Multipath Detection in TDOA Localization Scenarios

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***Abstract*—In this paper, we investigate the detection of multipath signal propagation in a Time Difference of Arrival (TDOA) localization scenario. Usually, TDOA measurements are obtained by determining the absolute maximum of the cross correlation function of signals recorded at different sensor nodes in a sensor network. Multipath signal propagation causes multiple peaks in the cross correlation function which lead to erroneous emitter localization. We use hypotheses of possible multipath signal propagation calculated from the autocorrelation functions to identify the line of sight (LOS) peak in the cross correlation function of a sensor pair.**

I. Introduction

Passive emitter localization in distributed sensor networks is a widely investigated topic with many civil and military applications. According to signal bandwidth, signal structure and other factors, different measurement techniques are used. Well known methods are angle of arrival (AOA) [8], [11], time of arrival (TOA) [9], time difference of arrival (TDOA) [10], [4], frequency difference of arrival (FDOA), received signal strength (RSS) and combinations of these techniques [7], [5]. In this paper, we focus on time difference of arrival measurements.

In urban or suburban areas and especially indoors, multipath signal propagation causes erroneous TDOA measurements. These TDOA measurements are usually obtained by cross correlating recorded signals from different sensor nodes. After the line of sight version of the signal, one or more reflected versions arrive at the sensor nodes. This leads to wrong measurements concerning the distance of the emitter and the corresponding sensor pair and thus results in errors in the emitter localization process. Multipath signal propagation can be advantageous if there exists knowledge about the surrounding area. If the positions of possible reflecting obstacles are known, multipath propagation can be used to localize non line of sight (NLOS) emitters (see [1], [2]).

We analyze a scenario where a mobile sensor network is deployed at the area of operations shortly before starting the localization process (see Figure 1). In such a scenario where we do not have knowlede of reflecting obstacles in the surrounding area, we are unable to use the signal multipath propagation in the way described above to gain more information. Thus a method to detect and suppress the resulting errors is proposed in this paper.

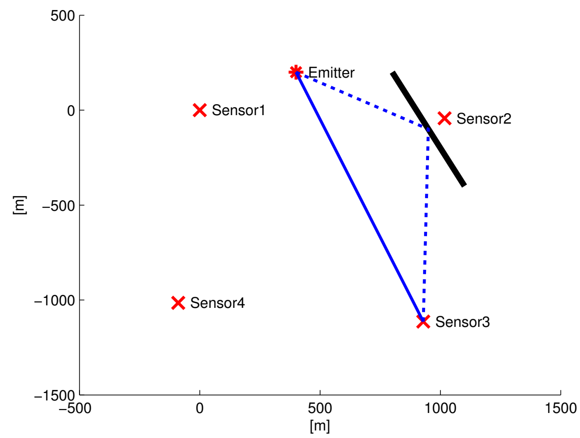


Fig. 1. Scenario with LOS and NLOS signal propagation

II. Scenario description

Given a sensor network consisting of N spatially seperated, time synchronized sensors s_i, $i = 1, ..., N$, the task is to localize an emitter e. Each sensor s_i is located at a fixed point (x_i, y_i, z_i) in three-dimensional space. The emitter is located at an unknown position (x_e, y_e, z_e). The sensors are time synchronized receivers consisting of one RF antenna and an A/D converter. The quantized, time-discrete signal measurement at sampling rate f_s of sensor s_i is given by $f_i(n)$.

The emitter sends an unknown signal at unknown time t_e. This signal propagates at speed of light c and thus, given the positions of the sensors and the emitter, is received at different times t_i at the sensor nodes s_i. The time of arrival t_i at sensor node s_i, assuming line of sight signal propagation, is given by

$$t_i = t_e + \frac{\Delta d_{i,e}}{c} \tag{1}$$

with $\Delta d_{i,e} = \sqrt{(x_i - x_e)^2 + (y_i - y_e)^2 + (z_i - z_e)^2}$ being the Euclidian distance between the sensor and the emitter.

The difference of the TOAs of two sensor nodes s_a and s_b gives the time difference of arrival. The TDOA measurement is defined by

$$\mathrm{TDOA}_{(\mathrm{a,b})} = t_a - t_b = \frac{\Delta d_{a,e}}{c} - \frac{\Delta d_{b,e}}{c}. \tag{2}$$

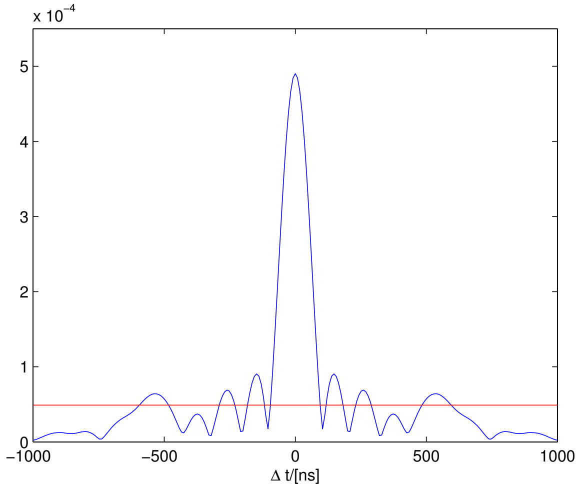


Fig. 2. Autocorrelation function with maximum at $m = 0$. Red line at $a_{max}\alpha$.

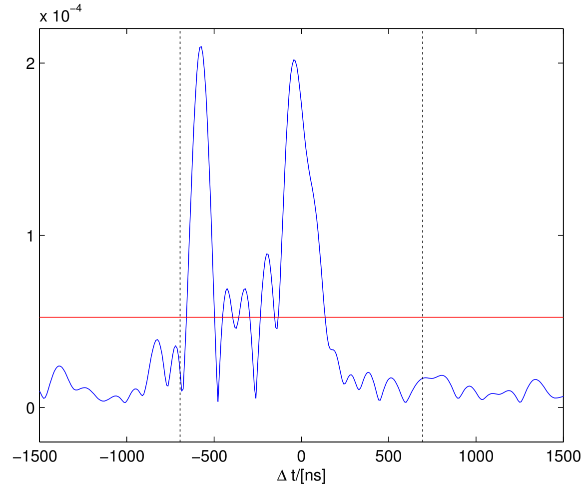


Fig. 3. Cross correlation function with threshold (red line) at $a_{max}\beta$ and bounds by sensor geometry (black dotted lines).

Since the exact determination of a time of arrival t_i of an unknown signal at a sensor node s_i may be impossible, TDOA measurements can be computed by looking at the maximum of the cross correlation function of the signal received by a sensor pair. The discrete cross correlation function is defined (see [6]) as

$$\mathrm{CCF(m)} = \sum_{n=-\infty}^{\infty} f^*(n)g(n+m), \tag{3}$$

where $f(n)$ and $g(n)$ are complex, discrete-time signals at sampling rate f_s and $f^*(n)$ is the conjugate-complex of $f(n)$. By determining

$$\arg\max_m \sum_{n=-\infty}^{\infty} f_a^*(n)f_b(n+m) \tag{4}$$

and by taking the sampling rate f_s into account, we can calculate the time difference of arrival of the signal between the sensor nodes s_a and s_b.

Given the TDOA measurement and the positions of the sensors, possible emitter positions can be limited to the surface of a hyperboloid in three-dimensional space.

III. Multipath detection

In environments with high multipath such as cities, due to signal propagation effects, the reception of the direct LOS signal may be weaker than the later arriving reflected versions of the signal. The maximum of the cross correlation function would then represent a measurement of an emitter which is farther away. To get an accurate localization result, the peaks of the reflected and the LOS version of the signal need to be identified.

In the following, we propose a method that uses the knowledge of the sensor networks geometry and information fusion from the autocorrelation and the cross correlation to decide which peaks (representing time delays) are plausible and which version of the signal is the non-reflected LOS one.

A. Bounds by geometry

The maximum TDOA is given by the geometry of the sensor network. Consider two sensor nodes s_a and s_b and one emitter e. The maximum possible TDOA is measured when the sensors and the emitter are positioned on a line, assuming there are no measurement errors. This largest time difference is then

$$\mathrm{TDOA}^{\max}_{(\mathrm{s_a},\mathrm{s_b})} = \frac{\Delta d_{a,b}}{c} + n, \tag{5}$$

where n is the measurement noise.

If we now search the cross correlation function CCF of a sensor pair (s_a, s_b) for peaks, we only need to examine an interval bound by $\mathrm{TDOA}^{\max}_{(\mathrm{s_a},\mathrm{s_b})}$:

$$\mathrm{abs(m)} \leq \left\lceil \mathrm{TDOA}^{\max}_{(\mathrm{s_a},\mathrm{s_b})} \mathrm{f_s} \right\rceil \tag{6}$$

with $\lceil x \rceil := \min\limits_{k\in\mathbf{Z},k\geq x}(\mathrm{k})\, x \in \mathbf{R}$.

This already eliminates multipath peaks that result from very large reflection paths for emitters that are located outside the sensor geometry and increasing the speed of the algorithm.

B. Generating multipath hypotheses from the autocorrelation function

At first, we look at the autocorrelation function of each signal. The autocorrelation function ACF is the cross correlation function of the signal with itself. The maximum of the ACF is at $m = 0$ and since we are only interested in positive and strong delays, we calculate the local maxima of the ACF for $m > 0$ (see Figure 2).

A local maximum $\mathrm{ACF(m)}$ is a possible multipath delay m if

$$\mathrm{ACF(m)} \geq a_{max}\alpha \tag{7}$$

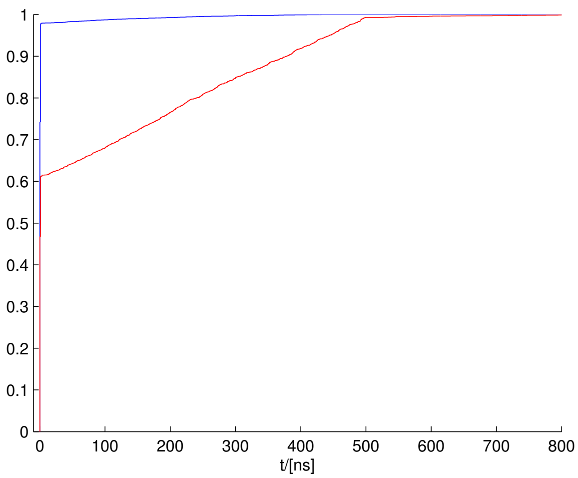


Fig. 4. Cumulative distribution function of the error with (blue) and without (red) multipath detection for simulated data.

where $a_{max} = \mathrm{ACF}(0)$ (the maximum of the ACF) and $\alpha \in \mathbf{R}_{\geq 0}$ is the decision coefficient which is dependent on the signal to noise ratio (SNR).

The vector $M_{s_i} = (m_1, m_2, ..., m_p)$ contains all possible multipath delays for the signal received at sensor s_i calculated with the method described in this section.

C. LOS detection using the cross correlation function

Assuming the maximum of the cross correlation function of a sensor pair (s_a, s_b) has the index m_{max} with amplitude $a_{max} = \mathrm{CCF(m_{max})}$. All local maxima

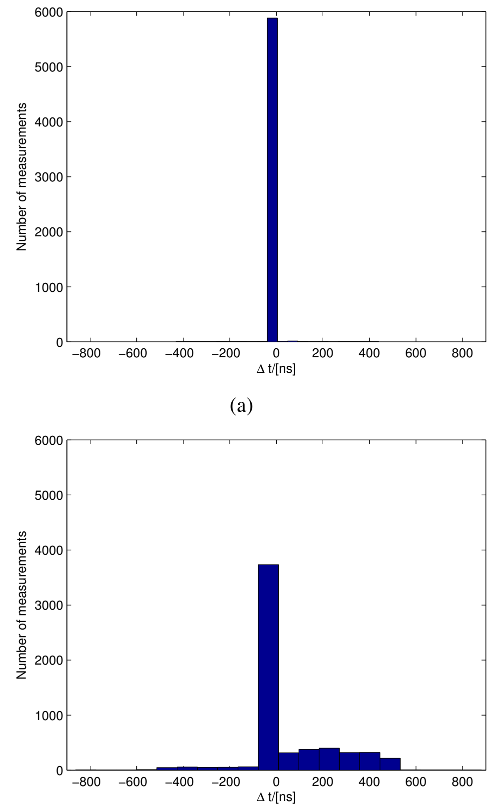
$$\mathrm{CCF(m)} \geq a_{max}\beta \tag{8}$$

with $m \in \left[-\left\lceil TDOA^{max}_{(s_a,s_b)} f_s\right\rceil, \left\lceil TDOA^{max}_{(s_a,s_b)} f_s\right\rceil\right]$, $\beta \in \mathbf{R}_{\geq 0}$ are selected (see Figure 3).

The multipath signal propagation hypotheses which were found for each single sensor of a sensor pair by looking at the autocorrleation of the sensors, should also be detectable in the cross correlation function of the sensor pair. By comparing these hypotheses to the possible multipath delays found in the cross correlation function, the peak resulting from the line of sight propagation can be identified:
The vectors $M_{s_a} = (m_{a1}, m_{a2}, ..., m_{ap})^T$ and $M_{s_b} = (m_{b1}, m_{b2}, ..., m_{bq})^T$ contain all possible multipath delays from the sensors s_a and s_b calculated from their autocorrelation functions as described above. The vector for all possible multipath hypotheses for the sensor pair (s_a, s_b) is then given by

$$\begin{aligned} M_{(s_a,s_b)} &= (m_{a1}, m_{a2}, ..., m_{ap}, -m_{b1}, -m_{b2}, ..., -m_{bq})^T \\ &= (m_1, m_2, ..., m_p, m_{p+1}, m_{p+2}, ..., m_{p+q})^T. \end{aligned} \tag{9}$$

The vector $C_{(s_a,s_b)} = (c_1, c_2, ..., c_r)^T$ includes all multipath delays that were detected in the cross correlation function



(b)

Fig. 5. Error histogram (a) with and (b) without multipath detection.

(see equation 8) of the sensor pair (s_a, s_b).

We now determine the line of sight TDOA from these vectors by calculating

$$\mathrm{TDOA_{los}} = \arg\min_{\mathrm{a}} \sum_{\mathrm{i=1}}^{\mathrm{r}} \sum_{\mathrm{j=1}}^{\mathrm{p+q}} (\mathrm{c_a} - \mathrm{c_i} + \mathrm{m_j})^2. \tag{10}$$

The argument a is the most probable index of the LOS peak in the cross correlation function and, using the sample rate f_s, gives the TDOA for the sensor pair (s_a, s_b).

IV. SIMULATIONS/ACCURACY ANALYSIS

The goal of our trials is to show the feasibility and the gain in localization accuracy of our approach. Two trials are performed.

The first trial consists of simulations where, according to the sensor and emitter positions, measurements are generated. To these simulated measurements, multipath signal propagation is added. We compare the error of the TDOA measurement (the difference between the calculated TDOA and the correct TDOA) when using multipath detection to the one without multipath detection. In a TDOA localization process for one measurement, we then compare the localization results without multipath detection with the ones where multipath detection is used.

For the second trial, we use real data collected by a sensor network and perform the same accuracy analysis. This shows the feasibility of the proposed method not only for simulated but also for real data.

A. Simulations

We simulate a sensor network with four stationary sensors. The sensors are positioned in the corners of a square with approximately 1 km edge length. For each simulated measurement, the emitter is positioned uniformly at random in an area of 4.3 km x 3.7 km around the sensors. The TOA t_i for each sensor node is given by $t_i = t_e + \frac{\Delta_{i,e}}{c}$. For each sensor, independent white noise is generated. To this noise a QAM-modulated (quadrature amplitude modulation) signal is added at time t_i. Random multipath delays between 10 and 500 ns and corresponding gain factors from 0,4 to 1,4 are generated. The signals, multiplied with their gain values, are now added again (see "Tapped delay line model" in [3]).
The TDOA for all sensor pairs are calculated from the cross correlation function using the methods above and then compared to the correct TDOA values, thus giving the error. To show the gain of this method, these errors are compared to the ones that are calculated without multipath signal detection (the global maximum of the cross correlation function). A series of 1000 measurements, resulting in 6000 TDOA values, is investigated.

The accuracy analysis gives the following error values. The error without multipath detection has a mean $\mu = 68.12$ ns, standard deviation $\sigma = 173.06$ ns and $\mathrm{RMSE} = 185.97$ ns. With multipath detection an improvement to $\mu = -0.38$ ns, $\sigma = 28.71$ ns and $\mathrm{RMSE} = 28.71$ ns is achieved. Figure 4 shows the cumulative distribution functions of the error with and without multipath detection. Error histograms are depicted in figure 5.

B. Field experiments

For our experiments with real data, we used a GPS synchronized sensor network. For this experiment, the sensors were deployed outdoors at the FKIE, where due to high fences and buildings, strong multipath signal propagation was observed. A vector signal generator was used as emitter to send a QPSK-modulated signal with 5 MHz bandwidth at 2005 MHz center frequency. The position of the emitter was determined with a D-GPS system. 107 measurements were recorded simultaneously at each sensor node.

For the measurements, where the correct TDOA peak is given by the global maximum of the cross correlation function, a wrong peak is never chosen by our multipath detection algorithm.

For the measurements with strong multipath signal propagation where the global maximum of the cross correlation function is caused by NLOS propagation, we compare the TDOA errors (the measured TDOA compared to the theoretical TDOA given by the sensor and emitter geometry) when using multipath detection with the ones without multipath detection. An improvement from $\mu = 72.42$ ns, $\sigma = 207.27$ ns and $\mathrm{RMSE} = 216.82$ ns (without multipath detection) to $\mu = -7.15$ ns, $\sigma = 52$ ns and $\mathrm{RMSE} = 51.7$ ns (with multipath detection) is achieved. Both errors still include GPS synchronization, positioning and other system errors. Figure 6 shows the cumulative distribution functions of the error with and without multipath detection.

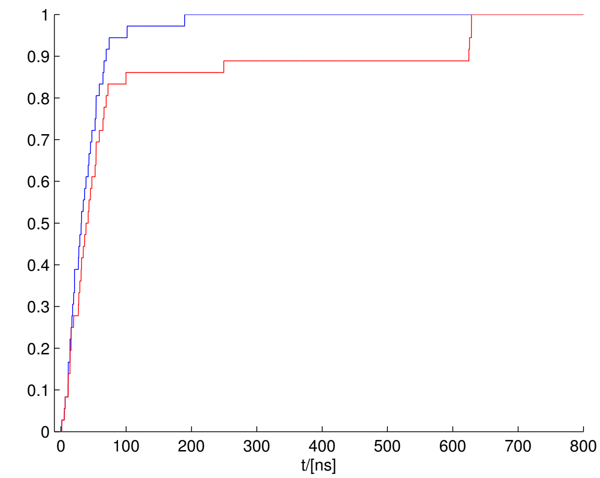


Fig. 6. Cumulative distribution function of the error with (blue) and without (red) multipath detection for real data.

Figure 7 shows the gain in localization accuracy as example for one measurement. The error in localization for this example is 7.84 m with multipath detection and 555.70 m without multipath detection.

V. Conclusion

We have proposed a method to detect the time difference of arrival of a LOS signal in environments with strong multipath propagation. Hypotheses of possible multipath delays are generated from the autocorrelation functions of a measurement for each sensor. These hypotheses are used to identify the TDOA corresponding to the LOS version of a signal in the cross correlation function of a sensor pair. The feasibility and the gain in localization accuracy are shown for simulated as well as for real data.

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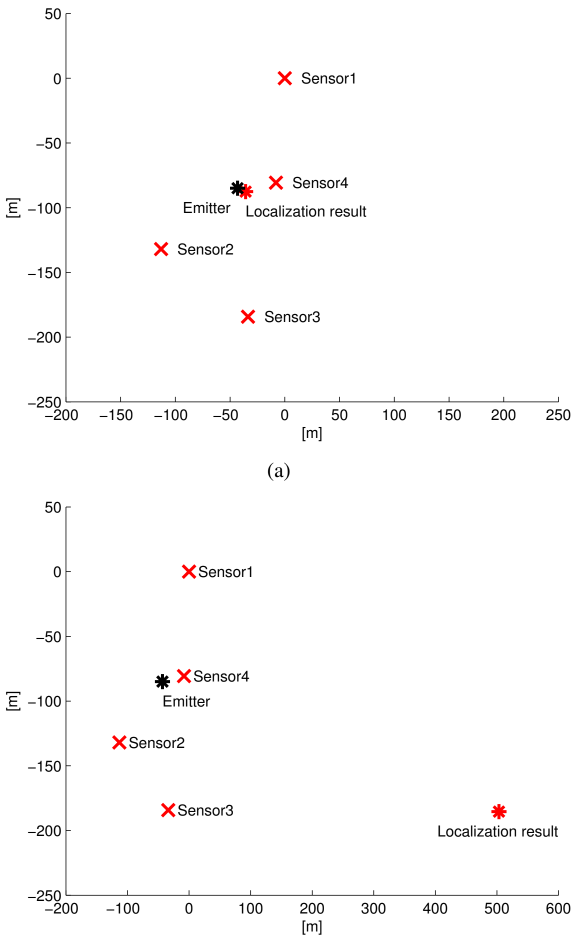

(a)

(b)

Fig. 7. Example of TDOA localization (a) with multipath detection (b) without multipath detection.

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