Signal Processing 119 (2016) 185–189

Contents lists available at ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

Fast communication

Source localization using a moving receiver and noisy TOA measurements

Yang Liu [a,*], Fucheng Guo [a], Le Yang [b,c], Wenli Jiang [a]

[a] College of Electronic Science and Engineering, National University of Defense Technology, Changsha, Hunan 410073, P.R. China
[b] Synergetic Innovation Center of Food Safety and Nutrition, Wuxi, Jiangsu 214122, P.R. China
[c] School of Internet of Things (IoT) Engineering, Jiangnan University, Wuxi, Jiangsu 214122, P.R. China

ARTICLE INFO

Article history:
Received 11 June 2015
Received in revised form
19 July 2015
Accepted 22 July 2015
Available online 20 August 2015

Keywords:
Source localization
Time of arrival (TOA)
Period estimation
Conditional Cramér–Rao lower bound
(C-CRLB)

ABSTRACT

This paper considers using a moving receiver to locate a stationary source that transmits periodically with an unknown period. The receiver records the time of arrivals (TOAs) of the intercepted signals for source localization. A new two-step localization algorithm is developed. Its first step ignores the signal propagation delay and identifies the signal period using existing period estimation techniques. Sufficient conditions for correctly relating the TOA measurements are established. The second step of the new algorithm jointly estimates the source position and the signal period using an iterative maximum likelihood estimator. Simulation results demonstrate the effectiveness of the newly proposed technique.

1. Introduction

Source localization is a central problem in various applications including sonar [1], radar [2] and wireless sensor networks [3]. Among the commonly used positioning parameters, the time of arrival (TOA) information of the received source signal is a popular choice because of its potentials in attaining high localization accuracy [4–7]. When multiple receivers are available and the signal transmission time is known, the source position can be determined via trilaterating the source–receiver ranges deduced from the TOAs obtained simultaneously. If the signal transmission time is not known in the case of, e.g., the source being non-cooperative, we may convert the TOAs into time difference of arrival (TDOA) measurements and invoke TDOA positioning to locate the source (see [6,7] and references therein).

Source localization using a single moving receiver is also possible [8–11], where the use of Doppler and/or bearing measurements was considered. Recently, TOA-based localization with a moving receiver was examined in [5]. Different from the multi-receiver scenario, multiple signal interceptions are needed to obtain a sufficient number of TOA measurements for source position estimation. But the system is less complex and we no longer require data transmission among receivers or that the receivers are synchronized, which is generally needed in the multi-receiver positioning. The single-receiver localization scheme developed in [5] explores the source signal periodicity and assumes the availability of the period of the signal emission. In this case, the source–receiver distances at different times can be extracted from the obtained TOAs for source localization.

We shall study in this paper the more general problem of locating a stationary source with periodic signal emissions using a moving receiver when the signal period is *unknown* and missed detections of signal emissions are present. The considered scenario is more practical and may arise, e.g., if the source to be localized is a pulse radar and/or there exist obstacles between the source and the receiver. It is significantly different from the scenario investigated in [5] in

* Corresponding author.
E-mail addresses: ruben052013@hotmail.com (Y. Liu), gfcly@21cn.com (F. Guo), le.yang.le@gmail.com (L. Yang), jiangwenlibetter@163.com (W. Jiang).

http://dx.doi.org/10.1016/j.sigpro.2015.07.029
0165-1684/

the sense that it is now difficult to find a simple way to relate the sequentially measured TOAs for source–receiver distance estimation. This renders the localization paradigm developed in [5] inapplicable.

To address the above limitation, a new two-step localization algorithm is proposed in this paper. The first step neglects the presence of the signal propagation delay from the source to the receiver and applies a period estimator, such as the modified Euclidean algorithm (MEA) [12] and the integer lattice line search (ZnLLS) method [13], to the TOA sequence to identify the period of the signal emission. The obtained source signal period estimate can be quite accurate if, e.g., the receiver happens to be stationary temporarily. However, in our case, the period estimate is in general biased, due to ignoring the signal propagation delay and the nondetection of some signal emissions. With the erroneous signal period estimate, it is still possible to relate the TOA measurements correctly [14]. We provide sufficient conditions for correctly determining the time interval between two signal emissions associated with two neighboring TOA measurements, which is an integer number of the signal period. The second step of the proposed localization algorithm identifies the source position while refining jointly the signal period estimate to produce improved source–receiver range difference estimates for better localization accuracy. The second-step processing is iterative. It could reach the conditional Cramér–Rao lower bound (CRLB) of the source position and the source signal period, if the sufficient conditions for correctly relating the TOA measurements in the first step are satisfied.

The contribution of this paper is two-fold. Firstly, we present a new algorithm for estimating jointly the unknown source position and source period from a sequence of TOA measurements obtained at a moving receiver, a problem that has not yet been addressed in previous literature. This makes our work significantly different from [5], where the source period is assumed known, and from the period estimation literature such as [12,13], where there is no relative motion between the source and the receiver. Secondly, the conditional CRLB of the unknowns is derived and sufficient conditions for the newly developed algorithm to reach the conditional CRLB are established.

In the rest of the paper, we first formulate the localization problem in Section 2. Section 3 derives the conditional CRLB of the source position and the source signal period. The new localization algorithm is presented in Section 4. Simulation results are given in Section 5 to illustrate the performance of the proposed technique. Section 6 concludes the paper.

2. Problem formulation

Consider the 2D localization scenario. The stationary source is located at the unknown position $\mathbf{u}=[x_t, y_t]^T$. It transmits a periodic signal with a period of T_s, which is intercepted by a moving receiver along its trajectory.

Suppose that during the observation interval, M source signal TOA measurements are obtained. The jth TOA measurement is

$$t_j = t_0 + \frac{\|\mathbf{u}-\mathbf{s}_j\|}{c} + N_j T_s + \Delta t_j \tag{1}$$

where t_0 is the starting point of the signal transmission and c is the signal propagation speed. $\mathbf{s}_j$ is the receiver position when t_j is obtained and $\|\mathbf{u}-\mathbf{s}_j\|/c$ is the signal propagation delay, where $\|*\|$ denotes the Euclidean distance. Δt_j is the TOA measurement error modeled as a zero-mean Gaussian random variable with variance σ_t^2. We further assume that the TOA measurement errors at different times are independent to one another.

N_j in (1) is a positive integer such that $N_j > N_i$ for $i<j$ and $t_0+N_jT_s$ represents the transmission time of the jth received source signal emission. Note that, in general, N_j may not satisfy $N_j = N_{j-1}+1$ due to the nondetection of some signal emissions. This may render the scaling of the signal period T_s unidentifiable, e.g., when the source is a radar with rotating antenna and few TOAs are received during each detection of the rotating beam so that $N_j - N_{j-1}$ may be large. In this case, we have that $N_jT_s = (N_j/N)\cdot(NT_s)$, where N is the greatest common divisor (GCD) of N_j. This scaling ambiguity, however, would not affect the applicability of the localization algorithm that will be developed in Section 4, because it does not affect the validity of the signal model in (1).

The TOA measurement equation given in (1) is different from the one in [5] in the sense that besides t_0 and the source position $\mathbf{u}$, the signal period T_s and the transmission time of the jth intercepted signal emission $t_0+N_jT_s$ are also unknown. It is also different from the point event model adopted in [13,15] for period estimation where the signal propagation delay $\|\mathbf{u}-\mathbf{s}_j\|/c$ introduced by the receiver movement was not taken into account.

The starting time of the signal transmission t_0 is a nuisance parameter for source localization. We eliminate it by first multiplying both sides of (1) by the signal propagation speed c and evaluating $ct_j - ct_{j-1}$ to arrive at

$$r_{j,j-1} = ct_j - ct_{j-1} = d_{j,j-1} + N_{j,j-1} d_{T_s} + n_{j,j-1} \tag{2}$$

where $j=2,3,\ldots,M$, $d_{j,j-1} = \|\mathbf{u}-\mathbf{s}_j\| - \|\mathbf{u}-\mathbf{s}_{j-1}\|$ is the range difference of arrival (RDOA) between the jth and the $(j-1)$th signal interception, $N_{j,j-1} = N_j - N_{j-1}$ and d_{T_s} is equal to cT_s. We shall also refer to d_{T_s} as the signal period in the rest of the paper. The noise term in (2) is $n_{j,j-1} = c(\Delta t_j - \Delta t_{j-1})$.

Collecting $r_{j,j-1}$ yields an $(M-1)\times 1$ vector

$$\mathbf{r} = \mathbf{f}(\mathbf{u}, d_{T_s}) + \mathbf{n} \tag{3}$$

where $\mathbf{r} = [r_{2,1}, r_{3,2}, \ldots, r_{M,M-1}]^T$, $\mathbf{f}(\mathbf{u}, d_{T_s}) = \mathbf{d} + \mathbf{k} d_{T_s}$ is the true value of $\mathbf{r}$, $\mathbf{d} = [d_{2,1}, d_{3,2}, \ldots, d_{M,M-1}]^T$ and $\mathbf{k} = [N_{2,1}, N_{3,2}, \ldots, N_{M,M-1}]^T$. The measurement error vector $\mathbf{n} = [n_{2,1}, n_{3,2}, \ldots, n_{M,M-1}]^T$ has a covariance matrix equal to

$$\mathbf{Q}_{(M-1)\times(M-1)} = c^2\sigma_t^2 \begin{bmatrix} 2 & 1 & 0 & \cdots & 0 \\ 1 & 2 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & \cdots & 1 & 2 & 1 \\ 0 & \cdots & \cdots & 1 & 2 \end{bmatrix}. \tag{4}$$

We are interested in estimating the source position $\mathbf{u}$ from the transformed TOA measurements in $\mathbf{r}$.