High-accuracy Positioning for Indoor Applications: RFID, UWB, 5G, and beyond

(Invited Paper)

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***Abstract*—Highly accurate and reliable indoor positioning—at accuracy levels in the 10 cm range—will enable a large a number of innovative location-based applications because such accuracy levels essentially allow for a useful real-time interaction of humans and cyber-physical systems. Activity recognition, navigation at "shelf" level, geofencing, process monitoring and process control are among the envisioned services that will yield numerous applications in various domains. This paper reviews the difficulties faced by indoor positioning systems, motivating the requirement for a large signal bandwidth and how a lack of bandwidth can be compensated by multi-antenna systems. The potential capabilities of upcoming generations of wireless systems will increasingly make high-accuracy positioning available in near future.**

I. Introduction

Robust and accurate indoor positioning is a key enabler for a wealth of future location-based services, ranging from supply-chain management and manufacturing to health-care and entertainment.

For example in healthcare, application examples include behavioral monitoring to assess the physical and mental health of individuals, emergency (fall) detection to alert caretakers or emergency services, real-time assistance to provide context awareness to medication management systems (to remind—for instance—to take medications before/during/after meals) or as an orthotic and rehabilitation tool for individuals suffering from cognitive decline, geofencing for people with dementia, and even as a navigation aid for visually impaired (see [1], [2] and the references therein).

In manufacturing and logistics, real-time positioning can be used to monitor the flow of items and hence the progress of processes. It can also be used to control processes in real time, for example the parametrization of tools has been envisioned, and hence to improve the efficiency and detect anomalies. Therefore, position information is a vital component of so-called smart factories [3]–[5]. However, sufficient *reliability* of the positioning service is required for that purpose.

In a smart sales-floor, products and user devices can be localized to realize a recommender systems similar as in an internet store [6], [7]. In this scenario, the customer may be navigated to the desired items, matching accessories or alternative choices can be recommended, a real-time inventory function can be realized that ensures the shop owner always knows what items are still on stock, and last-but-not-least, theft control can be realized. To implement these functions, it will be of key importance to recognize interactions between customers and (identified) tracked objects, which is the challenge to be addressed in this scenario.

These are a few specific examples that require cm or dm-level accuracies to yield robust activity recognition. Such a performance level cannot be achieved with current mass-market technologies. E.g. current RFID systems are already used for some of these applications, however with shortcomings concerning read range, false detections/missed detection due to multipath, and only imprecise positioning. Another difficulty is the heterogeneity of the scenarios and application environments. Therefore, as of today, the technologies for indoor localization have not converged towards a unique winning approach.

Radiopositioning is—in principle—a very promising sensing method, because radio transceivers can be integrated in existing devices like smartphones and built at small form factors with low power consumption. Among the competing modalities [8]–[14], video cameras and microphones [15]–[17], for example, suffer from occlusions and a lack of acceptance because of privacy concerns. For radio systems, on the other hand, the influence of the dense multipath radio channel in indoor environments still makes accurate and robust positioning a challenging task.

This paper first reviews the importance of a large signal bandwidth for accurate indoor positioning. We discuss the role of multi-antenna system configurations which can partly compensate for a lack of bandwidth. The diversity gains leveraged in MIMO (multiple-input multiple-output) radars [18], [19] can also be exploited in dense multipath channels, as faced in indoor environments, in order to obtain accurate positioning of RFID transponders [20].

Ultra-wideband (UWB) signals yield excellent accuracy, since they allow for a separation of the multipath components (MPCs) [21]–[24]. Hence, on the one hand, the direct signal path can be isolated from interfering MPCs; on the other hand, position-related information becomes accessible as well in later-arriving MPCs and turned into an advantage, as discussed in the second part of this paper. We will argue that with the advent of mm-wave communications in the 60 GHz band [25]–[27], a UWB localization system could operate synergetically with an existing communication system, e.g. using the IEEE

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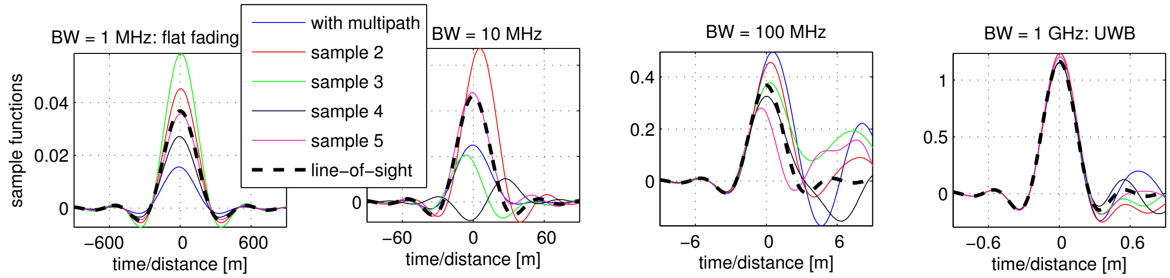


Fig. 1. Sample functions illustrating the ranging problem under DM over a wide range of BWs (neglecting AWGN).

802.11ad standard [28]. Beamforming technologies proposed for these systems [25] perfectly complement the needs of the localization system and vice versa: also the beamforming algorithms will benefit from the location information and from environmental radio maps, i.e. spatial characterizations of the propagation channel that can be estimated and tracked in realtime. Location awareness is created, which is expected to play an important role in future communication systems [29].

We finally speculate about the application of a UWB cognitive radar for the accurate, robust, and efficient positioning of RFID tags in challenging indoor environments.

II. Ranging and Positioning in Dense Multipath

This section illustrates the influence of the signal bandwidth on the potential ranging accuracy and shows that multi-antenna configurations can compensate for a lack of bandwidth.

Fig. 1 illustrates the effects of dense multipath [30]. The channel is modeled as a hybrid deterministic-stochastic channel model (GSCM) with the line of sight (LOS) component as deterministic component and all other components as dense or diffuse multipath (DM). This DM interferes with the LOS component and leads to multipath effects such as amplitude fading and pulse distortion. For the UWB case, the DM is well-separated from the LOS thus neither amplitude fading nor pulse distortion impair the received signal. Here, very accurate ranging can easily be achieved, also due to the short temporal extent of the UWB pulse. In the narrowband case the complete DM interferes with the LOS component and only amplitude fading occurs. The lack of distortion is beneficial but the "length" of the pulse of > 100 m nevertheless makes this configuration useless for indoor positioning. In-between these cases both amplitude fading and pulse distortion deteriorate the received signal.

A. Ranging Error Analysis and Diversity Gain

In [31] we developed the Crámer Rao lower bound (CRLB) for the ranging and positioning problem for a channel with a LOS component impaired by DM. The ranging error bound (REB, CRLB for the ranging problem) is depicted in Fig. 2 and compared to the standard deviation (STDV) of the estimation error for two estimators.

A naïve matched filter (MF, marked by circles) estimator, convolving the received signal with the transmitted pulse and searching for its maximum, deviates from the REB at about

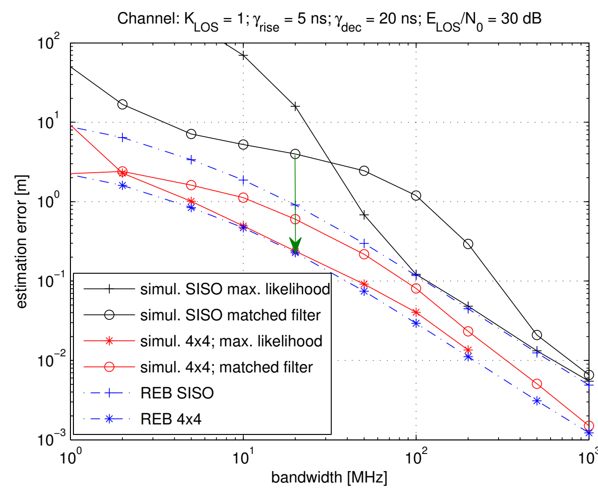


Fig. 2. Ranging Error Bound and range estimation standard deviations of different estimators. Channel Parameters: $K_{\mathrm{LOS}} = 0\,\mathrm{dB}$, $\tau_{\mathrm{rms}} = 17.5\,\mathrm{ns}$

500 MHz due to a positive bias and estimation outliers induced by the DM. Proper consideration of the DM by whitening the received signal prior to the estimation of the ToA is highly beneficial. This maximum likelihood (ML, marked by '+') estimator deviates at about 100 MHz from the REB.

At even lower bandwidth, the ML estimator fails and the MF estimator becomes more robust. This can be explained by the impact of the DM on the ranging solution: If the so-called signal to interference plus noise ratio (SINR) [31] drops below a certain threshold, the ML estimator cannot detect the LOS component in the resulting noise floor after whitening. (The SINR denotes the ratio of the useful LOS signal to the DM interfering with it.) For narrowband signals, the complete DM process interferes with the LOS pulse and the MF estimator can make use of the DM in the sense that it exploits the power in the DM process in addition to the power in the LOS component. Thus only fading and AWGN impair the ranging accuracy as long as the instantaneous signal-to-noise-ratio (SNR) is high enough. However, as can be seen in Fig. 2, the accuracy for small bandwidth is at a poor level. The results suggest a potential ranging STDV in the order of 15 cm at 100 MHz, in a single- input single-output (SISO) configuration.

By introducing multiple antennas at the transmitter and receiver sides, a multiple-input multiple-output (MIMO) system can be realized, which exploits diversity in a non-coherent

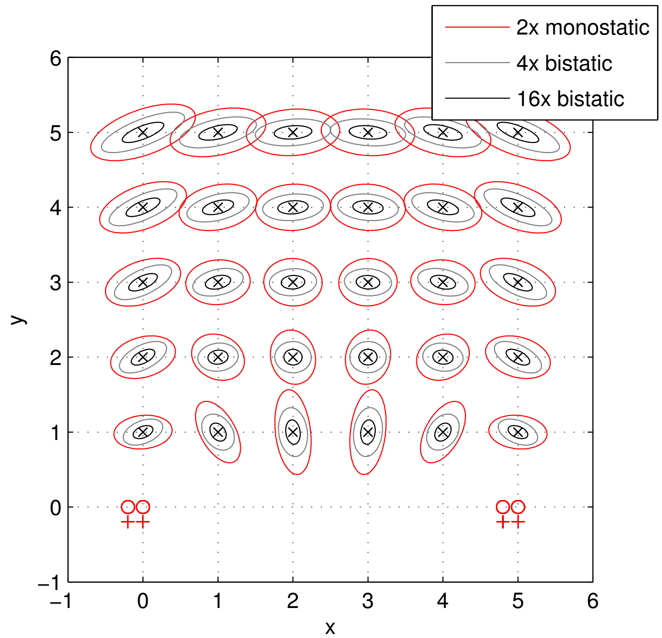


Fig. 3. Position error bound (2-fold STDV ellipses) and MIMO gain on a backscatter channel with a bandwidth of 50 MHz. The different antenna configurations are discussed in the text. Channel Parameters: $K_{\mathrm{LOS}} = 0\,\mathrm{dB}$, $\tau_{\mathrm{rms}} = 17.5\,\mathrm{ns}$

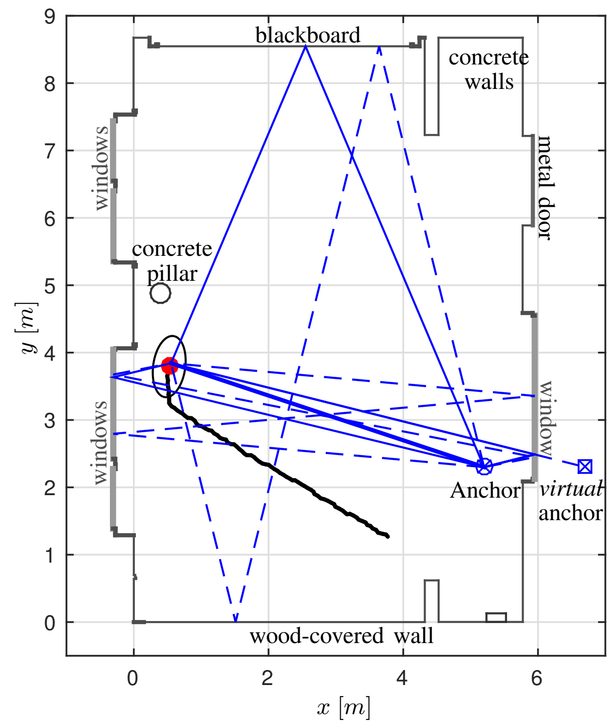


Fig. 4. Illustration of the MINT concept using a single anchor. Position-related information provided by the LOS component (bold line) as well as by numerous MPCs that can be associated to the geometry.

fashion [31]. Such a MIMO system shows two gains depicted in Fig. 2. The first gain is an accuracy improvement seen by comparing the REB for the SISO and the 4x4-MIMO system. This improvement is inversely proportional to the square root of the number of measurements, leading to a factor of $\frac{1}{4}$ for the 4x4-MIMO system. The second gain is a detection improvement of the LOS component which is coupled with the SINR. This gain makes the estimation more robust to outliers and thus the REB is achieved at lower bandwidths (for a more detailed discussion and a comparison with measured data see [32]). With the 4x4-MIMO system and the ML estimator, a potential ranging STDV in the order of 25 cm can be achieved at 20 MHz in comparison to an STDV of 4 m in case of the SISO configuration (MF) (see the green arrow).

B. MIMO Gain for RFID Positioning in Dense Multipath

In an RFID system, accurate range measurements can be conducted by superimposing wideband or ultra-wideband signals with the regular (e.g. UHF) interrogation signals. In [33] it was suggested to use a direct-sequence spread spectrum signal for this purpose with a bandwidth of approximately 50 MHz, while [34], [35] employ UWB signals. The probing signal undergoes a backscatter radio channel, which—for the analysis of the positioning performance—can be modeled as the convolution of uplink and downlink channels [20], [36]. Two cases have to be distinguished: If a single antenna is used for the TX and RX, the up and downlink channels are fully correlated, while a configuration with separated TX and RX antennas may see uncorrelated channels. In the latter case, the diffuse multipath has only half the power density from the former [36] with a beneficial effect to the ranging [20]. Introducing multiple TX and RX antennas at the readers, MIMO gains can be exploited in a similar fashion as in a MIMO radar [18], [19].

Fig. 3 illustrates the potential performance gain for a time-of-flight-based positioning system employing a bandwidth of 50 MHz with channel parameters as in Fig. 2. The performance is indicated in terms of the position error bound, which is derived from the ranging error bound of Fig. 2 [20]. The three ellipses—from largest to smallest—correspond to antenna configurations with a single TX/RX-antenna per reader (acquiring two "monostatic" range measurements over "fully correlated" up/downlink channels), a pair of separated TX and RX antennas per reader (acquiring four bistatic measurements over uncorrelated channels), and two pairs of separated TX and RX antennas per reader (yielding 16 bistatic measurements over uncorrelated channels). The performance improvement is by a factor of approx. $\sqrt{8}$ in STDV, reaching a level of 15 cm in the best case.

estimator

III. Multipath-assisted Indoor Navigation and Tracking (MINT)

At ultra-wide signal bandwidths, it becomes possible to resolve individual multipath components (MPCs), including specular reflections that can be modeled deterministically. These MPCs provide additional *position-related information*,

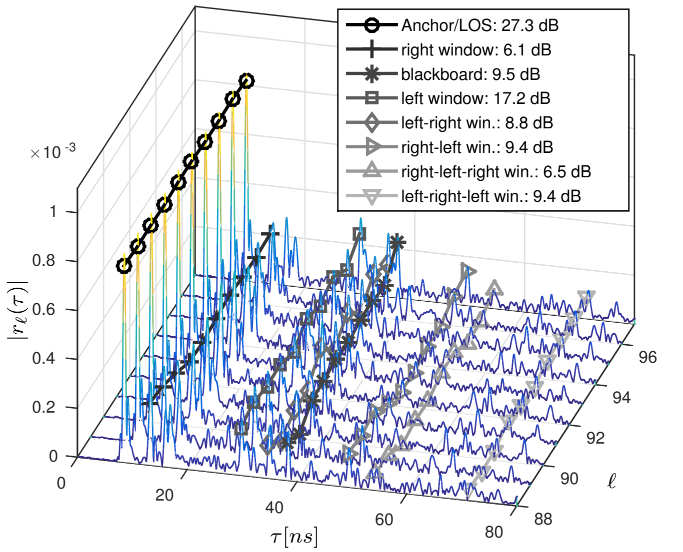


Fig. 5. Impulse response analysis with estimated SINRs of the respective MPCs, BW 2 GHz, $f_c = 7$ GHz.

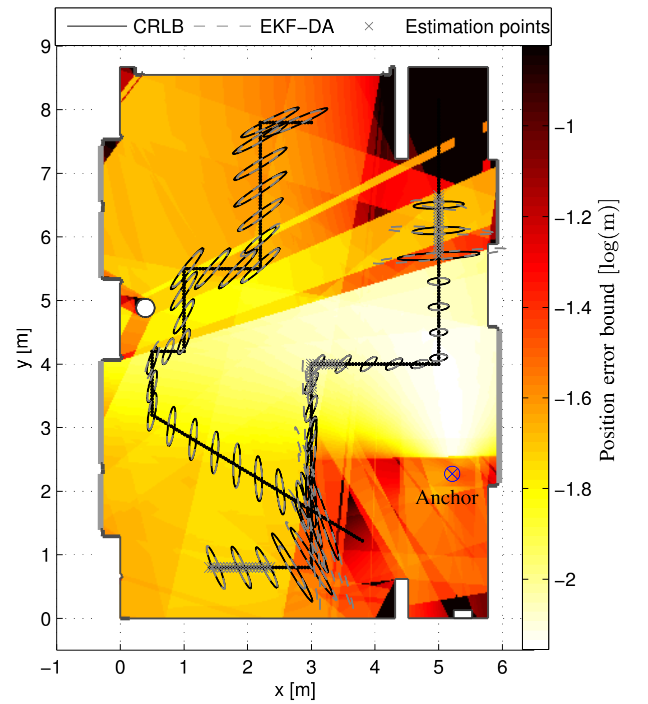


Fig. 6. Position error bound (PEB) and tracking results for bandwidth of 2 GHz, and a single fixed anchor. The PEB has been computed from estimated SINRs; gray crosses are 60 positions used for this SINR estimation [38]. Solid and dashed ellipses denote the standard deviation ellipses corresponding to the CRLB and to the error covariance matrices of an extended Kalman tracking filter, respectively, at several points along two trajectories. These ellipses are enlarged by a factor of 20 for better visibility. (c.f. [2])

i.e. they can be *exploited* to enhance the performance of a positioning system. This is viable for indoor localization systems, for which a reduction of the required infrastructure is of key importance while keeping the required level of accuracy and robustness. With properly designed algorithms, even *single-anchor configurations* (within each room) are feasible. To realize this *multipath-assisted* indoor navigation and tracking (MINT) system, algorithms are needed which actively take environmental propagation information into account. This section discusses such algorithms and their performance.

A. Single-Antenna Terminals

Using an a-priori known floor plan, the arrival times of specular deterministic MPCs can be modeled by *virtual anchors* (VAs), which are mirror images of the positions of the physical anchors at known positions [37]–[41] (Fig. 4). DM comprises all other—not geometrically modeled—propagation effects included in the signals.

Fig. 4 illustrates the concept of MINT in a representative environment. The estimated MPC delays are associated to the expected delays according to the VA model (blue rays in Fig. 4) such that they can be used for positioning. To properly weigh the position-related information of each range measurement [38], their SINR values are determined, which now define the power ratios between the useful deterministic MPCs and the DM *interference* plus noise at the corresponding delays. The SINRs are related to the range uncertainties of the MPCs that are associated with VAs [42], [43]. An online estimation of these range uncertainties also allows for an efficient selection of the VAs that provide reliable position-related information. This is shown in [40], in which a simultaneous localization and mapping (SLAM) approach is presented for MINT that omits the requirement of an a-priori known floor plan and infers the range uncertainties during the tracking.

Fig. 5 shows UWB signals (with 2 GHz bandwidth) that were measured in the scenario illustrated in Fig. 4. The delay and amplitude tracks for several associated MPCs are shown. From these, the corresponding SINRs have been estimated and indicated in the legend. At such a large bandwidth, the LOS component is almost entirely separated from later-arriving MPCs and DM, which results in a high SINR value and hence in a large amount of position-related information. Some later-arriving MPCs also have high SINR values and are thus useful for positioning.

An example how the SINR values (respectively the corresponding range standard deviations) can be translated via the geometry to a lower bound on the position estimation error is illustrated in Fig. 6 [2], [43]. It can be seen that an error below 10 cm is achievable over almost the whole scenario with only a single anchor. Also, the influence of the expected visibility regions of important reflectors is observable. The performance of an implementation of the MINT concept using an EKF with data association (DA) is depicted by showing the estimated position with uncertainty ellipses (gray) and the corresponding CRLB ellipses (black). Both agree well, indicating the correct weighting of the MPCs and confirming the usefulness of the environmental model given by the SINRs.

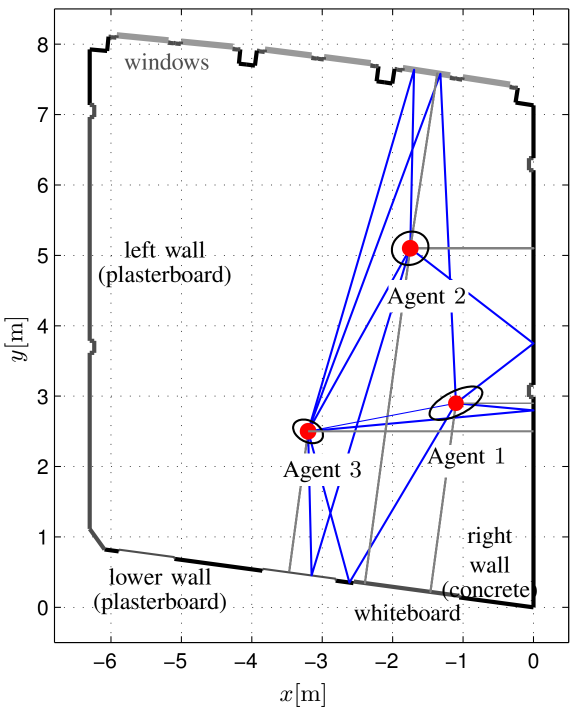


Fig. 7. Cooperative setup of three agents. The agents perform non-cooperative (grey) and cooperative (blue) measurements and utilize the multipath propagation for localization without the need of an anchor node.

B. Cooperative MINT

The previous section presented indoor navigation and tracking with reduced infrastructure. The agents localize themselves utilizing the multipath propagation between an agent and anchors. A promising way to further decrease the dependence on infrastructure is cooperation of the agents [44], [45]. The agents share the belief about their position with their neighbors and also perform cooperative measurements. This scenario is shown in Figure 7. The mobiles use *monostatic* measurements (gray) for non-cooperative self-localization by emitting a pulse and receiving the corresponding reflections. The *bistatic* (cooperative) measurements (blue) are performed between neighboring mobiles. The agents use these measurements for accurate and robust tracking without the need for anchor nodes.

C. 5G Systems – mm-Waves and Beamforming

Fig. 8 shows the likelihood function for the multipath-assisted positioning problem as a function of position [39], evaluated over a floor plan [2]. In this scenario mm-wave signals are used at a carrier frequency of 60 GHz, again with a bandwidth of 2 GHz, reflecting the proposed frequency range for 5G systems [28]. It compares (a) LOS and (b) obstructed LOS (OLOS) conditions with (c) OLOS with the use of beamforming. The bold black lines indicate the directions to the anchor, thin black lines the directions to first-order VAs, and black dashed lines the directions to second-order VAs. The black diamonds mark the estimated positions of the agent. Using a maximum likelihood positioning algorithm as in [39], an error in the centimeter level is achieved (2 cm for the LOS and 3 cm for the OLOS situations).

The potential use of beamforming shows a different great advantage: the multimodality of the likelihood function is reduced, which reduces the risk of converging to a wrong local maximum. Large modes at locations farther away from the true agent position are suppressed due to the angular resolution of the array antenna. Note, however, that MPC *delays* are still responsible for providing a high accuracy in a direction orthogonal to the LOS path. Without the processing of multipath, we would see a smooth maximum (along the circle) instead of a sharp peak. The likelihood function in Fig. 8c has been computed by using a phased-array beamformer for each exploited MPC. This is achieved by coherently adding the signals at the agent-side array positions, taking into account the relative phase shifts that correspond to the known arrival angles of the MPCs. The figure exemplary shows that such a processing, envisioned for 5G mm-wave communication systems, can greatly improve the robustness of the localization, since many local maxima can be ruled out.

IV. Cognitive Positioning of RFID Transponders

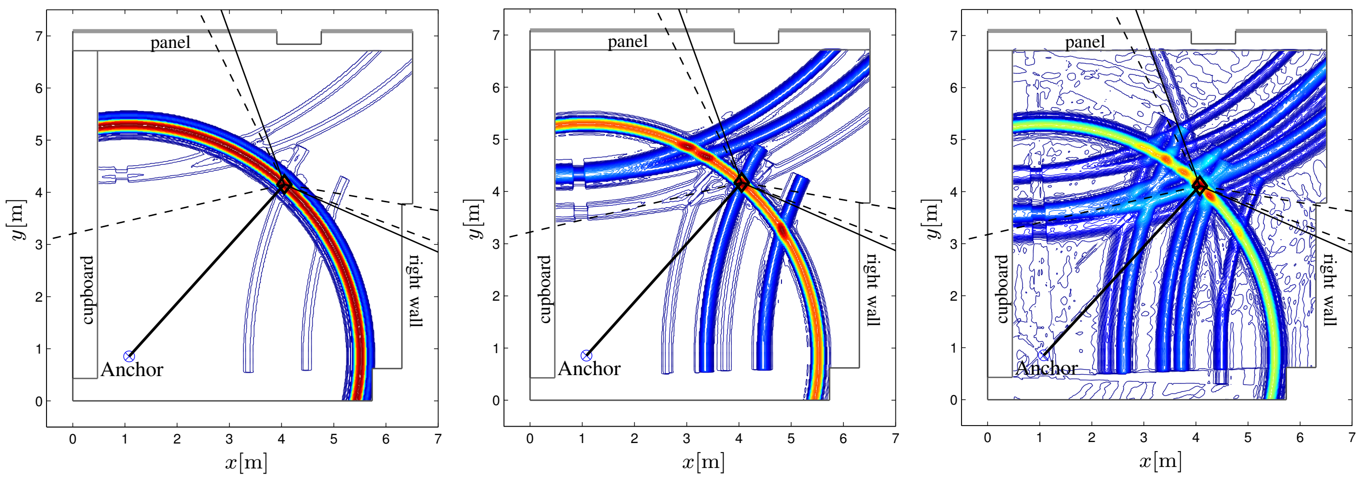
Given these multiple benefits, it is fair to anticipate that multipath can also be useful for the accurate positioning of RFID transponders. The use of UWB signals is a prerequisite for this, which was proposed e.g. in [34], [35].

An intriguing approach towards this goal is the application of a cognitive radar [46]–[48]. The RFID tags namely provide a spatial sampling of the radio channel properties (at the tag positions) which yields a map of the radio environment that can be utilized for robust positioning and efficient resource allocation—key properties of a cognitive radar. Visualize an application that aims at locating the merchandise in a fashion shop: Thousands of spatial samples may be collected throughout the shop floor, yielding a detailed picture of the propagation conditions. In [48] we propose to use time-reversal processing based on a known model of the deterministic MPCs to focus the transmitted UWB signals at the position of the RFID transponders. This strategy has been shown to improve the robustness in case of obstructed LOS paths. A cognitive positioning system was recently described in [49].

V. Conclusions and Outlook

This paper envisions accurate and robust indoor localization as a key enabler of future location-based services. Real-time interaction between users, objects, and cyber-physical systems, including the need for accurate recognition of activities and identification of objects, is the key feature such applications demand for.

The paper reviews the need for a large signal bandwidth to achieve cm-level positioning in presence of dense multipath as faced in indoor environments. Multi-antenna configurations can significantly relax the need for high bandwidth since



(a) $\log(p(\mathbf{r}|\boldsymbol{\psi}))$ LOS (b) $\log(p(\mathbf{r}|\boldsymbol{\psi}))$ OLOS (c) $\log(p(\mathbf{r}|\boldsymbol{\psi}))$ OLOS, beamforming

Fig. 8. Likelihood function over the floor plan for (a) LOS, (b) OLOS situation, and (c) OLOS situation with phased-array beamforming. The position error of the MLE is 2 cm and 3 cm for LOS and OLOS situations, respectively. Bold black lines show the directions to the anchors, thin black line the directions to first-order VAs, and black dashed lines the directions to second-order VAs. The black diamonds mark the estimated positions of the agent. (c.f. [2])

diversity gain can be exploited. Furthermore at ultra-wide bandwidth, individual multipath components can be resolved and used as an additional source of position information. The resulting "multipath-assisted" positioning system yields higher robustness and higher accuracy at a relaxed need for infrastructure (in form of anchor nodes).

Future 5G mm-wave communication systems could be an ideal platform for achieving high-accuracy indoor localization with this concept. In addition to a large signal bandwidth, beamforming capabilities are expected, which make the localization and tracking more robust and efficient. It becomes feasible to obtain accurate and robust indoor localization with only a single anchor node in a room.

The positioning of RFID tags in dense multipath channels could become the (missing) "killer" application for a cognitive radar. A large number of RFID tags potentially yields an accurate radio map of an environment that can be levaraged by the cognitive radar for higher robustness and efficiency.

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