TDOA Fingerprinting for Localization in Non-Line-of-Sight and Multipath Environments

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***Abstract*—Localization in urban areas with no direct line-of-sight between the target and anchor nodes turns out to be challenging for many well-known localization methods. In combination with multipath propagation of employed radio waves, the performance of the location estimates can be heavily deteriorated. In this paper we introduce a multilateration method that is able to cope with such conditions. Employing a discrete approach for the estimation of the emitter location, we show how prior knowledge of the environment, obtained from a ray tracer or ray launcher, can improve the system accuracy. The localization algorithm is based on time differences of arrival between the observing sensors. However, in non-line-of-sight these time differences change as opposed to common signal models that assume free-space propagation. This mismatch is resolved taking into account information of the propagation paths provided by the ray launcher. Simulation results demonstrate that the proposed method effectively mitigates the impact of non-line-of-sight and multipath propagation on the location accuracy.**

***Index Terms*—Time Difference of Arrival, Positioning, Ray Tracing, Ray Launching, Propagation, Spatial Sparsity**

I. INTRODUCTION

For the localization of wireless sensor nodes, mobile phones, or other types of radio wave emitters, numerous different approaches and related algorithms have been proposed. All approaches are based on explicit or implicit measurements of physical parameters of the propagating waves. To assist the localization and relate it to a known coordinate system, the signals are usually transmitted or received by anchor nodes whose locations are known. Possible physical parameters at the receiver are the signal strength, time, frequency, phase or direction of the arriving wave, which are further processed by the localization algorithm, e.g., taking differences, averaging or other types of combining. However, all these parameters are affected if no direct line-of-sight (LOS) path exists which forces the radio waves to arrive at the receiving antenna by means of reflections and diffractions. Thus, the accuracy of all methods that assume free-space propagation in their system model, will be deteriorated.

Various approaches have been proposed in order to overcome or avoid such problems. A scheme that tries to track and discriminate between line-of-sight and non-line-of-sight (NLOS) propagation at the different receivers is proposed in [1] assuming range measurements. In case of NLOS the range measurements of the particular receiver are corrected based on their statistics to obtain values resembling LOS. A similar error suppression approach is suggested by [2] which further investigates the statistics of the error in the NLOS case. Other approaches like [3] conduct more profound studies of geometrical properties of the wave propagation and thereby aim to suppress NLOS components in multipath propagation environments. The authors of [4] go a step further by assuming no LOS component but a closed room. An exact formulation of the differential equations of the wave field and a discrete grid enable the localization of an emitter behind a corner or in a another connected room. However, this last approach is only suitable for very specific scenarios with explicitly defined boundary conditions.

In order to tackle more generic scenarios with a good location accuracy, higher than that of statistics based methods but without detailed knowledge of the environment, fingerprinting has been introduced in [5] for example. Most literature about fingerprinting utilizes a metric based on the received signal strength indicator (RSSI) of the signals and assumes that a prior measurement campaign has taken place in order to obtain the fingerprints, which are calculated by the measured RSSIs at certain known positions. Those fingerprints are stored in a database and compared against the fingerprints obtained at runtime in order to perform the localization. In an attempt to reduce the effort and costs necessary for the collection of the fingerprints, the work in [6] suggests to obtain them from simulations by the means of a ray tracing or ray launching algorithm. In [7] this idea has been further extended to not only make use of the RSSI information but also the full information of the directions of arrival of different propagation paths at the receiver, which are available from the ray tracer. This is a powerful approach, however, it requires a calibrated antenna array at the receiver in order to obtain the same directional information from the received signal. As an alternative, ranging based methods have the advantage that they only need a single receive antenna and a single associated signal processing chain. Therefore, we propose an approach based on the fingerprinting of the time difference of arrival (TDOA) of a signal. In [8] we have developed a scheme for localization based on spatial sparsity of the emitter locations. The method utilizes a discrete grid of possible locations which eliminates the need to explicitly solve the nonlinear equations determined by the TDOAs and makes it suitable for fingerprinting. Thus, extending [8] with our ray launching algorithm [9] for multipath propagation leads to a TDOA based fingerprinting approach introduced in this paper.

The paper is structured as follows. Section II introduces the system model and develops the algorithm for TDOA estimation. Sections II-A shows how to estimate a location in free-space propagation, while Section II-B explains the incorporation of the ray tracing data into the problem. In Section III we provide numerical simulation results demonstrating the feasibility and the benefits of the proposed method and conclude the paper in Section IV.

II. SYSTEM MODEL

We consider a localization system with three or more observing receivers for the estimation of a transmitter location in a two-dimensional space. In the literature the receiver nodes, whose locations are known, are also known as anchors of the system. They are interconnected in order to exchange the received signals and synchronized to a common clock. Each receiver is using only a single antenna. By cooperative processing of the received samples, a hyperbola curve corresponding to the potential locations of an emitter can be determined for each receiver node pair based on the estimated TDOAs [10]. The intersection point of the curves yields the emitter location.

We first show how the proposed method is derived for a free-space propagation environment. After that we describe how environment aware fingerprinting is introduced into the system to handle multipath and NLOS propagation.

In a free-space propagation environment the TDOA for transmitter location $\mathbf{x}_j$ and receiver locations $\mathbf{z}_k$ and $\mathbf{z}_l$ can be geometrically determined as

$$\Delta(\mathbf{x}_j, \mathbf{z}_k, \mathbf{z}_l) = \frac{1}{c}\|\mathbf{z}_k - \mathbf{x}_j\|_2 - \frac{1}{c}\|\mathbf{z}_l - \mathbf{x}_j\|_2, \tag{1}$$

where c denotes the propagation speed of the wave. To estimate the TDOAs we start with a signal model for free-space propagation. We denote the emitted signal with $s(t)$ and consider the signals $y_r(t)$ received at different nodes. The received signal at the r-th receiver with channel coefficients h_r is then given as

$$y_r(t) = h_r s(t - \tau_r) + w_r(t), \tag{2}$$

where $s(t)$ can by any type of signal and $w_r(t)$ is assumed to be white Gaussian noise, τ_r stands for the delay which is related to the free-space propagation distance between the transmitter and receiver r. In case of multipath propagation the channel impulse response becomes a function of time and is convolved with the transmitted signal

$$y_r(t) = h_r(t) * s(t - \tau_r) + w_r(t).$$

For this case τ_r is the delay of the first arriving path.

A. Location Estimation

In [8] we have considered the case of multiple transmitters for free-space propagation. For multipath propagation, multiple transmitters in the same band are challenging as the assignment problem between the delays and the sources is further deteriorated. Therefore, we restrict our model in this paper to a single transmitter to obtain good location estimates under such severe conditions. Using the equivalent baseband model we assume that the vector $\mathbf{y}_r(\gamma)$ contains an ideally low pass filtered, Nyquist sampled portion of the received signal, delayed by γ

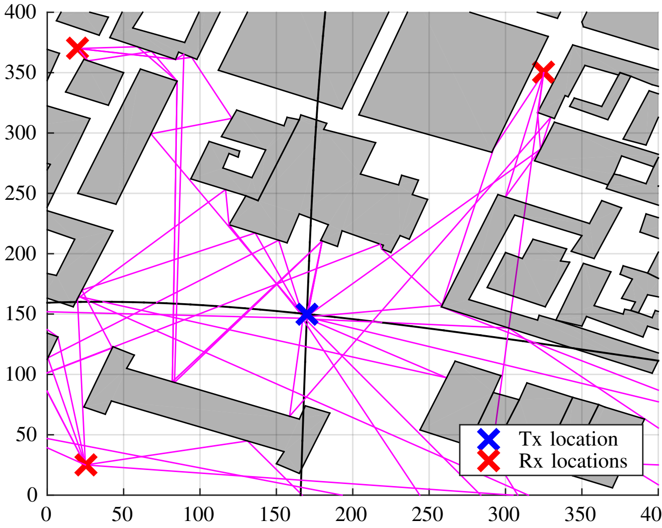


Fig. 1: Footprint of buildings in the inner city of Munich with propagation paths between the transmitter and the receiving anchor nodes in magenta, TDOA hyperbolas in black.

$$\mathbf{y}_r(\gamma) = \big(y_r(t_0 - \gamma), \ldots, y_r(t_{N-1} - \gamma)\big)^{\mathrm{T}} \in \mathbb{C}^{N\times 1}.$$

Furthermore, we define a grid of K location cells on the region of interest in order to determine the TDOAs in a joint manner. We select one receiver, e.g., $r = 1$ as a reference and denote its normalized output as $\bar{\mathbf{y}}_{\text{ref}}(\gamma) = \mathbf{y}_{\text{ref}}(\gamma)/\|\mathbf{y}_{\text{ref}}(\gamma)\|_2$. Based on the reference we construct matrices $\mathbf{\Psi}_r$ for all other receivers that contain time shifted versions of the normalized reference signal with time shifts $\gamma_{r,1}, ..., \gamma_{r,K}$ according to the locations cells and the TDOAs in (1)

$$\mathbf{\Psi}_r = \left[\bar{\mathbf{y}}_{\text{ref}}(\gamma_{r,1}), \ldots, \bar{\mathbf{y}}_{\text{ref}}(\gamma_{r,K})\right] \in \mathbb{C}^{N\times K}. \tag{3}$$

The time shifts are defined based on the TDOAs at the center of each location cell. By that, the element $[\mathbf{\Psi}_r]_{ij}$ corresponds to a unique location cell which is the same for all r, due to the arrangement of $\gamma_{r,k}$.

In that way one can find a common sparse formulation of the localization problem

$$\hat{\mathbf{y}}_r = \mathbf{\Psi}_r \mathbf{b}\,, \tag{4}$$

where $\mathbf{b}$ is a vector with sparse support corresponding to the possible location cells of the transmitter. Due to the additive noise and the effect of the channel, $\hat{\mathbf{y}}_r$ can only be an estimate for the received vector $\mathbf{y}_r$. It is important to emphasize that such model contains inherent errors due to the discrete sampling of the signal, the error between the real transmitter location and the center of the corresponding cell, the noise introduced by the receiver and the effect of the

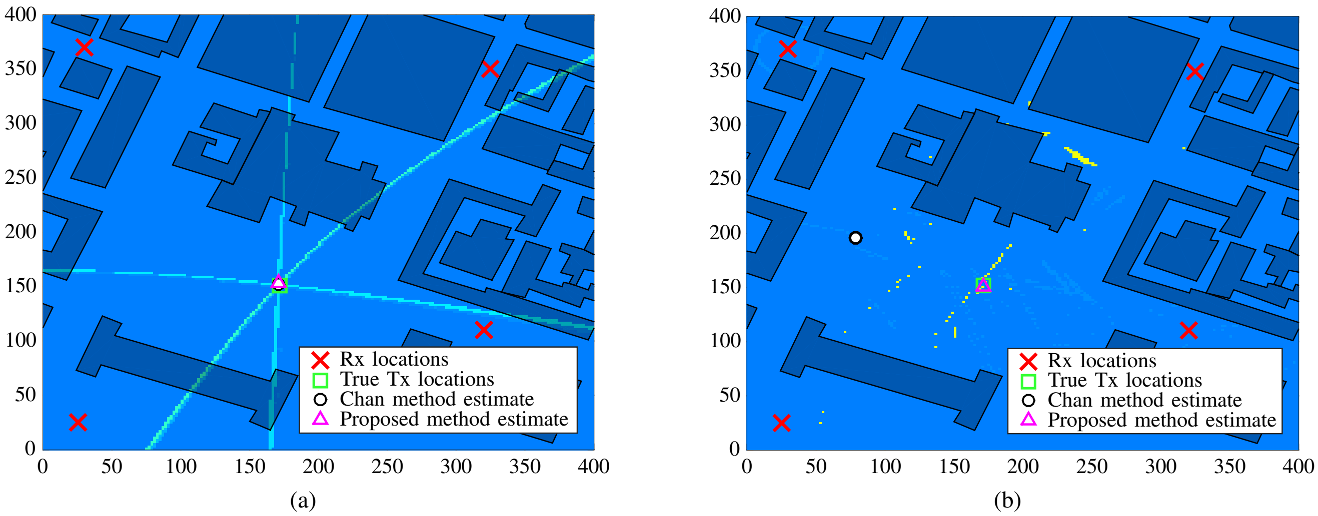


Fig. 2: Comparison of the distortion encountered by the algorithm in (5) for (a) free-space and (b) multipath propagation. Our proposed method is able to estimate the location correctly in both scenarios while Chan's method fails under NLOS.

multipath propagation. The former errors may be modeled as additional noise, while the fingerprinting technique introduced in this paper aims to suppress the effect of the channel. Note that at least three receivers, or two pairs, are necessary to find a unique solution for the support of $\mathbf{b}$. For a single pair of receivers, the possible support of $\mathbf{b}$ contains multiple nonzero elements corresponding to the TDOA hyperbola of the transmitter location. To determine the transmitter position based on the system model and the measured signal $\mathbf{y}_r$ and to resolve the ambiguity of single receiver pairs, the following algorithm is used. Calculate the correlations $\boldsymbol{\beta}_r$ for each receiver pair as

$$\boldsymbol{\beta}_r = \boldsymbol{\Psi}_r^H \frac{\mathbf{y}_r}{\|\mathbf{y}_\mathrm{r}(\gamma)\|_2}$$

and combine the correlation measures into

$$\boldsymbol{\beta}^* = \textstyle\sum_{r=2}^N \boldsymbol{\beta}_r. \tag{5}$$

An example for this can be seen in Fig. 2 where the values of $\boldsymbol{\beta}^*$ have been arranged according to their corresponding locations. Then the estimate for the location cell containing the emitter can be obtained by taking the maximum

$$\tilde{k} = \underset{k\in\{1,\ldots,K\}}{\operatorname{argmax}} \; |[\boldsymbol{\beta}^*]_k|.$$

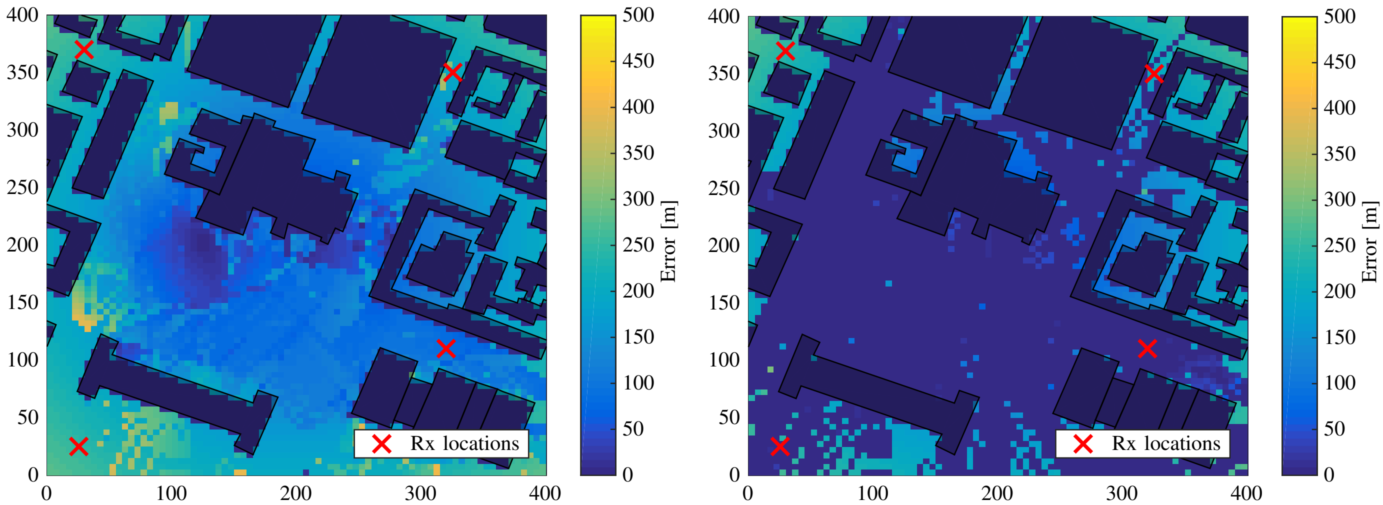
B. Ray launching Based Fingerprinting

Non-line-of-sight and multipath propagation of the radio waves introduce an inherent error into the localization as they alter the length of the propagation paths and add additional paths with different delays to the channel. In order to obtain the propagation information and resolve the problem by fingerprinting, either extensive measurement campaigns are necessary, or it can be simulated using ray tracing software and a model of the environment. For the results of the present paper, the PIROPA ray launcher [9] has been utilized. The algorithm is based on an input of 2.5D building data, i.e., buildings and other objects in the environment are modeled based on their footprints, as seen in Fig. 1, and their heights. PIROPA provides a precise output of each segment of a propagation path, therefore providing information about the angles of departure and arrival, as well as the path lengths, which immediately lead to the power delay profile.

To include the ray launching data into the localization algorithm it is necessary to model the TDOA related time shifts in (3) for each entry of the matrices $\boldsymbol{\Psi}_r$. Possible emitter location cells are straightforwardly represented by a grid of receivers in the ray launching algorithm. The algorithm is evaluated and a set of rays is obtained for each possible location. Based on the length of the rays the propagation delays, i.e., the times of arrival, can be evaluated. To resolve the multipath ambiguity in the delay, the dominant propagation path needs to be selected. For this paper we select the shortest arriving ray to determine the time. However, it is also possible to select a weighted combination of rays. Then, to calculate the TDOAs, a pair of ray launching results of two receivers has to be combined by subtracting the times of arrival at both receivers for each location cell. In that way the relevant time shifts $\gamma_{r,1}, \ldots, \gamma_{r,K}$ for the location cells can be obtained. The TDOA based fingerprint data can be stored and used during runtime of the localization algorithm. As with other fingerprinting approaches this step has to be performed in an offline phase before the final deployment of the system. It has to be re-evaluated only whenever the position of one or more observing receivers or the scenario is changed, e.g., when a new base station is added as part of a mobile network.

III. RESULTS

Simulation results have been obtained for scenarios in the inner cities of Aachen and Munich. The Munich data set comes from the land register data while the Aachen data is extracted from the OpenStreetMap (OSM) project. Government data sets usually contain much better information about the building heights which can also be extracted from LIDAR scans.



(a) (b)

Fig. 3: Error of localization in Meters evaluated on a 400 m × 400 m region of interest, 5 m resolution, in the inner city of Munich, Germany for (a) Chan's method and (b) proposed method.

For the German state of North Rhine-Westphalia, where the authors' university is located, comprehensive LIDAR scan data is available and is updated by the local administration every 5 years. The OSM data on the other hand has proven to be a reasonable and royalty-free alternative with ever increasing accuracy. Therefore, the PIROPA ray launching tool supports various input filters for different data sets.

For the localization scenario three receivers are placed in a $400\text{m} \times 400\text{m}$ target area. A transmitter is placed on a location in the outdoor area as PIROPA does not support outdoor to indoor propagation modeling. The transmitted signal is a binary phase shift keying (BPSK) signal with a bandwidth of 100 MHz. Since we do not have real world measurement date we use the channel impulse responses provided by the ray launching to convolve it with the signal as given in (2). The size of the location cells for the proposed algorithm is $1\text{m} \times 1\text{m}$. In order to speed up and simplify the simulation we precalculate the channel impulse responses for each cell and allow transmitter locations only at those coordinates. In Fig. 2 a step from the proposed algorithm (5) is shown, in order to visualize how the NLOS propagation environment distorts the TDOAs. For each possible location we determine the error of the localization in meters and compare it to the well known algorithm for TDOA localization given in [11]. The results of this, as shown in Fig. 3, indicate the error of both algorithms. It can be observed that the proposed approach results in a clearly improved accuracy.

IV. CONCLUSION AND OUTLOOK

An approach for enhanced localization in urban areas based on fingerprinting of the TDOAs of an emitted signal has been introduced. As explained, the prior information needed for the fingerprinting can be obtained by ray tracing of a model of the target area. Our simulation results demonstrate the feasibility of the proposed method, while for future research it is desirable to obtain experimental results from real world measurements in order to evaluate the accuracy of the model.

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