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Fast track article

Opportunistic Time-of-Arrival localization in fully asynchronous wireless networks

Danilo Spano [a,1], Fabio Ricciato [b,*]

[a] SnT - University of Luxembourg, Luxembourg
[b] Faculty of Computer and Information Science, University of Ljubljana, Slovenia

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ABSTRACT

We present a novel Time-of-Arrival localization scheme for fully asynchronous systems, where each node clock is affected by unknown bias (temporal offset) and drift (frequency offset). The proposed method relies exclusively on the measurement of reception times, and does not require knowledge nor control of the transmission times. Therefore, it can exploit opportunistically signals and packets that are already available over-the-air for communication purposes. We formalize the problem and provide a low-complexity resolution algorithm based on pseudo-ranges. Simulation results are provided to validate the resolution approach and to assess the sensitivity of the localization accuracy to the main scenario parameters.

1. Introduction

Despite the widespread adoption of Global Navigation Satellite Systems (GNSS), alternative positioning systems remain of interest for applications where GNSS signals are not available (e.g., indoor, tunnels, urban canyon) and/or the integration of GNSS receivers is not feasible due to size, energy or cost constraints (e.g., in low-cost sensor networks). In order to preserve cost-effectiveness and ease of adoption, it is desirable to develop localization methods that reuse *opportunistically* legacy radio signals already available over-the-air for communication purposes and Commercial Off-The-Shelf (COTS) transceivers. One possible approach is to rely on power measurements by leveraging the Received Signal Strength Indicator (RSSI), nowadays a commodity feature in almost all COTS transceivers [1]. RSSI-based localization functions can be implemented on top of existing wireless communication systems and several tools are already available for different technologies, including WiFi and IEEE 802.15.4. Generally speaking, formalized RSSI-based methods rely on the assumption that the *average* received power is tied to the transmitter–receiver distance through the so called "Path-Loss Model" [2–4]. Such methods exhibit low accuracy in practice, since in real environments the received power is heavily affected by other channel factors like multipath and antenna patterns, in addition to transmitter–receiver distance [5,6]. For these reasons, several authors have adopted machine learning approaches to develop detailed RSSI maps for specific environments, in the direction of so-called "RSSI fingerprinting" (e.g. [7]).

Another class of methods is based on *time* measurements. Time-based localization is potentially more accurate than RSSI-based methods, since the relation between distance and reception time is generally tighter than for received power [8]. However, the traditional approaches to time-based localization require the system to support some form of

* Corresponding author.
E-mail address: fabio.ricciato@fri.uni-lj.si (F. Ricciato).

1 This work was done while D. Spano was with the University of Salento.

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node synchronization (e.g. [8–11]) or at least accurate *measurement or control of transmission times* (e.g. [12–15]). Both these functionalities are difficult or costly to achieve in practice. Node synchronization requires the distribution of synchronization signals, either via additional wired infrastructure or wireless protocols, and the implementation of dedicated functions into the devices that consume additional energy, bandwidth, and computation resources. Controlling or measuring the actual transmission time is also difficult in packet-oriented networks with standard hardware, due to unpredictable delay components between the construction of the packet and the transfer to the network interface on one hand, and the intrinsic variability of channel access delays due to MAC dynamics on the other [16]. For these reasons, it is impractical to deploy these methods on low-cost COTS devices [17–20].

In this contribution we present a localization method based on Time-of-Arrival (ToA) measurements that does not require clock synchronization nor imposes any constraint onto the timing or format of the transmitted signals. In other words, we address the problem of time-based localization in fully asynchronous systems. Our method relies exclusively on the measurement of *reception times*, and does not assume any knowledge nor control of the *transmission times*. While in synchronous ToA systems clock differences are eliminated *ex-ante*, we consider here an approach where clock differences are accounted for *ex-post*, i.e., they are estimated from the available measurement data along with the (unknown) position of the blind node.

Only a few recent works have started to consider this approach. In particular, Jean and Weiss [21] as well as our previous work [22,23] have assumed semi-idealized scenarios where clock frequencies are perfectly tuned across all nodes. In other words, their clock error model considers non-zero (unknown) *time offset* (termed "clock bias" hereafter) but zero *frequency offset* (equivalently: "clock drift" or "clock skew"). Following [20], we will refer to such systems as *quasi-synchronous*, to distinguish them from *fully asynchronous* systems that are affected by both clock bias and clock drift.

The applicability of quasi-synchronous models to real-world systems is rather limited since, in practice, clock frequency deviations cannot be neglected in COTS radios. The fully asynchronous scenarios including frequency errors has been considered in [24,25] that followed the so-called "Differential Time-Difference of Arrival" (DTDoA) approach, wherein most of the unknown variables are eliminated upfront by taking double differences of reception timestamps. Here we follow a different and more compact approach, similar to the one adopted in [21] for the quasi-synchronous scenario, where all unknown quantities are treated as nuisance parameters in the estimation process, rather than discarded upfront.

With respect to those earlier work, in this contribution we make two key novel contributions. First, advancing over [21–23], we consider a more realistic clock error model that includes a *frequency offset (clock drift)* in addition to *time offset (clock bias)*. This makes our model much closer to real operating conditions of wireless systems composed by COTS radios, whose internal clock are unavoidably affected by a certain deviation from the nominal frequency, normally contained within a few tens of ppm. Second, we propose a general low-complexity approach to localization in asynchronous systems that does not require to subtract upfront the available measurements, as done in [24,25] (and partially in [22,23]). For well-connected topologies the system matrix is rank-deficient by one, and we provide a means to estimate the resulting pseudo-ranges in closed-form. This allows to adopt an efficient iterative least squares procedure, similar to the one used in standard (synchronous) GNSS methods, to finally obtain an univocal estimate of the unknown position.

The rest of the paper is organized as follows. In Section 2 we relate our work to previous studies in time-based localization. In Section 3 we discuss several system-level aspects of the proposed solution and define the system model. In Section 4 the estimation problem is formalized along with the resolution method. Section 5 reports a series of numerical simulation results that, on one hand, validate the correctness of the proposed approach, and on the other hand explore the relationship between the final accuracy and the key scenario parameters. This section includes also a comparison with the DTDOA method developed in the recent work [25]. Finally, conclusions and indications for future work are given in Section 6.

2. Related work

The bulk of previous work on time-based localization in asynchronous networks relies on the measurement or tight control of transmission times, in addition to reception times. This applies also to proposals based on two-way message exchange (e.g. [13–15]) aimed at measuring the *Time-of-Flight* (as opposite to *Time-of-Arrival*). Our approach is different: we rely exclusively on reception timestamps, and do not make any assumption about (the knowledge of) transmission times. This is a key feature that avoids the need to introduce additional protocols and message exchange dedicated to perform timing measurements, as needed instead by previous methods. For this reason, our method can exploit "opportunistically" the (reception timestamps of) packets and signals that would be transmitted anyway for node-to-node communication purposes, regardless of the PHY/MAC protocol in place and without necessarily requiring cooperation by the signal source. In case of multi-radio receivers, the proposed scheme allows in principle to exploit any other legacy signal present over-the-air (e.g., DVB broadcasts, UMTS/LTE beacons and alike) that are typically transmitted by non-cooperating sources.

Only a few previous papers have addressed the problem of localization based exclusively on reception timestamps from non-synchronized clocks [21–25]. In particular, [21–23] address the quasi-synchronous scenario, i.e., they do not model clock drifts—a gross limitation for real-world implementations. Clock drifts were considered in [24,25]: the resolution approach adopted therein is based on *double subtraction* of timestamps between a quadruplet of nodes (2 TX + 2 RX). This method, known as Differential Time Difference of Arrival (DTDOA), eliminates upfront most of the unknown quantities, i.e., clock bias terms and transmission times, while linear regression was used to estimate (and compensate for) relative clock drifts. Notably, some forms of *single subtraction* between node triplets were adopted also in [22] (1 TX + 2 RX)