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Jakub Kmiecik, Pawel Kulakowski
Department of Telecommunications
AGH University of Science and Technology
Al. Mickiewicza 30
30-059 Krakow
POLAND
Phone: +48 12 617 3967
Email: jkbkmiecik@gmail.com, kulakowski@kt.agh.edu.pl

Paul Meissner, Erik Leitinger, Klaus Witrisal
Signal Processing and Speech Communication Laboratory
Graz University of Technology
Inffeldgasse 16c
A-8010 Graz
AUSTRIA
Phone: +43 316 873 4364
Email: paul.meissner@tugraz.at, erik.leitinger@tugraz.at, witrisal@tugraz.at

EXPERIMENTAL VALIDATION OF PASSIVE INDOOR LOCALIZATION AND TRACKING USING UWB SYSTEMS

Jakub Kmiecik[1], Paul Meissner[2], Erik Leitinger[2], Klaus Witrisal[2], Pawel Kulakowski[2]

[1] Department of Telecommunications, AGH University of Science and Technology, Poland
[2] Signal Processing and Speech Communication Laboratory, Graz University of Technology, Austria

ABSTRACT

Passive localization is known to have very advantageous features: it does not require the localized object to have any wireless device attached and it performs very well in NLOS and multipath radio channels. In this technical document, we present results of a measurement campaign conducted in the Signal Processing and Speech Communication Laboratory at Graz University of Technology validating the performance of this wireless localization technique. For the same office room, both ray tracing calculations and a series of measurements are conducted. We introduce a localization and tracking algorithm working well for both ray tracing and experimental data. We compare the localization accuracy in both cases, showing good agreement between these two approaches.

1. INTRODUCTION

Wireless localization as a service becomes nowadays more and more ubiquitous. The whole areas of applications: monitoring and surveillance, people and vehicle tracking, localizing and guiding to points of interests may be developed when the position of an object or person can be estimated. Among many popular techniques like time-of-arrival, angle-of-arrival and receive-signal-strength, it is the passive localization that has gained significant interest in recent years. This technique is based on the fact that a localized object or person, appearing in its environment, creates changes in the radio propagation between nearby wireless transceivers [1]. These changes, especially the changes of radio channels' power delay profiles can be followed. Then, usually with the aid of a ray tracing algorithm, the radio rays that are blocked by the object can be identified. The localized object position is estimated in the point where the blocked rays intersect.

Passive localization has a few important merits that could decide about its future commercial success. First of all, unlike other localization techniques, a localized object does not need to have any wireless device attached. It makes this technique much more suitable for all surveillance systems trying to detect and locate intruders entering a monitored area. Second, passive localization does not need line-of-sight visibility between the system elements (transceivers) and the localized object; it works quite well in multipath and NLOS conditions which are a nightmare of all classical localization techniques [2]. Third, passive localization may be used indoor, unlike the most popular GPS navigation system based on the satellite Navstar constellation.

Passive localization was already the topic of a few IC1004 contributions. The technical document TD (12)05056 [3] presented computer simulations analysing the performance of a UWB passive localization system. The TD (14)11020 [4] continued this research line, but discussed a slightly different passive algorithm applied for localization and tracking of multiple passive targets. The TD (14)11014 [5] investigated and experimentally testified a UWB passive technique exploiting the radio signals reflected from the localized objects.
In this TD, we validate the approach of [4] through an extensive measurement campaign performed in the Signal Processing and Speech Communication Laboratory at Graz University of Technology. In a seminar room, we placed 3 transmitters and 4 receivers on known positions within the room, thus creating a set of 12 fixed radio channels. The aim was to detect the presence and to track the motion of (a) a person and (b) a cardboard box with radio frequency absorbers on its surface. Both objects were moving along specific paths in the environment. This provides the ability to compare the localization accuracy obtained during the experiments with the theoretical values resulting from ray tracing calculations. However, in this TD, we only use the measurements using the cardboard box as a first proof-of-concept.

The rest of the TD is organised as follows. In Section 2, the passive localization algorithm used both in simulations and experiments is described. The methodology of the experimental part is introduced in Section 3. The details of how the simulations were prepared are given in Section 4. Section 5 compares the results of both approaches, while Section 6 gives the conclusions of the work.

2. LOCALIZATION AND TRACKING ALGORITHM

For both types of data, originated from the ray tracing calculations as well as from the experiments, we had the same localization algorithm applied. The algorithm was similar to the one used in [4], with few modifications. Due to the misdetection of blocked rays (see Fig. 1) the use of the algorithm in [4] could result in a situation in which tracked object is not even detected (some rays could exclude each other). The localization system consisted of 3 UWB transmitters and 4 receivers. Section 4 provides details about the measurements. In general, the channel impulse responses between each TX and RX was compared for two cases: without and with the localized object. First, the blocked radio rays were identified. In the case of the ray tracing calculations, it was simple: these rays just did not exist when the object was present in the room. In the case of the experiments, the rays were only attenuated and we needed a criterion to decide if a ray disappeared or not. We use a channel model similar as in [8], i.e. the received signal at the l-th receiver transmitted from the j-th transmitter is modelled as:

$$r_l^{(j)}(t) = \sum_{k=1}^{K_l} \alpha_{k,l}^{(j)} s\left(t - \tau_{k,l}^{(j)}\right) + s(t) * v_l^{(j)}(t) + w(t). \quad (1)$$

The received signal consists of a sum over K_l deterministic MPCs, i.e. specular reflections of the radio signal that can be modelled using virtual anchors [9]. For these MPCs, visibility regions can be computed using optical ray-tracing as in [9]. The second term in (1) is called diffuse multipath (DM). It is used here to consider any components of the channel response that are not accounted for by the deterministic MPCs. Using training measurements without

the presence of any blocking object, we can estimate the statistics of each of the specular MPCs. These statistics reflect the signal-to-interference-plus-noise power ratios (SINRs), the power ratios of the deterministic MPCs to the DM interfering with it [8,9]. They are estimated using an approximate maximum likelihood channel estimator as in [8]. For each MPC, a vector $[\alpha_1, \dots, \alpha_N]_k^{(j)}$ of complex amplitudes is estimated within a small local area, where N is the number of training measurements. Ideally, the deterministic component hardly changes within this measurement vector, while the DM is statistically independent.
From these vectors, the mean $\overline{|\alpha_k^{(j)}|}$ and the standard deviation $\sigma_{|\alpha_k^{(j)}|}$ of the corresponding absolute values are estimated. To detect whether an MPC is blocked by an object, we use a Gaussian model for $|\alpha_k^{(j)}|$ and test the currently estimated amplitude $|\alpha_{k,i}^{(j)}|$ in the i-th time step of the online phase with respect to its deviation in terms of the standard deviation. We decide that the MPC is blocked if $|\alpha_{k,i}^{(j)}| < \overline{|\alpha_k^{(j)}|} - \gamma\sigma_{|\alpha_k^{(j)}|}$. Here, γ is a tuning parameter and is usually chosen between 3 and 4.
Of course the Gaussian model for the absolute value is only an approximation and only justified for MPCs that have large amplitudes. An evaluation of the validity of the Gaussian approximation and the usage of other models such as Rice distributions are the subject of current work. The evaluation of the SINR of MPCs is also discussed in [10, 11].

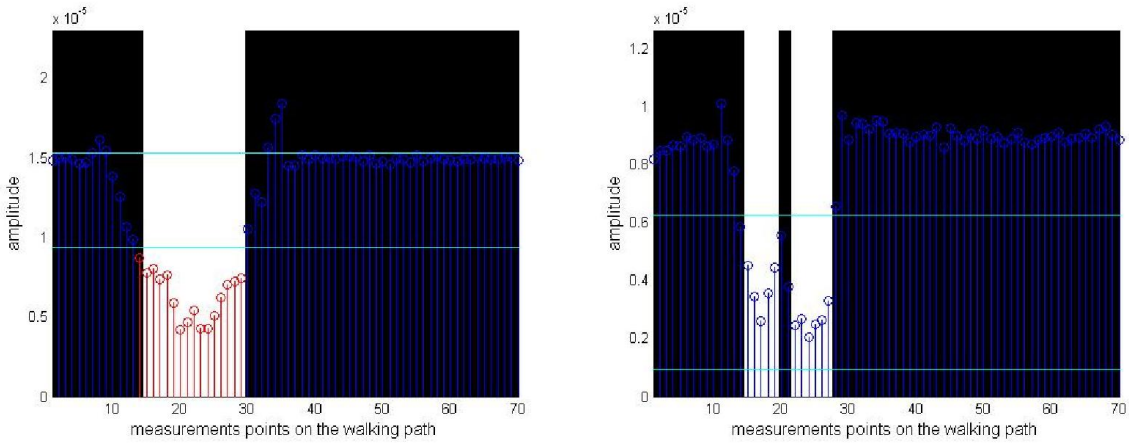

Fig.1. Examples of correct detection of blocked rays (left plot) and incorrect detection (right plot). Black regions indicate amplitudes which should be blocked and white regions indicate amplitudes which are not blocked based on geometrical calculations. Cyan lines indicate the mean value of the amplitude as well as the decision threshold obtained in training measurements, respectively.

The localized object was 50cm x 50cm large. The whole room where the system was working was 8.8 x 6 m^2 large (c.f. Fig. 2) and for the purpose of localization, it was divided into small 10cm x 10cm sectors. We had a matrix **A** of size 88 x 60 initially filled with zeros, where each element of the matrix corresponded with a single 10cm x 10cm sector. Now, each radio ray that was identified as blocked was analyzed separately. For each such blocked ray, we identified all possible object positions that would block this ray. Then, for each such possible position of intruder, we increased by 1 the values of the 25 (5 x 5) respective matrix elements. Everything was repeated for each blocked radio ray, increasing the values of the matrix elements.

In the result of the whole procedure, we obtained the matrix **A** that could be treated as a map of the room (see an example in Fig. 2). The large values of the matrix elements meant

there was a high probability that the object was located on the corresponding sectors. In order to finally estimate the object location, we took the matrix elements equal or higher than 80% of the largest matrix element. If these elements corresponded to a single zone of sectors on the map, the centre of this zone was taken as the object location. If there were many zones, we took the zone with highest median of values of matrix elements or, in case of a mobile object, the closest to its previous location.

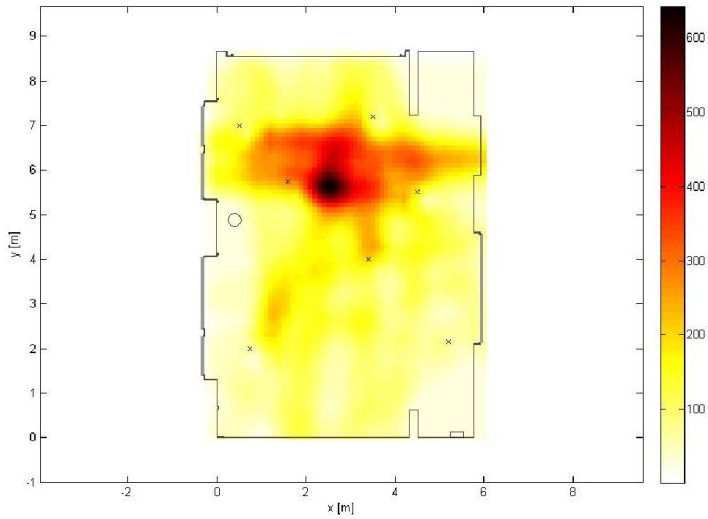

Fig.2. An example of image of matrix **A** in considered room; darker areas indicate sectors which have the highest values.

3. MEASUREMENTS METHODOLOGY

The measurements have been obtained in time-domain using an Ilmsens Ultra-Wide Band M-Sequence device [7]. The measurement principle is correlative channel sounding. A filtered binary code sequence with suitable autocorrelation properties (a large peak-to-off-peak-ratio) is transmitted over the channel. At the receiver, the channel impulse response is recovered using a correlation with the known code sequence.
This M-sequence radar has one transmitter and two receiver ports. The transmit power of the M-sequence device in FCC mode (frequency range from 3.1-10.6 GHz) is 18dBm. The employed 12-bit M-sequence has a length of 4095 samples. At the clock rate of 6.95 GHz, this allows for a maximum delay of $\tau_{max} = 589\,ns$, corresponding to a maximum path length of $d_{max} = 176{,}7\ m$.

Fig. 3 shows photos of the seminar room in which the measurements have been performed. It is a seminar room of the Signal Processing and Speech Communication Laboratory. The front wall is largely covered by a (well reflecting) blackboard (see left figure), and has a metal door as well as windows on the outer side and one window on the inner side (left and right in the left part of Fig. 3). The back wall is wood covered. Behind this cover, acoustic attenuation material is used, which impairs the reflections from this wall [9]. This is shown in the right part of Fig. 3, as well as the apparatus that has been used for the blocking object. We employed an empty cardbox of 50 cm side length, covered with radio frequency absorbers.

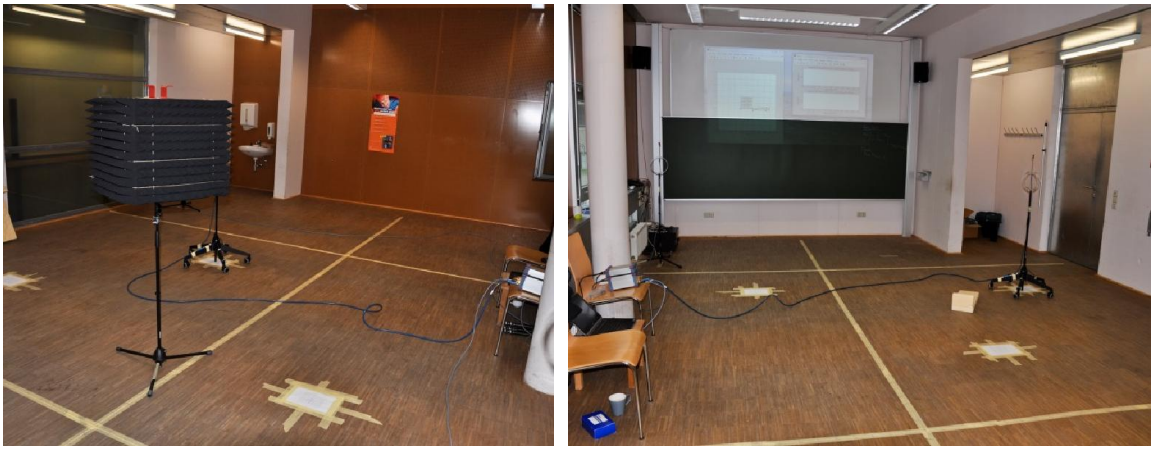

Fig.3. Photos of the measurement environment.

Fig. 4 shows the geometric layout of the measurement campaign. A floor plan of the room as well as all RX and TX positions are shown. For the latter, on each of the 3 main TX positions, an 11x11 grid with 1cm spacing was measured for the training phase, i.e. in the absence of the blocking object. For the online phase, the blocking object was moved along the 3 paths indicated in Fig. 4. Path 1 consists of 70 points, while paths 2 and 3 consist of 50 points each. For every path, the spacing of positions has been selected as 5 cm.
Fig. 4 also indicates a subset of the expected geometrical signal paths of up to 2nd order specular MPCs between TX1 and RX2. The subset is chosen as the one for which a signal-to-interference-plus-noise-ratio (SINR) between specular MPC and diffuse and measurement noise can be estimated. This procedure is explained in detail in [8,9]. We expect that for these paths, the Gaussian approximation of the absolute values of the MPC amplitudes may be justified. In the evaluation of the online phase, we restrict the set of ray paths that we test for blockage to this set.

4. RAY TRACING CALCULATIONS

The motivation of this work was not only to measure the accuracy of the passive localization system but also to validate the approach presented in [4], thus we also performed ray tracing calculations. We modelled in details the geometry of the room where the measurements were conducted. Then, for each TX-RX pair (3 transmitters and 4 receivers), we calculated its channel impulse response. The basic idea of the ray tracer was the same as in [4], the computational engine used for that was a part of the software developed at the Signal Processing and Speech Communication Laboratory at Graz University of Technology. Its description was already published in [8,9] and references therein. Shortly speaking, for each TX-RX pair, the direct path as well as the reflected paths were checked, up to third-order reflections. The first-order reflected paths were created by calculating the mirror images of the TX relative to the all possible reflecting surfaces. Each mirror image is represented by a virtual source of a radio ray. Creation of second-order reflected paths required to calculate the mirror images of the first-order mirror images, and so on. Obviously, the obstacles in the room, especially the moving cardbox could block some propagation paths. In the ray tracer, the corresponding peaks in the channel impulse response were just absent, which was the main difference between CIRs when the cardbox was moving through the room.

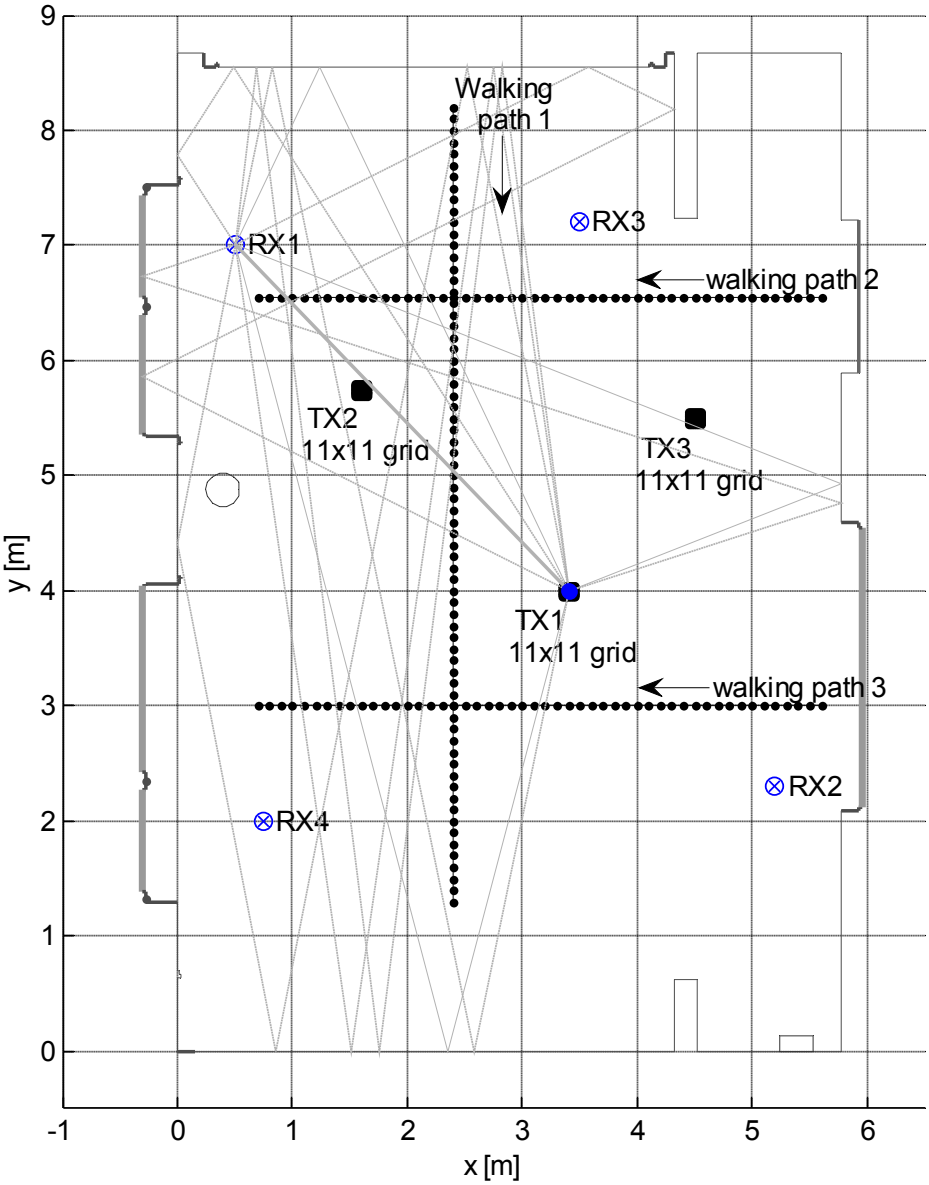

Fig.4. The geometric layout of the measurement campaign. The four receiver positions as well as the three 11x11 transmitter grids with 1cm spacing are shown. Grey lines indicate the significant specular MPCs that are possible in the channel between RX1 and the center position of the TX1 grid.

5. COMPARISON OF CALCULATIONS AND EXPERIMENTAL RESULTS

As the results of both measurements and geometrical ray tracing, the localization error was calculated. The error was defined as the Euclidean distance between the (experimentally measured or geometrically computed) estimated position of the cardbox and its real location. The measurements and calculations were performed once for each point on each of 3 paths.

Figures 4, 5 and 6 show the localization error for the cardbox measurements and calculations for paths 1, 2 and 3, respectively.

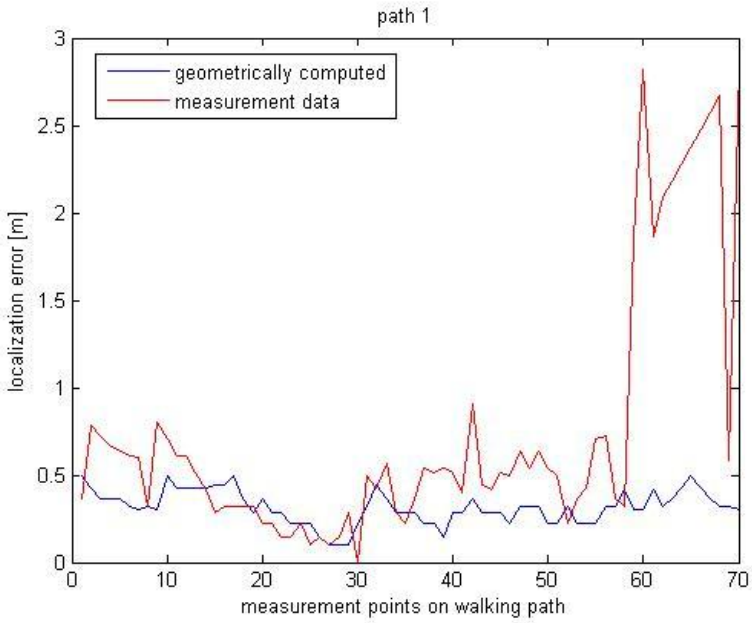

Fig.5. The localization error for the measurements and ray tracing calculations on the path 1.

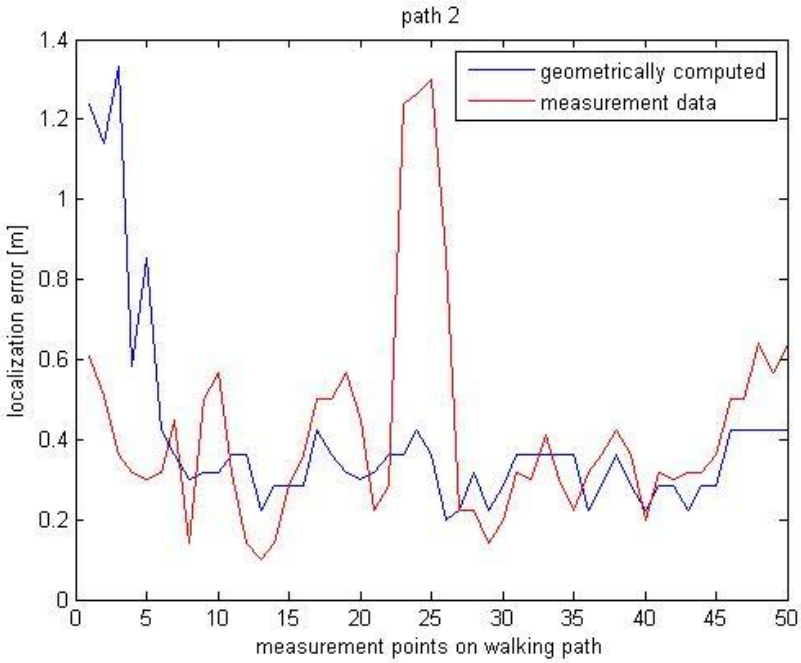

Fig.6. The localization error for the measurements and ray tracing calculations on the path 2.

As it can be seen from the Figs. 4-6, the system was able to efficiently localize the cardbox at most of the points, however there were some regions where the accuracy was really not satisfactory. The localization error was the largest (nearly 3 meters) at the end of the path 1 in the bottom part of the room. It was probably caused by the back wall of the room which consists of an attenuating material that suppresses reflections from this wall. The errors on the paths 2 and 3 were generally smaller (about 50 cm), except some isolated points. On the other hand, the ray tracing calculations resulted in similar errors (again about 50 cm or lower), except the beginning of the path 2: according to the geometrical ray tracer, there is only one blocked ray here, so the position of the cardbox cannot be estimated more accurately as “somewhere on this ray path”.

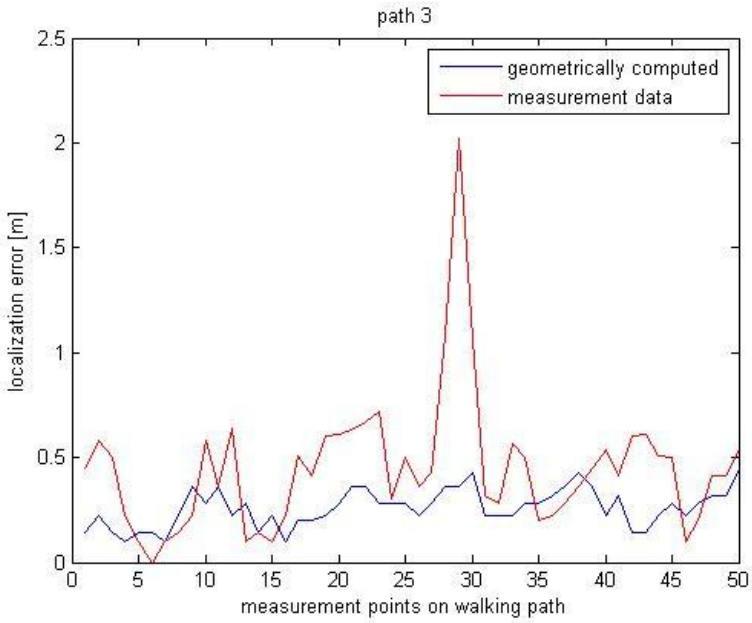

Fig.7. The localization error for the measurements and ray tracing calculations on the path 3.

6. SUMMARY

In this technical document, we have reported results of a measurement campaign performed in the Signal Processing and Speech Communication Laboratory, aimed at measuring the applicability and accuracy of a passive localization system based on UWB transmitters and receivers. The campaign was motivated by earlier theoretical works on passive localization. It was aided by geometrical ray tracing calculations in order to fully validate the basic ideas and compare both approaches: computational and experimental. The obtained results show that a quite good accuracy (about 50 cm in most of the cases) was achievable with a UWB system consisting of 3 transmitters and 4 receivers. There were, however, some areas where the localization error was much larger, about 2-3 meters, which was caused by the adverse room topology.

The results were collected for 3 paths where the cardbox was being moved along the predefined paths in the room. The localization errors were calculated for each point alone, not taking into account any space dependency between the subsequent object positions. These errors could be probably diminished when using appropriate tracking and filtering (e.g. Kalman) techniques which are going to be our further works on this topic. Also, the statistical models (Gaussian) for the multipath amplitudes that were employed are approximations and their applicability as well as more realistic models are a subject of a current work.

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