Indoor Localization and Communication Enhanced by Directional UWB Antennas

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***Abstract*—In this paper, we demonstrate the advantage of using directive ultra-wideband antennas for time-of-flight positioning methods. We show how the employment of a switched sector antenna system assists in multipath-resolved indoor positioning with a single anchor. The antenna system improves the joint time and angle resolution which enables resolving multipath components even in unfavorable situations to increase the robustness of positioning methods.**

I. Motivation

In indoor environments, radio signals are affected by dense multipath propagation. Accurate positioning methods are based on time-of-flight (ToF) estimation of probing signals. To estimate the ToF accurately, high bandwidths are needed to achieve high time resolution where the multipath deterioration is reduced. With ultra-wideband (UWB) signals, one can even exploit the multipath, because the line-of-sight (LOS) component and the interfering multipath components (MPC) can be resolved in time domain. This enables robust positioning using a single anchor by associating the MPCs with an environment model [1].

Path overlap is an issue that may arise for these methods in unfavorable positions. It occurs when one or more MPCs arrive shortly after each other making it impossible to resolve them in time domain. To tackle this issue, one can explore additionally the angle domain. One way to achieve this is with multiple (array) measurements from antennas distributed over a small region in the environment. The measurements can be coherently combined which improves the angular resolution and thus the positioning accuracy [2]. However, this comes at the cost of an expensive (multi-antenna) infrastructure and implementation issues with the coherent processing of the measurement signals. Alternatively, the angle domain can be explored using multiple directional antennas, each covering a subspace of the angle domain, thereby enabling indoor positioning methods based on received signal strength [3], [4].

In our approach, we stick with measurements from a single anchor position using a switchable system that employs a set of directional UWB antennas. Each antenna thus "shouts" towards one sector around it. Fig. 1 shows the used scenario with four sector antennas [5], [6]. The switching system is indicated by the beam patterns on top of the anchor position $\boldsymbol{a}$, labeled according to the cardinal directions (North, West, South, East). Measurements with this setup were performed with the shown agent at position $\boldsymbol{p}$. To estimate channel statistics, a measurement grid was used around the agent position which is also shown in Fig. 1.

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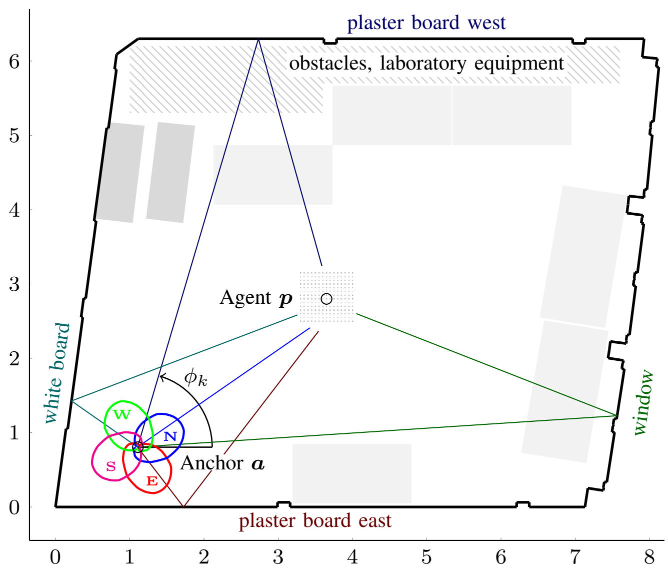


Fig. 1. Floorplan of measurement environment. Tables (light-gray) and cupboards (dark-gray) are shown, as well as patterns of the used antennas at the anchors. The axis describes the distance in meters.

In this work, we investigate the received signals for each antenna and compare them to measurements from an omni-directional antenna in terms of the capability to resolve MPCs. We will also report the positioning performance of a simple positioning algorithm using the sector antennas compared to an omni-directional antenna. The performance is represented by the cumulative distribution function of the position error.

An additional motivation for this switching system is a possible application for UWB PHY communication systems, where we expect an improvement in link quality by making use of the gained location awareness [7]. Also, an application in multi-user interference scenarios could be considered [5].

II. Signal model

The agent at position $\boldsymbol{p}$ records radio frequency measurements originating from one anchor located at position $\boldsymbol{a}$ (or vice versa). The agent is equipped with a single omni-directional antenna, while the anchor employs the described switching system with $M = 4$ antennas, referred to by $m = 1 \ldots M$. Antenna m transmits the signal $s(t)$ and the signal $r_m(t)$ is observed at the agent. Based on our previous work [1], we model this received signal as a sum of deterministic MPCs, described by amplitudes α_k and path delays τ_k, plus contributions of diffuse multipath (DM) $\nu_m(t)$, and additive, white Gaussian noise (AWGN) $w(t)$, according to

$$r_m(t) = \sum_{k=1}^{K} \alpha_k b_m(\phi_k) s(t - \tau_k) + s(t) * \nu_m(t) + w(t).$$

An addition for this work is the influence of the beampattern $b_m(\cdot)$ which affects on the one hand the amplitude of the MPCs and on the other hand the DM $\nu_m(t)$ that has been spatially filtered by the antenna. The angle ϕ_k denotes the angle-of-departure at the anchor (see Fig. 1).

The same signal model was used in [6] where we evaluated position error bounds, outlined simple positioning algorithms and investigated the resulting position likelihood and error statistics.

III. Measurement setup

The measurement setup follows the one described in [6]; a short summary follows.

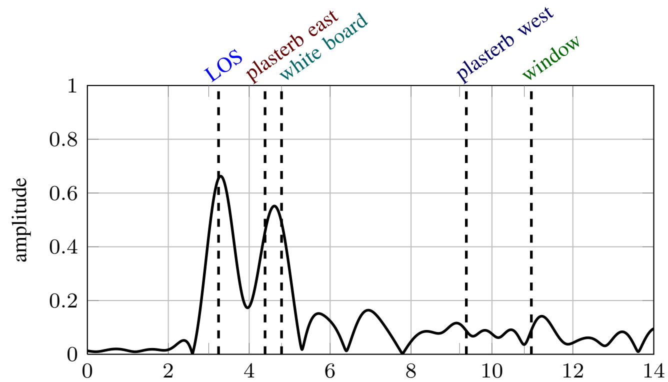
The directional antennas were mounted at the anchor position $\boldsymbol{a}$, rotated $90°$ apart such that they point in the four cardinal directions as shown on Fig. 1. Each antenna exhibits a half-power beamwidth of approximately $90°$, hence the whole azimuth plane is covered. In an additional measurement, an omni-directional antenna was used at the same anchor position. The agent employed an omni-directional antenna for all measurements. The measurements between agent and anchor were performed using an Ilmsens Correlative Channel Sounder [8]. The measured signals were convolved by a raised cosine pulse with pulse duration of $T_\mathrm{p} = 2.4\,\mathrm{ns}$ (equivalent to a bandwidth of about 500 MHz), roll-off factor of $R = 0.9$ at a carrier frequency of $f_c = 5.2\,\mathrm{GHz}$. Multiple measurements were made by moving the agent on a 15×14 grid with $5\,\mathrm{cm}$ spacing.

IV. Results

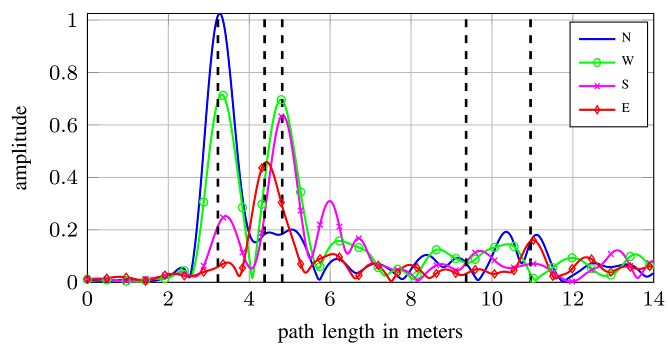
In this section, we examine the received signals for the center position of the grid, comparing the sector antennas at the anchor with an omni-directional setup. We also demonstrate the performance gain in terms of the position accuracy.

A. Capability to resolve MPCs

In Fig. 2 the amplitude as the absolute value of the received baseband-equivalent signal is shown over the path length (obtained by multiplying the delay time by the speed of light c). The amplitude is normalized to the maximum value among all the shown signals to make them comparable. The vertical dashed lines indicate the expected arrival times of the MPCs resulting from reflections on the surfaces stated at the top of the figure (compare with Fig. 1).



(a) omni-directional antenna



(b) sector antennas

Fig. 2. Received signal of agent at $\boldsymbol{p}$ transmitted from anchor at $\boldsymbol{a}$ which uses an omni-directional antenna (a) and the directional sector antennas (b). Specific MPCs are indicated by the dashed vertical lines (compare with Fig. 1).

Comparing the signals of the directional sector antennas in Fig. 2b to the signals from the omni-directional antenna in 2a, we can see that the directivity increases the strength of the MPCs that are in the respective directions of the antennas, while also decreasing the DM between the MPC peaks. Moreover, a large benefit can be seen when examining the *plaster board east* and *white board* MPCs. These MPCs arrive very close after each other which results in path overlap that causes a single peak between the MPC positions as shown in Fig. 2a. In Fig. 2b we can see that the directive antennas can clearly resolve this issue, where the *West* and *South* antennas can focus on the *white board* MPC and the *East* antenna can focus on the *plaster board east* MPC.

B. Positioning accuracy

As a closure, we present one result based on [6] where we evaluated the position accuracy using the switching system compared to an omni-directional antenna. An approximate maximum likelihood algorithm was used to estimate agent position $\hat{\boldsymbol{p}}$ for each grid point (see Fig. 1) based on the measurements described above. The resulting cumulative distribution function of the position error is shown in Fig. 3.

It can be seen that an accuracy gain is achieved, where 90% of the estimations using the sector antennas exhibit an error of only $25\,\mathrm{cm}$, whereas the omni-directional antenna

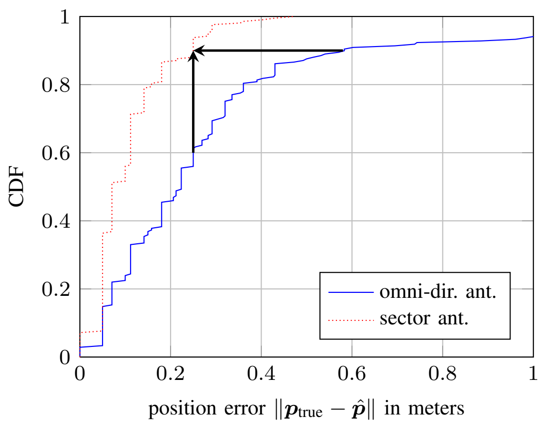


Fig. 3. Cumulative distribution function (CDF) of the position error using an approximate maximum likelihood algorithm as described in [6].

measurements result in an error of 60 cm (c.f. the horizontal arrow in Fig. 3). Moreover, a robustness gain is observable when we examine how many of the measurements can reach a low error of 25 cm (55% with the omni-directional antenna, against 90% with the sector antennas, c.f. the vertical arrow in Fig. 3). Lastly, the highest error occurring with the switching system is around 40 cm, while with the omni-directional antenna there are points where the error is above one meter (about 5% of the points).

V. Conclusions

In this paper, we investigated the application of multiple directive UWB sector antennas for ToF positioning. We showed that the switched antenna system can significantly enhance a single-anchor-based multipath-resolved indoor positioning system. The combined time and angle resolution makes MPCs resolvable even in unfavorable positions and thus increases the robustness and / or reduces the required bandwidth. These capabilities enable practical implementations with commercially available devices such as the DW1000 transceiver front-end. In the future, we will investigate the application of the antenna system for UWB communications.

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