Self-Positioning and mapping of rectangular rooms with sectorized narrowband antennas

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Abstract: **A system for simultaneous 2D estimation of rectangular room and transceiver localization is proposed. The system is based on two radio transceivers, both capable of full duplex operations (simultaneous transmission and reception). This property enables measurements of channel impulse response (CIR) at the same place the signal is transmitted (generated), commonly known as self-to-self CIR. Another novelty of the proposed system is the spatial CIR discrimination that is possible with the receiver antenna design which consists of eight sectorized antennas with 45° aperture in the horizontal plane and total coverage equal to the isotropic one.**

The dimensions of a rectangular room are reconstructed directly from spatial radio impulse responses by extracting the information regarding round trip time (RTT). Using radar approach estimation of walls and corners positions is derived. Tests using measured data were performed, and the simulation results confirm the feasibility of the approach.

1. INTRODUCTION

In this paper, we propose a novel system, which addresses positioning and mapping problems of rectangular rooms utilizing inferred context information from measurements of wireless communication properties. The idea of simultaneously obtaining location and environment map has received considerable attention in robotics in the last 30 years inside Simultaneous Localization and Mapping (SLAM) problem. It was originally developed by Hugh Durrant-Whyte and John J. Leonard [1] based on earlier work by Smith et al. [2]. The procedure consists of collecting the measurements and incremental building of the map, within an unknown environment without any a priori knowledge. Since it is more a concept type than a specific algorithm, different SLAM techniques have been used and proposed in the literature. Their extensive overview can be found in [3, 4]. We believe that these techniques from robotics can be extended to the context of wireless anchor-less positioning where anchor-less refers to the ability of the devices to infer their own coordinates, in a local relative system, without any fixed reference node, base station or access point.

Several studies reported in the recent literature attempted to address SLAM problem with radio signals based on Impulse Radio Ultra-Wide-Band (UWB) techniques [5-9] or a bat-type UWB radar approach [10]. Other contributions requiring a highly specific hardware configuration have also been proposed, for example central transmitter with receiver antennas array [11] or monostatic CIR measurements (i.e. self-to-self channel sounding) [12]. Most of the approaches rely on the geometrical interpretation of the arrival times of the resolved echoes. These echoes are assumed to result from simple electromagnetic interactions (e.g. simple-bounce reflections on the walls), enabling a unique correspondence between the pattern of path arrivals and nodes positions. Simple relationships are invoked to link elements of geometry (including relative nodes locations) with the observed multipath inter-delays and to deliver a four-wall map of the room. Regardless of approaches differences, bottom line is that all of them require large bandwidths and as such introduce significant hardware restrictions.

Contrary to UWB methods, we propose to shift hardware constraints from bandwidth to the design of the receiver antennas. This is achieved by limiting the system to narrow-band (NB) signals (100MHz) and introducing eight sectorized antennas with 45° horizontal aperture. By using self-localization, the signal emitted at omnidirectional is received at eight sectorized antennas. The presence of walls and corners is evaluated using RTT measurements. Some preliminary results of this approach are published in [13], focused on determining all three dimensions of an unknown rectangular room. In this contribution 2D mapping algorithm is improved by detecting the position of transceivers close to corners and by carrying out self-localization on two cooperating transceivers. This is seen as simplification of SLAM problem where transceiver is a part of an “intelligent” mobile robot platform that is updating its positions and the room map based on the observations obtained at consecutive locations. Here, the number of consecutive locations is limited to two. The performance of the approach is evaluated under realistic synthetic test environment based on NB ray tracing simulations.

2. DESCRIPTION OF THE ENVIRONMENT

Synthetic test environment of ICT-WHERE2 project [14] is based on measurements collected during the ICT-WHERE1 [15] which are complemented by detailed 3D description of the site geometry and deterministic ray-tracing simulations of CIR calculated for three different bandwidths (UWB, Wide Band (WB) and NB). It represents a typical indoor office environment, as specified in section 6.1.5 in deliverable D1.1b. [16]. The size of the simulated environment is approximately 30x12m. Transmitters (Tx) and receivers (Rx) heights are set to 1.5m. Rx positions are defined in a grid of approximately 1mx1m density, as shown in Figure 1, with a total of 363 positions. Tx positions are located on the same grid but their number is reduced to 51 to ease the computational load. Tx antenna is always isotropic while CIRs where calculated for two types of Rx antennas: isotropic and eight sectorized 45° horizontal aperture antennas.

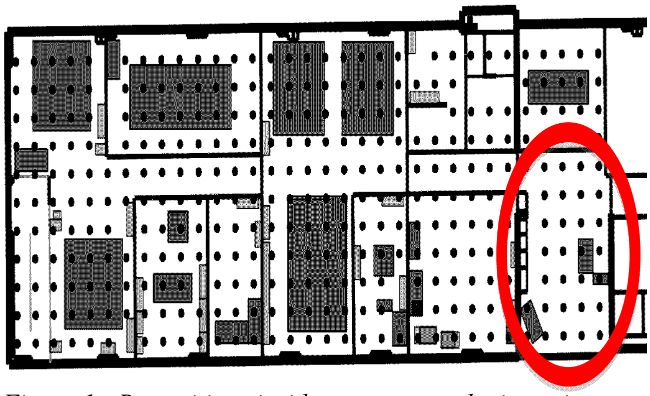

Figure 1 - Rx positions inside common synthetic environment

In this paper synthetic narrow-band environment obtained by SIGINT 3DTruEM software was used [17]. The software is calibrated at 3.5GHz central frequency and 100MHz bandwidth using real measurements data. Unlimited number of refractions and up to one diffraction were taken into account. The emitting power of transmitter was set to $10dB_m$, while the receiver sensitivity was set to -110dB, as defined in [18].

3. ALGORITHM IMPLEMENTATION

The algorithm is developed to solve self-localization problem of two cooperating nodes located inside unknown rectangular room. As a result of localization the distances of the nodes with respect to room walls are provided allowing the construction of room 2D map. Transceivers support full duplex self-to-self CIR, meaning they are able to transmit and receive simultaneously. Signal is emitted by omnidirectional antenna while reception is available with eight sectorized antennas. The mutual distance and orientation of the nodes is assumed to be known. This is an initial assumption in order to obtain the performance bounds of the algorithm.

When representing rectangular room with geometrical model, walls are seen as reflecting lines in a two-dimensional space, while corners are characterized by double reflections from two orthogonal walls. The influence of initial antenna orientation inside an unknown environment should still be investigated, but if found critical the possible solution could be to replace Rx sectorized antennas with 2D array of eight isotropic antennas. As a result, beam-forming could be used for detecting antenna sections perpendicular to the walls (minimum RTT measurements). Hence, the orientation of the transceivers is predefined with four sectors of Rx antenna orthogonal to the walls. This means that their TOA calculations correspond to typical radar reading where half of self-to-self TOA calculation matches the distance of the transceiver to the wall orthogonal to that section.

Sectors of Rx antennas that are pointing to the corners may receive double reflection signals. Therefore, their reading of distance should be systematically corrected as explained in [13]. The correction parameter is labeled C_p and is set empirically to values between 0.75 and 1 depending on the calculated distance from the wall:

$$C_p = \begin{cases} 0.75 + \dfrac{d}{30}, d \le 7.5m \\ 1 \quad , \quad d > 7.5m \end{cases} \tag{1}$$

where d is distance obtained from the RTT as:

$$d = \frac{RTT \cdot c}{2} \tag{2}$$

with c being the speed of light. The relation in (1) is obtained by fitting the corner distance estimation to true corner distance of 35 Tx positions located in 8 rectangular rooms of the synthetic environment.

Each of the received reflections is actually sum of different reflection signals due to indoor multipath propagation. Because of the the receiver time resolution, multiple delayed signal versions cannot be discriminated and they are modeled with a single path (single reflection). This simplification impacts RTT approximation, but its impact is limited through the diversity, that is, introduction of second transceiver that also performs the room dimensions estimations. The RTT is defined here as the time required for the strongest peak to reach the transceiver. Usually this is also the first peak inside CIR but, since the room is not empty, the first peak is not selected, as its reflection source might be the furniture and not the wall. Since the bandwidth is limited to 100MHz the precision of CIR's time scale is 10ns, which corresponds to resolution of 1.5m.

The test room (marked with ellipse in Figure 1) is a reception hall with three doors (upper left corner, upper right corner and middle of the bottom wall). Its furniture is composed of metallic bookcase (on the left wall) and two wooden tables. The room is not perfectly rectangular with approximate size of 5.1mx7.3m and 2.4m height. The algorithm is applied to two transceivers, one located in the upper left corner and other close to room center.

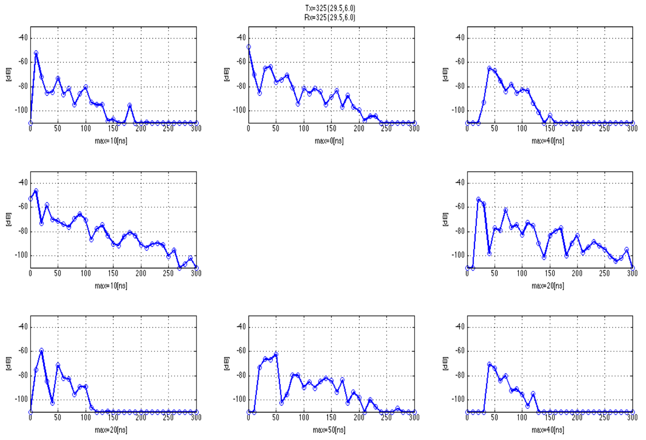

Figure 2 - self-to-self CIRs of transceiver at upper position

Eight CIRs data, obtained at transceiver located close to upper left corner are seen in Figure 2. Each CIR corresponds to one Rx sector antenna, which is pointing in the direction of the position of sub-image. In other words, the first line of 3 images would correspond to upper left corner, upper wall and upper right corner CIRs.

When determining the wall position we part from three observations for each wall obtained at both transceivers (one direct radar reading and two corner estimations). This produces six RTT calculations per wall. However, since the precision of RTT readings is directly dependent on bandwidth this must be taken into account:

$$d = \left\langle \frac{c}{2}RTT,\quad \frac{c}{2}\left(RTT + \frac{1}{BW}\right) \right\rangle \qquad (3)$$

where BW is signal bandwidth. In other words if RTT of the orthogonal section, obtained with 100MHz bandwidth, is 20ns, we cannot claim that the wall is exactly at 3m distance, but we could presume it is positioned between 3m and 4.5m from the transceiver. Eventually this statement constructs two distance values for each RTT observation. By incorporating this strategy, the overall number of wall observations is increased to twelve. Four correspond to radar readings:

$$\begin{aligned} d_{1..2} &= \frac{c}{2}RTT_j^o \\ d_{3..4} &= \frac{c}{2}\left(RTT_j^o + \frac{1}{BW}\right) \end{aligned} \qquad (4)$$

where superscript o stands for orthogonal section, and subscript j=1..2 correspond to transceivers count.

In case of corner calculations, if we initially assume that the antenna pointing to the corner is actually pointing at 45° angle with respect to two perpendicular walls, a simple trigonometric calculation produces the wall distance by multiplying corner reading by scaling factor $\sqrt{2}/2$ (corresponds to *cos(45°)* or *sin(45°)*). Afterwards, the obtained RTT distance is modified by coefficient C_p before producing the wall observations:

$$\begin{aligned} d_{5..8} &= \frac{c}{2}RTT_j^{c_i}\frac{\sqrt{2}}{2}C_p(d) \\ d_{9..12} &= \frac{c}{2}\left(RTT_j^{c_i}C_p(d) + \frac{1}{BW}\right)\frac{\sqrt{2}}{2} \end{aligned} \qquad (5)$$

with superscript c_i ,i=1..2, corresponding to two corner sections of each of the j=1..2 transceivers.

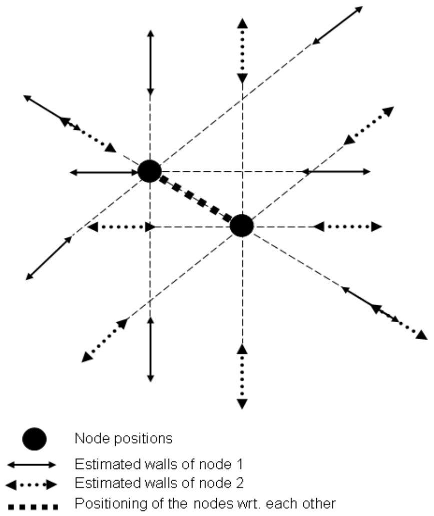

Figure 3: Estimation of walls and corners positions based on RTT of self-to-self CIRs obtained at sectorized Rx antenna

These 12 estimations ($d_{1..12}$) are graphically described in Figure 3 where two transceivers are marked with filled circles. Their relative position with respect to each other is known (employing sensors implemented at robot platform) and is depicted with dashed line. The arrows represent possible, estimated positions of walls and corners. The length of arrows corresponds to the precision of RTT readings ($c/2BW$).

Before producing the final wall estimation two constraints, that are used for discrimination of inadequate estimation, are put on each observation:

1) If the transceiver is in a corner its distance with respect to each of corner walls cannot be smaller than 0.25m and larger than 1.5m. We assume that the transceiver is in a corner if two orthogonal readings, together with the corner observation between them, produce the maximum energy reading at 0ns.
2) If both transceivers are inside the room, walls cannot be in-between.

If any of these constraints is not met, the distance estimation is regarded as unreliable and is not taken into account. The mean value of the rest of observations produces the wall estimation.

4. SIMULATION RESULTS

The results for two transceivers located inside office room, marked with ellipse in Figure 1, are presented in Figure 4. The upper transceiver is set at position (0,0) and all other measurements are done with respect to this point. As can be seen, the estimated room dimensions are slightly larger than the real ones. This could have been expected as we opted not to base RTT calculation only on the first CIR peak, but to use the maximum peak and afterwards to add bandwidth precision to produce the second estimation with the same importance weight. Lower vertical error presented in this example, can be a result of line-of-sight conditions between the transceiver and vertical walls at both transceivers location. In case of horizontal walls, the bookcase at left path, and table on right path are seen as the source of higher horizontal errors of the transceiver located in the center of the room.

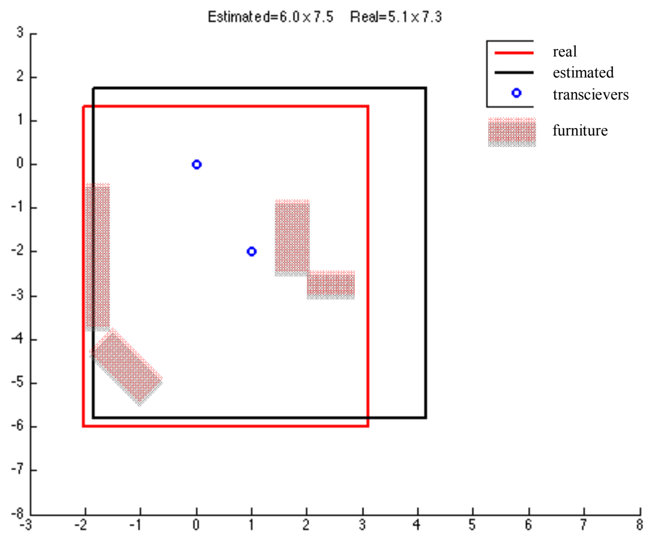

Figure 4 - Example of wall estimation and Tx positioning

The cumulative density function (CDF) of relative error obtained for horizontal and vertical 2D room dimension are depicted in Figure 5. The simulations were done for more than 80 different pairs of transceiver positions inside the same office room. The CDF show that in over 85% of calculations the relative error of the obtained dimensions is bellow 15%, while in 50% of calculations the relative error of room dimensions would be less than 7%. When compared to the results presented in [13] the two constraints implemented in this algorithm shift the error slope to the left by approximately 5%. The CDF confirm that the estimation of horizontal walls is susceptible to higher errors as furniture covers higher percentage of these walls.

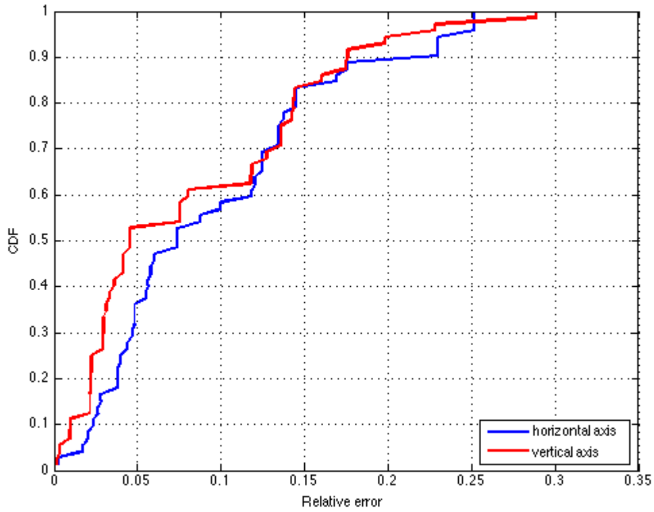

Figure 5 - CDF of relative horizontal and vertical error [%]

When observing the localization error of the transceivers inside the room, we focus on absolute error since relative error of corner estimations (which are close to the wall) can produce misleading conclusions. The absolute error of transceiver distance to each wall is presented in Figure 6. The results show the effectiveness of presented NB estimation procedure of two cooperating transceivers, as the localization error is kept below 1.2m in 95% of cases. It can be observed that the maximum error is below 1.8m, but the errors over 1.2m can be regarded as outliers (occurs in 10% of scenarios). It is also interesting to notice the different CDF error slope that is more abrupt for smaller errors, as in 75% of cases the error is below 0.7m. This large amount of values with low errors support the claim that this approach is adequate for positioning inside the rectangular rooms with furniture.

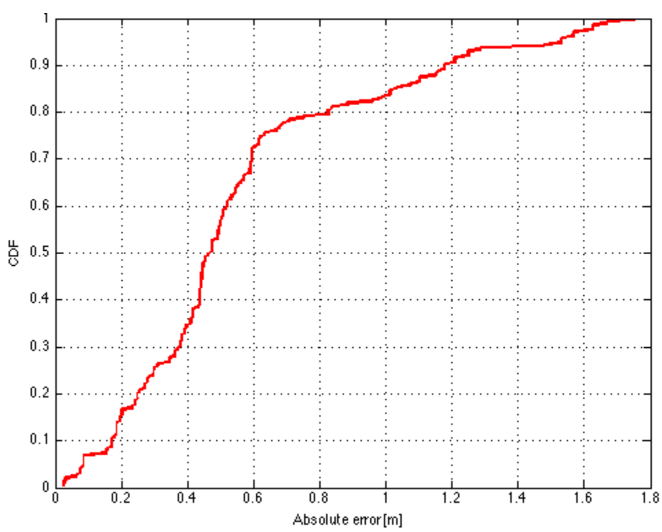

Figure 6 - CDF of absolute positioning error

5. CONCLUSION

The algorithm for indoor localization and 2D mapping of rectangular rooms with spatial discrimination and 100MHz RF signal is presented. The algorithm is carrying out self-localization with two cooperating transceivers. The spatial discrimination of the received signal is possible with sectorized multiple receiver antennas whose total coverage equals the isotropic antenna coverage. The method is tested using synthetic data obtained with deterministic ray-tracing simulations of CIRs. The test room is not perfectly rectangular, and consists of one glass wall, two brick ones, two wooden doors and furniture.

It is shown that the even with 100MHz signal (up to 1.5m localization error per estimation due to sampling rate) the relative mapping error can be maintained in more than 85% of points below 15%, while in 50% of calculations the relative error of room dimensions would be less than 7%. By detecting the position of transceivers close to corners and by excluding the presence of walls between the transceivers, the improvement of 5% of relative estimation error is obtained when compared to the results in [13].

The absolute positioning error with respect do real wall distance is below 0.6m in more than 70% of calculations. This confirms that the algorithm is appropriate and can be used for indoor localization and mapping of rectangular rooms with furniture.

Further work would include applying realistic mobility model and SLAM analysis. Additional research to estimate the Rx antenna sector orientation should also be valuable for SLAM problem solution.

6. ACKNOWLEDGMENTS

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