless sensor networks composed of multiple sensor nodes in the ocean. Estimating the target's location relies on fusing information collected across the sensor nodes, which is achieved by direct inter-node communication or transmission to a central node. However, the separation of tasks for sensing, localisation, and communication introduces inefficiencies in terms of bandwidth, energy, and location information. Recent advancements in integrated sensing and communication (ISAC) systems provide an alternative by using communication signals as a potential source of information for localisation [2]. Analysis of the delay-doppler ambiguity function for communication signals shows that single-carrier signals perform better in underwater environments [2]–[5]. Consequently, we evaluated the localisation performance of these communication signals within the ISAC systems. The localisation efficacy is analysed by computing the Cramér-Rao lower bound (CRLB), which establishes the theoretical lower bound on the variance of any unbiased estimator of the target's position, using all available information at the sensor nodes.

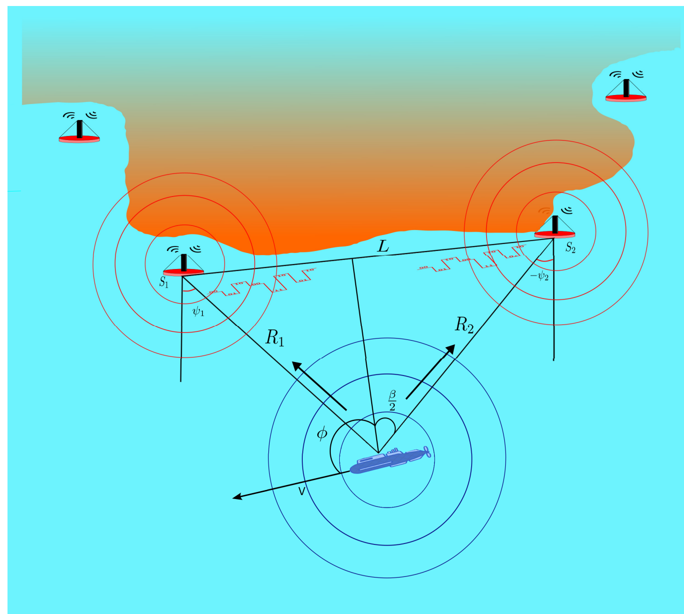
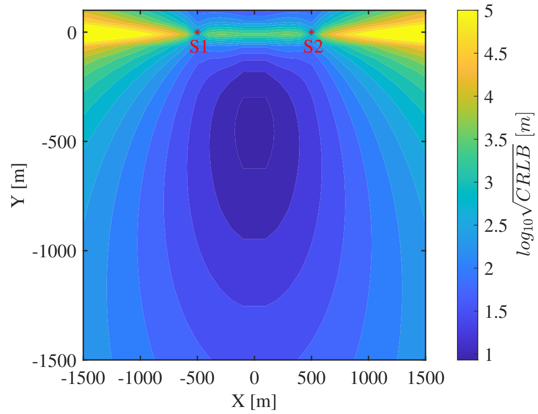


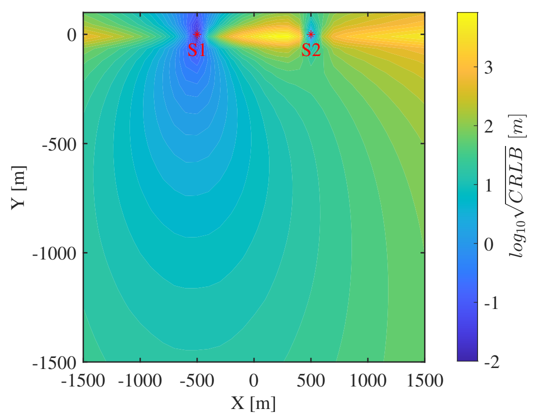
Fig. 1: Illustration of the considered underwater wireless sensor network. The communication signal is used both for information transfer and bistatic sensing.

III. System Setup

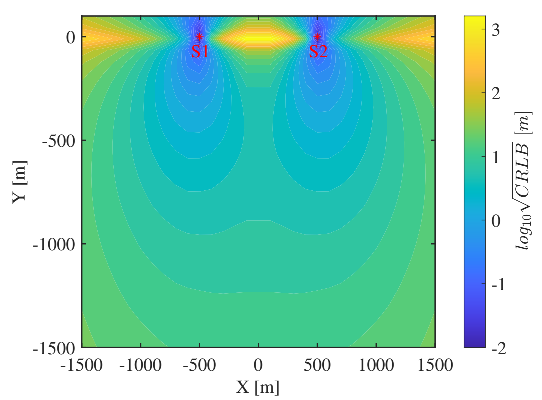
The setup of the underwater wireless network is shown in Fig. 1. The sensor nodes, consisting of a uniform linear array, are positioned at known locations and synchronised in time. The underwater channel is modelled to account for delays and Doppler scaling caused by the moving target. The underwater noise is assumed to be colored temporally but spatially independent. To communicate information, polar-coded multiple frequency shift keying (MFSK) comprising 64 bits is considered. The signal is transmitted with a carrier frequency of $f_c = 6$ kHz and a bandwidth of 4 kHz, having the spectral efficiency of 0.2228 bits/sec/Hz. The SNR of the setup is modelled considering the underwater noise levels (depending on the sea state), the source level at the receiver, the transmission loss, and the effective signal reflected from the target. The target is assumed to be an AUV with a size of 10 m, a weight of approximately 1 ton. The target is considered



(a) Only bearing measurements.



(b) Bearing measurement at S_1 + bistatic measurement.



(c) Bearing measurements at S_1 and S_2 + bistatic measurement.

Fig. 2: CRLB contours plots evaluated at different target locations using multiple information from the sensor nodes.

to be moving with constant velocity and at a constant ocean depth. To ensure a communication link with a low bit error rate and an adequate transmitted signal power level, the SNR for direct path transmission is kept above 0 dB [4]. Hence, based on the SNR conditions, the signal is transmitted at a power level of ~ 114 dB. Consequently, the CRLB for the given target position and communication signal is evaluated.

IV. Results

Fig. 2a and 2c present the CRLB contours for cases when the target is detected at both of the sensor nodes. Fig. 2a shows the CRLB contours for the case when only the bearing information from the sensor nodes are communicated and fused. Whereas, Fig. 2c shows the case where the communication signal, reflected from the target, is also used as a potential source of location information. The results showcase the enhancement of the localization performance by utilizing additional information from the bistatic measurements. In Fig. 2b, the CRLB contours are shown for the case when the target is detected at only one node, i.e, S_1. Using the bistatic and the single bearing measurements at the sensor node S_2, the CRLB is evaluated.

For slow-moving targets such as AUVs, the efficacy of the signal in target localization can be evaluated by analyzing the contour plots of localization error. For instance, in Fig. 2b, the accuracy near the position (1000, -1000) would be considered inadequate for an AUV. However, for a larger target, such as a submarine with a length of 170 meters, the localization performance would be deemed acceptable.

V. Conclusion

To summarize, the simulations indicate that utilizing communication signals for bistatic sensing in underwater sensor networks can significantly improve localization accuracy. Consequently, integrating ISAC (Integrated Sensing and Communication) in such networks enhances both energy and bandwidth efficiency. Moreover, ISAC contributes to improved spectral efficiency by reusing the communication waveform for sensing purposes, eliminating the need for dedicated sensing signals. Longer communication signal durations also facilitate easier detection under low SNR conditions, as the extended duration allows for better signal integration and noise suppression. Although longer signals may pose challenges for fast-moving targets due to motion-induced distortion, this is less of a concern in underwater environments where targets such as AUVs and submarines typically exhibit slow dynamics. Therefore, the use of long-duration communication signals is well-suited for underwater ISAC applications.

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