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Emitter geolocation using single moving receiver[☆]

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ABSTRACT

Emitter geolocation using a single moving receiving-station is explored. We propose algorithms for transponder-aided geolocation of an emitting station where the transmitted waveform is either known or unknown a priori. The emitter position is estimated directly (in a single-step) from the received signal samples. Numerical examples are provided to illustrate the performance. The results are compared with single-step algorithms for multiple-receivers geolocation system and with the Cramér–Rao lower bound.

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1. Introduction

The problem of locating a static emitter from passive measurements of time delay, Doppler shift and angle of arrival (AoA) has been considered as a fundamental problem in radar and sonar applications for several decades [1–3]. Typical solutions for this geolocation problem are based on applying two-step localization algorithms to a geolocation system that consists of multiple receivers. Such algorithms involve an estimation step of parameters that are embedded in the received signals, which are characterized by the emitter's position. The position is estimated by finding the location that best fits the lines of position (LOP) associated with parameters such as time delay, angle of arrival, and frequency shift. In this paper the passive emitter geolocation problem is analyzed for a novel geolocation architecture termed "single platform geolocation" (SPG). The SPG system consists of a single receiver (equipped with antenna array) and multiple passive signal transponders, which are placed at known locations and may be either static or dynamic. The concept of SPG has been recently introduced in [4], where the analysis assumed that the Doppler shifts were negligible. In contrast, the work presented here discusses a fast-moving receiver (w.r.t. the emitter), which enables one to augment the emitter position estimation with Doppler frequency-shifts information.

As the superiority of single-step geolocation (a.k.a., direct-position-determination/DPD), over two-step geolocation has been recently discussed in the literature (see, e.g., [4–6]), our numerical analysis focuses on the comparison between transponder-aided single-receiver geolocation vs. multiple-receivers (multiple-RX) geolocation, where in both cases single-step geolocation algorithms are applied.

As will be shown later on, the SPG algorithms achieve a similar performance to multiple-RX DPD algorithms. This highlights the main advantage of using SPG over multiple-RX geolocation, which lies in the reduced system cost. The multiple-RX geolocation algorithms are developed under the general assumption that multiple, synchronized receivers observe the emitter's signal simultaneously.

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The receivers either estimate position-dependent parameters embedded in the captured signal, or simply capture and transfer the raw signal to a central mobile location center (MLC), where the emitter location is estimated. This implies that a network connectivity between all the receivers and the MLC is required (a.k.a., "backbone network"). Transferring the information from the receivers to the MLC in real-time has to be done over an out-of-band (OOB) channel (i.e., outside the wireless channel occupied by the emitter and the receivers, e.g., an IP-based wired connection). The OOB bandwidth requirements vary depending on whether the MLC uses two-step or single-step geolocation (i.e., DPD), where in the latter case the OOB bandwidth significantly increases due to the transfer of raw signal samples vs. few parameters in the former case.

In contrast, with SPG not only most of the receivers are replaced with much-cheaper signal transponders, but the system deployment costs including the backbone network infrastructure are significantly reduced. Since in SPG the raw signal samples are transferred "in-band" (i.e., as multipath), the backbone connectivity is required only between the (single) receiver and the MLC. Compared to multiple-RX, for single-step geolocation, when using SPG the amount of raw signal data that needs to be transferred over the SPG backbone is also reduced by a factor of L (which corresponds to the number of signal-transponders in the SPG system). It should also be noted that in multiple-RX geolocation architectures the receivers are required to be tightly synchronized in time and frequency – a task that requires means such as atomic clocks, GPS receivers and message exchange protocols. This requirement is accomplished implicitly with SPG and without an extra cost.

As will be described in the sequel, the SPG scheme does not require any synchronization between the emitter and the receiver. In that sense, SPG may be considered as a type of an asynchronous geolocation system. Such systems, which have been drawing an emerging interest recently (see, e.g., [13–15]), are based on cooperation between various nodes constructing the network (e.g., "anchor nodes" that are placed in locations known to a central location server). Typically, these systems rely on time-difference measurements provided by the "anchor nodes" to locate the so-called "blind nodes" within the network. In many cases, these "blind nodes" also need to actively participate in their own geolocation process (e.g., by referencing their own timing measurements to signals transmitted by the "anchor nodes", by reporting these timing measurements back to a location server, and so on).

Though the SPG transponders may be viewed as a type of "cooperative anchor nodes", there are several fundamental differences that distinguish SPG from those systems. First, unlike the anchor nodes aforementioned, the transponders do not conduct any measurement of the emitter signal. Conversely, they are used only to form a multipath channel for the receiver. Second, in the SPG scheme, except from transmitting its signal, the emitter is completely passive during the location process: it does not need to actively participate in its location process; further, it is even unaware of being located. This makes SPG suitable for various kinds of military and security location applications. Third, as opposed to the approach pursued by [13–15], which relies on a two-step location estimation via time-difference measurements, all the algorithms discussed in this paper are based on single-step location, in which the emitter position is extracted directly from the received signal samples.

Main contributions: We derive a novel received signal model for transponder-aided geolocation using a single moving receiving station. Based on this model we derive novel maximum-likelihood (ML), single-step (direct) geolocation algorithms for known and unknown (deterministic) signals. We also provide a detailed (textbook) derivation of the "concentrated" Cramér–Rao lower bound (CRLB) on the emitter position estimation for the received signal model. Using numerical analysis of the CRLB expressions we highlight and demonstrate the system layout limitation when using transponder-aided geolocation.

Paper organization: Section 2 outlines the problem formulation. Single-step algorithms for SPG of a static emitter under the assumptions of known and unknown signal waveforms are derived in Section 3. Numerical performance examples of these algorithms are given in Section 4. The final conclusions are given in Section 5. Finally, in the appendix we provide the derivation of the CRLB, along with the reference multiple-RX DPD algorithms used for comparison with the devised SPG algorithms.

2. Problem formulation

Consider a stationary source transmitting a narrow band signal whose carrier frequency is f_c and its envelope is $s(t)$. The bandwidth of $s(t)$ is W, which satisfies $W \ll f_c$. An appropriate signal model would be $s(t)e^{\imath 2\pi f_c t}$, where $\imath \triangleq \sqrt{-1}$. When the signal is observed by a moving receiver the observed signal becomes $s(\beta t)e^{\imath 2\pi f_c \beta t}$, which is an expansion or compression of the signal time scale, known as the Doppler effect. Let v be the sensor-source relative velocity and c the signal propagation velocity, then $\beta = 1 + v/c$. Since β is nearly one the effect on the slowly varying envelope will be negligible however the carrier frequency will be shifted considerably (see, e.g., [7, p. 241]). In this case the observed signal can be approximated by $s(t)e^{\imath 2\pi f_c \beta t}$. When the distance between the source and the receiver is considerable, the signal will be delayed by τ and the observed signal becomes $s(t-\tau)e^{\imath 2\pi f_c \beta t}$ up to the complex constant $e^{-\imath 2\pi f_c \beta \tau}$ which has no effect on the signal amplitude, the signal delay or the signal frequency. This simple model will be used in the sequel.

The location of the static emitter is estimated using a geolocation system that consists of a single (moving) receiver, and L static, passive signal-transponders acting as ideal signal reflectors. The transponders reflect the emitter signal towards the receiver and assist in the geolocation of the transmitter. This scenario is depicted in Fig. 1. Our model assumes that the transponders do not amplify the signal and therefore do not generate any further processing delay. Assume that the emitter is located at $\mathbf{p}_0 = [x_0, y_0, z_0]^T$ and let $\mathbf{p}_\ell$, $\ell = 1 \ldots L$, denote the position of the ℓth transponder.

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