Time of Arrival Complementing Method for Cooperative Localization of a Target by Two-Node UWB Sensor Network

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Abstract. *Recently, the detection, localization and tracking of moving persons in emergency situations using ultra-wideband (UWB) sensors have attracted the attention of researchers and final users as well. Experiences with single UWB sensors in real applications have shown that their reliability and accuracy in person detection and localization may be considerably reduced. In contrast, the improved performance of a UWB sensor-based localization system can be provided by a UWB sensor network, which benefits from cooperation among spatially distributed sensor nodes. This cooperation extends the coverage of the monitored area and improves detection capability and localization performance, especially in the case of complex environments and multiple targets. In this paper, we will introduce a new approach to cooperative localization of a target, referred to as the time of arrival complementing method (TOACOM). TOACOM, developed for a two-node UWB sensor network, is based on the time of arrival (TOA) complementing and combining algorithms in combination with the conventional direct calculation method (DC). Its properties will be analyzed for through-the-wall single moving person localization. The obtained results will show the superior performance of TOACOM as compared with person localization by a single UWB sensor, or by a two-node sensor network. In the conclusion, we will outline that the presented version of TOACOM can be further modified for a multiple target scenario and an N-node sensor network.*

Keywords

Radar signal processing, target tracking, TOA complementing method, UWB sensor network

1. Introduction

The detection and localization capability of human beings is one of the most attractive features of UWB radars. Sensors of that kind, operating in the frequency band DC-5 GHz, allow for detection and tracking of living persons not only in line-of-sight scenarios, but also of persons located behind non-metallic obstacles (e.g. behind a wall). Therefore, they can be very helpful in such applications as searching for people who have survived at natural disaster but are under rubbles (e.g. after earthquakes, tsunamis, earth slides, avalanches, building collapses, etc.), or for detection and tracking of criminals, terrorists, hostages and soldiers located behind a wall (e.g. for the support of law enforcement and military troops) [1].

For that purpose, handheld UWB radar systems can be used with advantage. Usually, they are equipped with one transmitting and two receiving channels. Hence, a trilateration method can be applied to target localization. The reliability and accuracy of UWB sensor performance depend on their construction and operational parameters (e.g. operational frequency band, emitted power level, maximum range, range resolution, radar antenna system, etc.), on the complexity of the investigated scenarios (single person or multiple person scenarios, operation in the presence of interference or jamming, etc.) and on the complexity of the environment in which the sensors are used (e.g. the presence of metal objects or large reflectors, non-homogeneous objects, etc.). Our experiences with applying a the single UWB sensor to complex scenarios and complex environments have shown that the reliability and accuracy of its performance under these conditions may be reduced. Such performance of UWB sensors is characterized by a drop in detection probability and localization accuracy of the target. These difficult conditions are typical for standard applications of UWB sensors to person detection, localization and tracking. Therefore it has been necessary to look for proper approaches to improving their operation. It has been shown (e.g. in [2–8]), that a proper approach to improving target detection and localization by UWB sensors is to use a multistatic radar (more precisely, a sensor equipped with more receiving antennas than a standard handheld localization system) or more (at least two) networked independent handheld systems for monitoring the area of interest. Such a UWB sensor network benefits from the cooperation of spatially distributed sensor nodes. This cooperation extends the coverage of the monitored area and improves the detection capabilities and localization precision, especially in the case of multiple targets and complex environments.

Very interesting approach for target localization based on the multistatic localization system has been introduced in [8]. In this paper, an asynchronous elliptical position measurement system employing 1 transmitter (Tx) and N receivers (Rx) has been proposed for line-of-sight (LOS) indoor localization. The mentioned system consists of a UWB transmitter and energy detection receivers whose positions are known. The position measurement process starts with the locator (Tx) emitting a UWB pulse. Upon arrival, the pulse is amplified and retransmitted by the target to be located. Signals from both the locator and the target are captured by the receivers. Together with the knowledge of the transmitter and receiver positions, the absolute range that the pulse travels is calculated. The sum of transmitter–target range and target–receiver range defines an ellipse and the target resides on the intersections of several such ellipses. For the target localization, three least-square (LS) position estimation algorithms have been considered, namely the ordinary LS, the constrained LS and a combination of LS method and the iterative Gauss-Newton method (referred to as the recursive LS). The obtained experimental results for $N = 4$ have shown that the described approach can provide the target positioning with the mean value of target position estimation error about 1 cm at the standard deviation smaller than 12 cm.

On the other hand, several approaches for the cooperative localization of moving persons by UWB sensor networks have been suggested in the past. These methods have included an imaging method [2], application of 2D probability-hypothesis density filters (PHD filters) [3], [4], a UWB sensor network with a centralized architecture employing single or multiple target tracking system (STT or MTT) [5], [6] and the method of joining intersections of ellipses (JIEM) [7].

The imaging method and PHD filters are based on the creation and processing of so-called radar images or 2D PHD functions where the targets are represented by moving hot spots. These methods provide a direct approach to the fusion of data obtained from particular receiving channels of different sensors. Because they are based on 2D signal processing (2D image, 2D PHD filters), they are characterized by high computational complexity, which is their substantial disadvantage.

On the other hand, the UWB sensor network with a centralized architecture [5] is based on the fusion of data representing target coordinates estimated by particular sensor network nodes. In the case of a sensor network of this kind, the STT/MTT system can be regarded as a key method in terms of the cooperative localization and tracking of moving targets [9], [10]. STT/MTT provides data association, fusion and target tracking and hence very efficient estimation of target positions with an acceptable computational complexity.

However, because of the complex monitored environment, there are situations where not all receiving channels of the node of the sensor network are capable of detecting the targets. Under these conditions, the radar is unable to determine target coordinates, and hence, target localization and tracking efficiency by a UWB sensor network with a centralized architecture can be decreased. In order to overcome this problem, data fusion at the level of the estimated times of arrivals (TOAs) associated with the targets detected by particular receiving channels can be used. This idea has been exploited e.g. by the JIEM algorithm [7]. This method is based on the combination of the direct calculation method (DC) and the creation of a proper cluster of potential target positions. It has been shown in [7] that JIEM can provide an improvement of target localization accuracy in comparison with DC. However, a deeper analyse of JIEM has revealed some shortcomings of this approach. We have found that some outliers can be found in estimates of the target trajectory obtained by JIEM. This behavior of JIEM (due to the creation of imperfect clusters of possible and at the same time proper positions of target) will be illustrated also in this paper. This deficiency of JIEM could be eliminated e.g. by the application of a more robust method for the creation of the cluster of proper positions of the target. Moreover, the high computational complexity is another drawback of the JIEM.

In order to overcome the outlined problems, a new approach to cooperative localization of a target, referred to as the time of arrival complementing method (TOACOM), developed for a two-node UWB sensor network, is presented in this paper. TOACOM is based on the combination of DC employing all TOAs estimated by the sensor network nodes, the estimation of target positions combining TOAs provided by the different sensors (the TOA combining algorithm), the TOA complementing algorithm and finally target localization (the arithmetic average application). The performance of TOACOM will be compared with those provided by the simple DC (for single UWB sensors), JIEM and two-node sensor network with a centralized architecture (SN). The comparison of the mentioned methods will be done through processing of radar signals obtained by through-the-wall measurement with a two-node UWB sensor network for a single person scenario. The obtained results will show the superior performance of TOACOM in terms of its higher probability of detection and better accuracy of the localization of the target in comparison with DC, JIEM and SN.

TOACOM as a new cooperative method of localization was originally introduced in [11] and [12]. Compared to these papers, we will present in this contribution only a short description of TOACOM, but also a more detailed description of the problems to be solved by TOACOM (Sec. 2), a slightly adapted description of TOACOM (Sec. 3), a deeper analysis of the TOACOM performance properties (Sec. 4) and an outline of the TOACOM modification for a multiple moving person scenario and N-node sensor network (Sec. 5).

2. Problem Statement

Let us consider the basic scenario of a through-the-wall localization of a moving target by means of two UWB radar systems, denoted as radar system A (RS_A) and radar system B (RS_B) (Fig. 1). Here, every radar system is equipped with one transmitting (Tx_R, $R = A, B$) and two receiving antennas ($Rx_{R,i}$, $R = A, B, i = 1, 2$). In the analyzed scenario, it is assumed that the antenna positions are known and their coordinates are given by $Tx_R = (x_{R,t}, y_{R,t})$ for $R = A, B$ and $Rx_{R,i} = (x_{R,i}, y_{R,i})$ for $R = A, B, i = 1, 2$ for transmitting and receiving antennas, respectively. We will assume, that the antennas of RS_A (RS_B) are located on the x-axis (y-axis) for $x > 0$ ($y > 0$), and the monitored area is defined as the part of the xy-plane for $y > 0$.

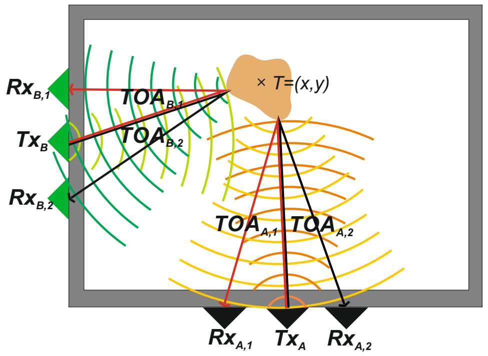

Fig. 1. The basic scenario of target localization by a two-node UWB sensor network.

In order to localize and track a moving target, the transmitting antenna emits electromagnetic waves into the monitored area, they are reflected from objects located there (including a target), and finally the reflected waves are received by the receiving antennas. Raw radar signals retrieved from particular radar systems can be interpreted as a set of impulse responses of the surroundings through which the electromagnetic waves were propagated [1]. Hereinafter, we will assume that the sensor systems are synchronized in such a way that both radar devices are controlled approximately by the same system clock. Then, we can assume that the radargrams obtained by the measurements by all four receiving antennas have the same propagation and observation time axes and that the radargram samples are taken in the same time instants. The other kind of radar system synchronization is not assumed. For the target track estimation by a single UWB sensor (RS_A or RS_B), the complex procedure of raw radar signals for moving person detection, localization and tracking consisting of signal processing phases such as background subtraction, target detection, TOA estimation, wall effect compensation, trace connection, localization and tracking can be used (e.g. [13]). In terms of the objectives of this paper, TOA estimation can be considered the most important and interesting phase of this procedure. Therefore, we will outline our approach to TOA estimation in the next passage.

Similarly to the positioning methods introduced in [8], the localization method, we will develop in this paper, is also based on TOA estimation corresponding to the distance Tx-target-Rx. However in contrast to [8], we will deal with through-the-wall localization (i.e. not LOS scenario) of tag-free moving person not providing any retransmission of signals emitted by the radar (i.e. the target echo to noise and clutter ration is very low). As it was shown in [14], TOA estimation is mainly affected by noise, multipath components, obstacles and interferences. In dense multipath channels, which have to be considered for our scenarios, the first path is often not the strongest, making the estimation of the TOAs challenging. Moreover, a human being represents so-called distributed target, i.e. the same target can provides several reflections of an incidence waves at the same time instant, but these reflections propagating through a multipath environment are received multiply however with the different TOAs.

Taking into account these facts, we have to estimate the target TOA (i.e. one TOA per the target for one time instant) for time-variable dense multipath channel (environment) and very low target echo to noise and clutter ratio. Therefore, for TOA estimation we cannot use simple solutions based on energy detector applications. The TOA estimator considered in this paper is based on the combination of a CFAR detector [15] and trace connection TOA estimator [16]. The application of CFAR detector provides the first rough estimate of TOAs of the potential targets. On the other hand, the trace connection TOA estimator subsequent to CFAR provides the only one TOA estimate per target. For that purpose, the specific association methods described in [16] are used (an association of the CFAR detector response corresponding to the same target, an association of the outputs of the receiving channels corresponding to the same target). The detail description of the trace connection TOA estimator is too complex and hence it is beyond this paper. A reader interesting in this topic can find it in [16].

Let us return to the analyzed scenario. Let $TOA_{R,i}$ for $R = A, B, i = 1, 2$ represent the estimation of TOA of the electromagnetic wave transmitted by Tx_R, reflected by the target $T = (x, y)$ and received by $Rx_{R,i}$. We presume that $TOA_{R,i}$ has been estimated by the algorithms mentioned in the previous paragraph. Then, the distance $d_{R,i}$, between the transmitting antenna Tx_R, the target T and the receiving antenna $Rx_{R,i}$ (usually referred to a bistatic range) can be expressed as

$$d_{R,i} = c\mathrm{TOA}_{R,i}, \quad R = A, B, i = 1, 2, \tag{1}$$

or

$$\begin{aligned} d_{R,i} = & \sqrt{(x - x_{R,t})^2 + (y - y_{R,t})^2} + \\ & \sqrt{(x - x_{R,i})^2 + (y - y_{R,i})^2}, \\ R = & A, B, i = 1, 2, \end{aligned} \tag{2}$$

where c is the propagation velocity of the electromagnetic waves emitted by the radar. In our consideration, c is

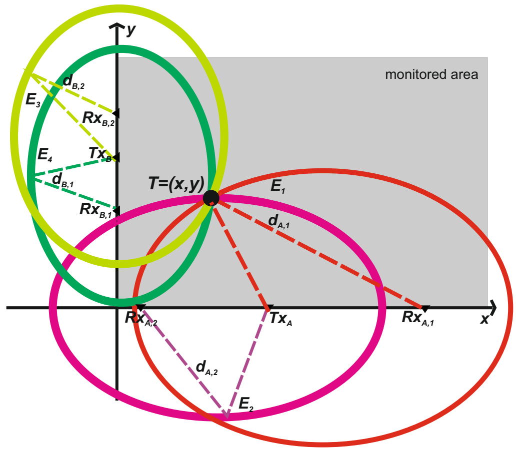

Fig. 2. Geometrical interpretation of the target localization. Perfect TOA estimations.

set to the electromagnetic wave propagation velocity in air, i.e. $c = 3 \times 10^8$ ms^{-1}.

The expression (2) represents the equation of the ellipse with the foci $Tx_R = (x_{R,t}, y_{R,t})$ and $Rx_{R,i} = (x_{R,i}, y_{R,i})$ and with the length of the semimajor axis $d_{R,i}/2$. Thus, a group of the four ellipses for $Tx_R - Rx_{R,i}$ pair ($R = A, B, i = 1, 2$) with the foci in Tx_R and $Rx_{R,i}$ can be created, for all possible values of $d_{R,i}$ [7]. Since the target coordinates have to satisfy (1) and (2) and the coordinates of the transmitting and receiving antennas are known, the target coordinates can be determined as the intersection of the ellipses formed by two different $Tx_R - Rx_{R,i}$ pairs. These intersections can be obtained by the solution of a couple of the corresponding nonlinear equations of (2). If the target coordinates are computed as the intersection of two ellipses corresponding to the same radar system, then this approach is referred to as DC [7]. The outlined approach of target localization by the evaluation of the ellipse intersections is usually referred to as a geometrical interpretation of the target localization. Since this approach is indeed very visual, it will be used throughout this paper. Of course, an analytical calculation of the intersections of two ellipses (in general located in any mutual position) is still necessary for target localization. Because of the limited scope of this paper, a detailed solution of this mathematical problem is not provided here. Readers can find a comprehensive solution of this mathematical task e.g. in [7].

Let us return to the basic scenario outlined in Fig. 1. By using $\text{TOA}_{R,i}$ for $R = A, B, i = 1, 2$, four ellipses E_i for $i = 1, 2, 3, 4$ can be constructed. A possible system of the ellipses E_i for perfect estimates of $\text{TOA}_{R,i}$ is sketched in Fig. 2. It can be seen in this figure that there is only one joint intersection of all ellipses in the monitored area. This intersection, estimated by the solution of (2), represents the target position. Unfortunately, $\text{TOA}_{R,i}$ is normally never estimated with zero error. This is due to the non-zero resolution of the radar range, the radar antenna lay-out, the low level of target echo-to-noise and clutter ratio, etc. The scenario for imperfect estimations of $\text{TOA}_{R,i}$ for $R = A, B, i = 1, 2$ is outlined in Fig. 3. It can be observed from this figure that

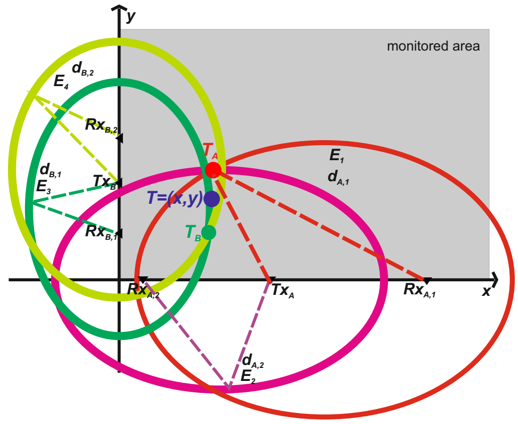

Fig. 3. Geometrical interpretation of target localization. Imperfect TOA estimations.

there are 4 intersections representing the possible positions of the target. Moreover, there are situations where the target is not detected by some receiving channel. This is usually due to the complex environment (e.g. shadowing effect, localization of relatively large metal components and other strong reflectors in the monitored area, etc.), the radar antenna patterns, the low level of target echo-to-noise and clutter ratio, etc. If the target is not detected, it is not possible to estimate the corresponding TOA, and hence, some TOAs and ellipses as well are missing. Depending on which TOAs are missing, the target can be localized using DC by only one sensor (the pair of TOAs corresponding to the same sensor is available), or the target cannot be localized using DC (the pair of TOAs corresponding to the same sensor is not available).

Summarizing these facts, at the standard operation of a two-node UWB sensor network applied to a person localization, we can create 0-4 ellipses having 0-4 intersections (i.e. 0-4 possible positions of the target) in the monitored area. The problem to be solved within our paper is estimating the target coordinates for this scenario. For that purpose, we will introduce TOACOM in the next section.

3. TOA Complementing Method

Let us assume that the raw radar data gathered by the particular radar systems have been processed by the radar signal processing procedure described in [13]. With the exception of the localization phase, other phases of the procedure mentioned are independent of the number of radar systems applied to target tracking. Therefore, we will focus in this Section on the solution of the localization task consisting in the estimation of the target coordinates $T = (x, y)$. Here, it is assumed, that input data of the localization phase are represented by the set of $\text{TOA}_{R,j}$ for $R = A, B, j = 1, 2$ obtained as the result of the TOA estimation phase. As we mentioned in the previous section, some TOAs can be missing. Then, depending on the number of the estimated TOAs, the localization of the target by TOACOM can be described as follows:

1. No TOA or only one TOA is estimated. Under such an assumption, the target position cannot be estimated.

2. $\mathrm{TOA}_{A,1}$ and $\mathrm{TOA}_{A,2}$ from $\mathrm{RS_A}$ have been estimated. $\mathrm{TOA}_{B,1}$ and $\mathrm{TOA}_{B,2}$ from $\mathrm{RS_B}$ are missing. Thus, there is a pair of ellipses E_1 and E_2 for the $Tx_A - Rx_{A,i}$ pair ($i = 1, 2$). The target position T is given by the intersection of the ellipses E_1 and E_2 (Fig. 4). The target coordinates can be obtained by DC [7].

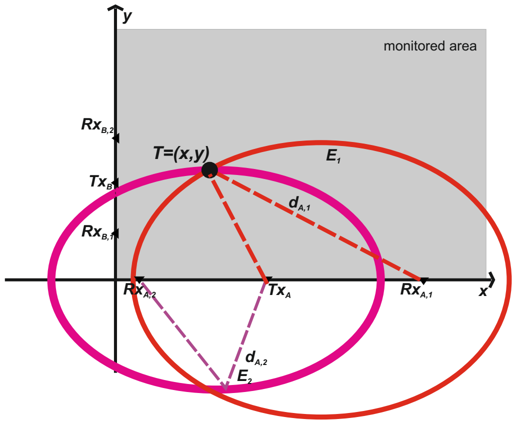

Fig. 4. Target localization by $\mathrm{RS_A}$.

3. $\mathrm{TOA}_{B,1}$ and $\mathrm{TOA}_{B,2}$ from $\mathrm{RS_B}$ have been estimated. $\mathrm{TOA}_{A,1}$ and $\mathrm{TOA}_{A,2}$ from $\mathrm{RS_A}$ are missing. Thus, there is the pair of the ellipses E_3 and E_4 for the $Tx_B - Rx_{B,i}$ pair ($i = 1, 2$). The target position T is given by the intersection of the ellipses E_3 and E_4 (Fig. 5). The target coordinates can be obtained by DC [7].

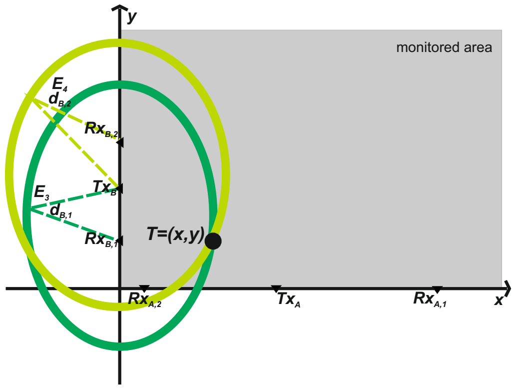

Fig. 5. Target localization by $\mathrm{RS_B}$.

4. Only one $\mathrm{TOA}_{A,i}$ for $i = 1$ or $i = 2$ from $\mathrm{RS_A}$, and only one $\mathrm{TOA}_{B,i}$ for $i = 1$ or $i = 2$ from $\mathrm{RS_B}$ have been estimated. The other TOAs are missing. Then, the target position is given by the intersection of the ellipses E_1 or E_2 and E_3 or E_4 (Fig. 6). The ellipses E_1 or E_2 are determined by the pairs $Tx_A - Rx_{A,i}$ ($i = 1$ or $i = 2$) and the ellipses E_3 or E_4 are determined by the pairs $Tx_B - Rx_{B,i}$ ($i = 1$ or $i = 2$). The target coordinates $T = (x, y)$ can be determined using Bezout's theorem [17]. This step of TOACOM is referred as TOA combining algorithm.

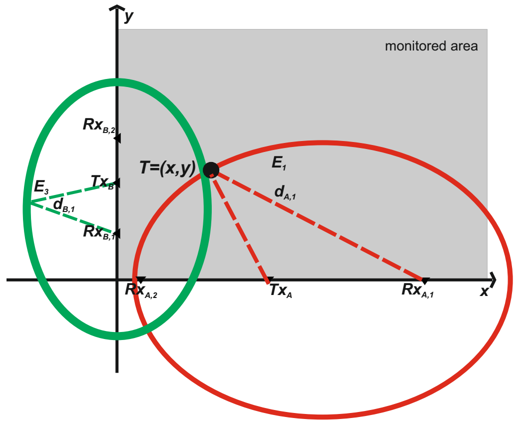

Fig. 6. Target localization by TOA combining algorithm.

5. Three TOAs have been estimated. One TOA is missing. Let us assume e.g. $\mathrm{TOA}_{A,2}$, $\mathrm{TOA}_{B,1}$, $\mathrm{TOA}_{B,2}$ have been estimated and $\mathrm{TOA}_{A,1}$ is missing. Then, the ellipses E_2, E_3, E_4 determined by the pairs $Tx_A - Rx_{A,2}$, $Tx_B - Rx_{B,i}$ ($i = 1, 2$) can be created. The potential target position estimate referred to T_B is given by the intersection of E_3 and E_4 (Fig. 5). The target coordinates T_B can be obtained by DC [7].

   In order to use the estimated $\mathrm{TOA}_{A,2}$ for target localization by $\mathrm{RS_A}$, $\mathrm{TOA}_{A,1}$ has to be also determined. For that purpose, the following algorithm referred to TOA complementing algorithm can be used. Firstly, the intersection of E_2 with E_3 referred to P_1 and the intersection E_2 with E_4 referred to P_2 are computed (Fig. 7). The ellipse intersections located out of the monitored area are removed. In the next step, point P can be constructed (Fig. 7). Its coordinates are given as the average of the corresponding coordinates of points P_1 and P_2. After that, the missing $TOA_{A,1}$ can be computed as $\mathrm{TOA}_{A,1} = (|Tx_A, P| + |P, Rx_{A,1}|)/c$, where the symbol $|X, Y|$ is set for the Euclidean distance between points X and Y. Then, using the computed $\mathrm{TOA}_{A,1}$, ellipse E_1 can be constructed. The potential target position estimate referred to T_A can be obtained as the intersection of E_1 and E_2. The final estimate of target coordinates $T = (x, y)$ is obtained as the arithmetical average of the corresponding coordinates of points T_A and T_B (Fig. 3).

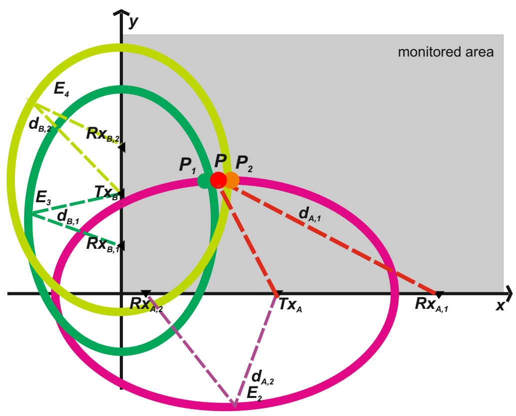

Fig. 7. Target localization by TOA complementing algorithm.

6. Four $\mathrm{TOA}_{R,i}$ for $R = A, B$ and $i = 1, 2$ have been estimated. No TOA is missing. In this case, the potential target positions T_A and T_B are obtained as the intersections of E_1 and E_2, and E_3 and E_4, respectively. In contrast to JIEM, the final estimate of the target coordinates $T = (x, y)$ is obtained as the arithmetical average of the points T_A and T_B (Fig. 3) only. Because these points estimated independently represent with a high probability the positions of the target and not ghosts, we expect that the performance of TOACOM will be more robust compared with JIEM which uses almost all intersections of the four ellipses.

4. Experimental Results

To evaluate the TOACOM properties, we performed the measurement intent on through-the-wall localization of a moving person by two M-sequence UWB radar systems (Figs. 8–10). The analyzed scenario is outlined in Fig. 10. The thickness of the first and the second brick wall was 24 cm and 28 cm, respectively. The person to be localized and tracked was walking inside a fully furnished room (Fig. 8) from reference position P1, through positions P2, P3, P4, P5, P6, P7 up to position P8 (Fig. 10).

Fig. 8. Room interior.

Fig. 9. M-sequence UWB radar system.

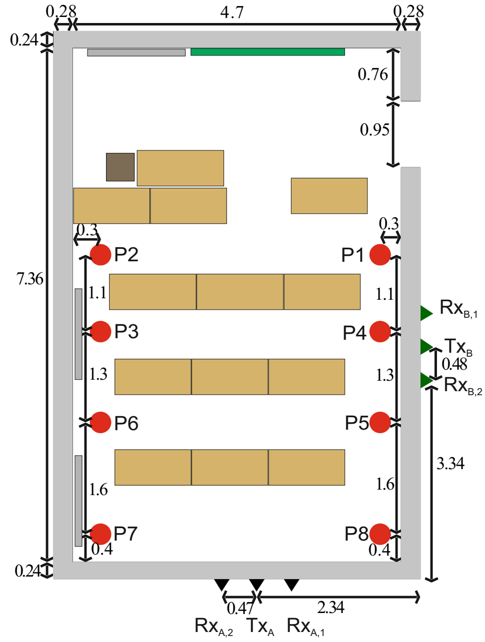

Fig. 10. The scheme of the measurement.

A moving person was detected and localized by means of two M-sequence UWB radar systems equipped with one transmitting and two receiving antennas [1]. The radar antenna lay-outs are outlined in Fig. 10. The system clock frequency of both radar devices was about 4.5 GHz, which results in the operational bandwidth of about DC-2.25 GHz. The impulse responses provided by the radars cover 511 samples regularly spread over 114 ns. The measurement rate was 13.5 impulse responses per second. The total power transmitted by the particular radars was about 1 mW.

The raw radar data acquired by $\mathrm{RS_A}$ and $\mathrm{RS_B}$ have been processed by the radar signal procedure described in [13]. The true and estimated $\mathrm{TOA}_{R,i}$ for $R = A, B$ and $i = 1, 2$ are depicted in Fig. 11 and 13. In these figures, the intervals of missing TOAs can be clearly identified. Therefore the TOA complementing algorithm has been used for the estimation of the missing TOAs. Then, the true and complemented $\mathrm{TOA}_{R,i}$ for $R = A, B, i = 1, 2$ are depicted in Fig. 12 and 14.

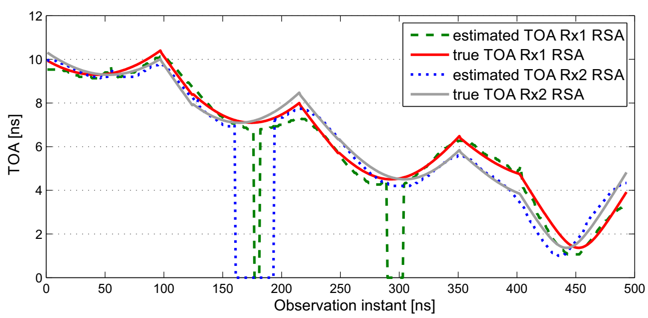

Fig. 11. $\mathrm{RS_A}$: the true and estimated TOAs.

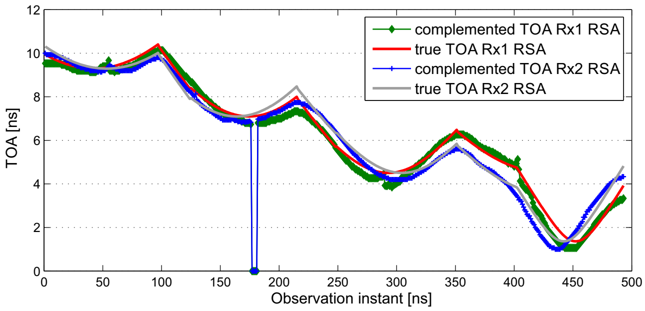

Fig. 12. RS_A: the true and complemented TOAs.

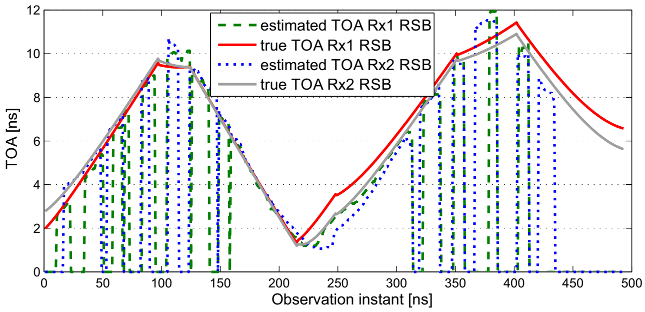

Fig. 13. RS_B: the true and estimated TOAs.

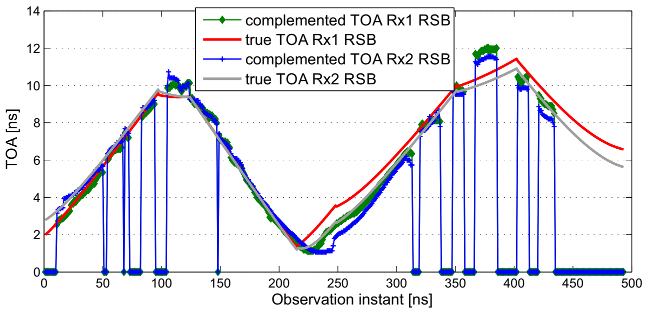

Fig. 14. RS_B: the true and complemented TOAs.

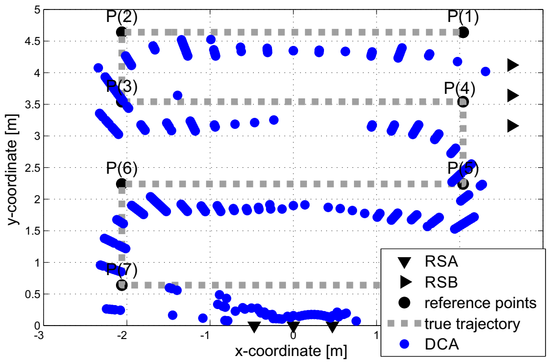

Fig. 15. Target localization by DCA.

By using the estimated and complemented TOAs (in the case of TOACOM only), the target trajectory has been estimated by DC for RSA (DCA), DC for RSB (DCB), SN, JIEM and TOACOM. In the case of SN, the target coordinates have been estimated as the arithmetic average of the target coordinates estimated independently by RSA and RSB. The true and estimated trajectories obtained by these methods are given in Figs. 15–19.

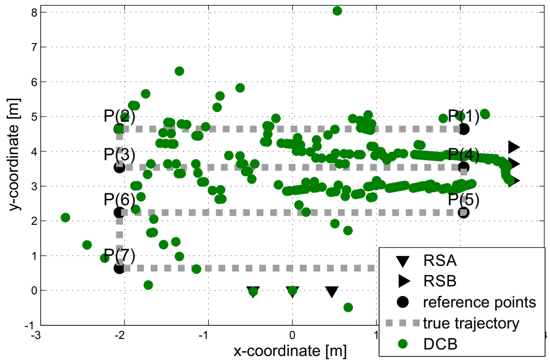

Fig. 16. Target localization by DCB.

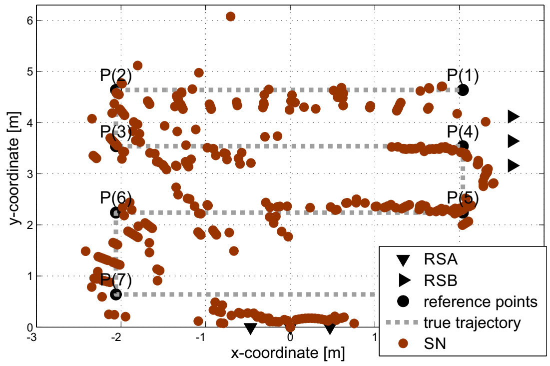

Fig. 17. Target localization by SN.

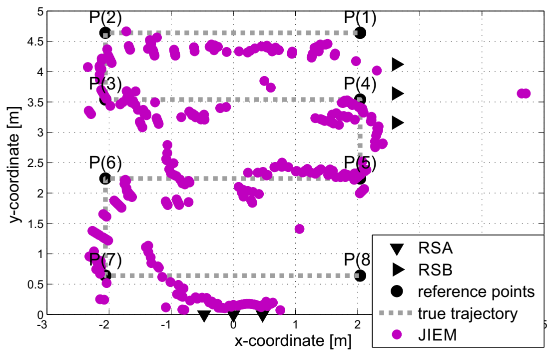

Fig. 18. Target localization by JIEM.

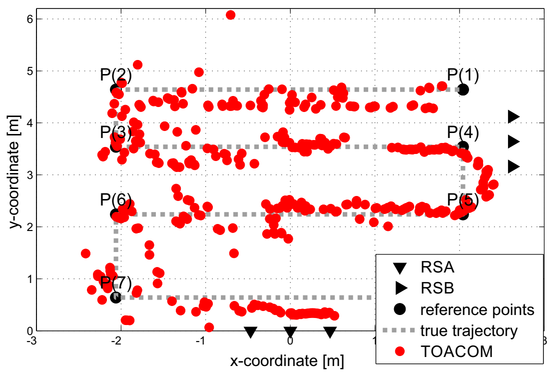

Fig. 19. Target localization by TOACOM.

The standard approach how to increase the accuracy of target position estimation obtained by the localization phase is to apply tracking filters. Because we have dealt with the

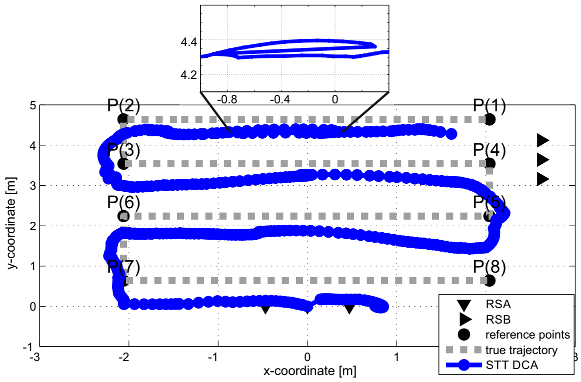

Fig. 20. Target tracking by DCA.

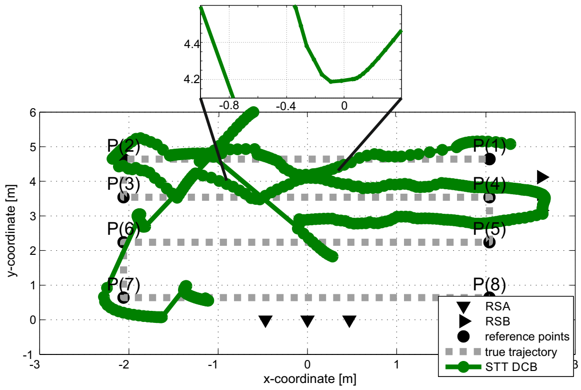

Fig. 21. Target tracking by DCB.

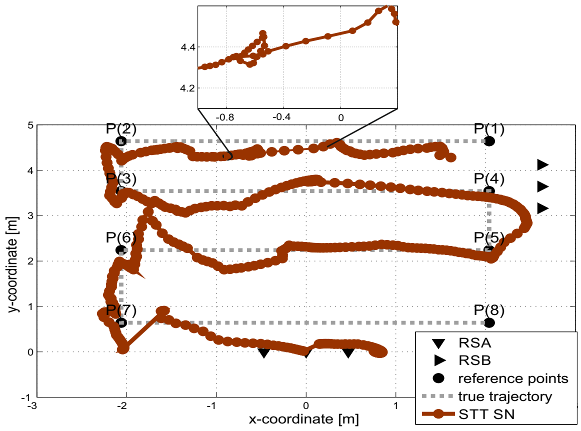

Fig. 22. Target tracking by SN.

single target scenario, we have applied STT for that purpose. This approach is based on the combination of data gating algorithm and linear Kalman filtering. The target tracks obtained by that approach applied to the target trajectories obtained by DCA (STT DCA), DCB (STT DCB), SN (STT SN), JIEM (STT JIEM) and TOACOM (STT TOACOM) are given in Figs. 20–24.

Finally, using true and estimated TOAs and target trajectory and tracks, the set of proper indicators illustrating the performance properties of the tested localization methods has been evaluated and summarized in Tab. 1. The set of indicators includes the probability of target localization (PrL), mean (ME) and root mean square (RMSE) values of the target localization errors for the estimated positions.

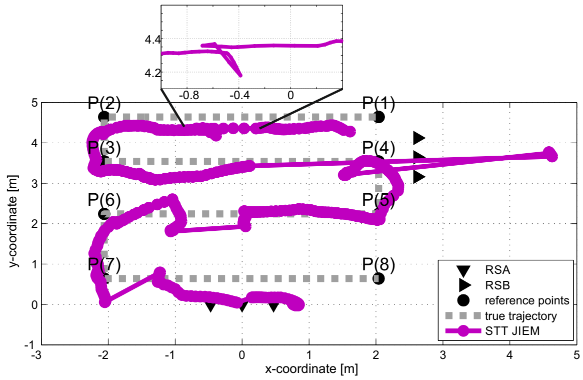

Fig. 23. Target tracking by JIEM.

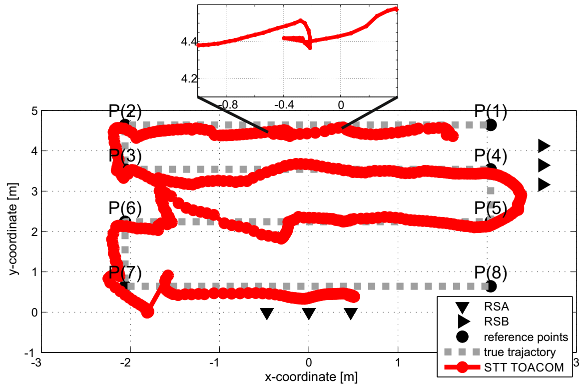

Fig. 24. Target tracking by TOACOM.

Now, after this short summary of the obtained results, we can discuss some outcomes in detail. Let us begin with a comparison of the true and estimated TOA given in Fig. 11 and 14. It can be seen in these figures that RS_A has been able to estimate TOA quite well. The probability of target localization by RS_A is about 0.78. The target trajectory and track follow the true direction of the target motion, but they are shifted along the y-axis. On the other hand, the performance of RS_B based on DCB is the worst in comparison with all the tested approaches. In this case, quite a number of TOA has been missing, and hence the probability of the target localization has only been 0.52. The estimated trajectory of the target is spread. The target track tries to follow the true direction of target motion, but it is shifted along the x-axis.

	PrL	ME [m]	RMSE [m]
DCA	0.78	0.473	0.508
DCB	0.52	0.737	0.917
SN	0.78	0.394	0.478
JIEM	0.71	0.418	0.586
TOACOM	0.82	0.375	0.495
STT DCA	0.99	0.551	0.595
STT DCB	0.95	0.99	1.259
STT SN	0.99	0.409	0.472
STT JIEM	0.99	0.529	0.856
STT TOACOM	0.99	0.379	0.452

Tab. 1. Indicators of performance of the tested localization methods.

We assume that the shifts of the trajectories and tracks estimated by RS_A and RS_B could be due to a wall effect impact [18]. Unfortunately, the impact of that effect is clearly visible in the Fig. 11 and 14, even though the wall effect compensation method of the 1st kind has been used in order to decrease the TOA estimation error [18]. Here, better results could be provided by the application of the more efficient wall effect compensation method (e.g. wall effect compensation method of the 2nd kind [18]), but at a cost of higher computational complexity. Summarizing these facts, it can be concluded that the reliability and accuracy of person localization by using a single radar system depend strongly on radar localization, and hence a robust performance of a single sensor system for complex scenarios cannot be expected.

On the other hand, cooperative localization methods such as SN, JIEM and TOACOM are capable of proving a more robust performance than a single sensor system. This is confirmed by the estimates of the target trajectories and tracks (Fig. 18–19, Fig. 23–24). A deeper comparison of the mentioned trajectories and tracks, and performance indicators (Tab. 1) has shown that the best performance is provided by SN and TOACOM. This is enhanced especially by the probabilities PL (PT) for TOACOM indicating that almost 60 % (70 %) of the estimates of the target coordinates at the localization (tracking) phase output is smaller than 0.60 m. The better performance of TOACOM compared to those provided by DC, SN and JIEM is also confirmed by the values of further indicators such as ME and RMSE of the estimated target positions (Tab. 1). In spite of the fact that the wall effect compensation method of the 1st kind has been used for the wall effect compensation also of the SN and TOACOM application, no significant shift of the estimated trajectories and tracks in the xy-plane as in the case of DCA and DCB can be identified. The values of the performance indicators for TOACOM are a bit better than those for SN. This results from the fact that TOACOM benefits from the TOA complementing algorithm whereas the SN is based only on the fusion of the target coordinates estimated by RS_A and RS_B.

5. Conclusion

In this contribution, we have dealt with through-the-wall localization and tracking of a moving person by using a two-node UWB sensor network. For that scenario, we have suggested using TOACOM for target localization. TOACOM is a cooperative method of localization based on the fusion of data retrieved from particular sensors on the TOA level using TOA combining and TOA completing algorithms.

The obtained results for single moving person localization and tracking have confirmed clearly our assumption that the cooperative methods of target localization (two-node sensor network) can provide a more robust performance and at the same time better accuracy than a single UWB sensor application. We have also shown that TOACOM can provide the better performance than the other tested cooperative and non-cooperative methods of target localization.

In this contribution, we have developed TOACOM for single target localization and a two-node sensor network only. This TOACOM version can be further modified also for a multiple target scenario and an N-node sensor network for $N > 2$. The creation of proper clusters of intersections of all the created ellipses associated with the particular targets will be the new key part of this TOACOM modification. We assume here, that one cluster will include the intersections associated with the same target. Therefore, the TOACOM presented in this paper will then be applied in successive steps to particular clusters. It is well known that in the case of multiple moving person localization, the probability of target detection can be dramatically decreased due to mutual shadowing of the targets [19]. Therefore we believe that the outlined modification of TOACOM will be able to provide further improvement of TOACOM efficiency as compared to the other methods of the target localization mentioned in this paper. The development of the outlined modification of TOACOM will be done within our subsequent research.

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References

[1] SACHS, J. *Handbook for Ultra-Wideband Short-Range Sensing: Theory, Sensors, Applications*. 1st ed., Weinheim (Germany): Wiley-VCH Verlag GmbH & Co. KGaA, 2012. ISBN: 9783527408535. DOI: 10.1002/9783527651818

[2] ZETIK, R., JOVANOSKA, S., THOMA, R. Simple method for localisation of multiple tag-free targets using UWB sensor network. In *Proceedings of the IEEE International Conference on Ultra-Wideband (ICUWB)*. Bologna (Italy), 2011, p. 268–272. DOI: 10.1109/ICUWB.2011.6058843

[3] JOVANOSKA, S., THOMA, R. Multiple target tracking by a distributed UWB sensor network based on the PHD filter. In *Proceedings of the 15th International Conference on Informational Fusion (FUSION)*. Singapore, 2012, p. 1095–1102.

[4] GULMEZOGLU, B., GULDOGAN, M. B., GEZICI, S. Multiperson tracking with a network of ultrawideband radar sensors based on Gaussian mixture PHD filters. *IEEE Sensors Journal*. April 2015, vol. 15, no. 4, p. 2227–2237. DOI: 10.1109/JSEN.2014.2372312

[5] ROVŇÁKOVÁ, J., KOCUR, D. Short range tracking of moving persons by UWB sensor network. In *Proceedings of the European Radar Conference (EuRAD)*. Manchester (UK), 2011, p. 321–324.

[6] ZHOU, Y., LAW, C. L., YONG, L. G., et al. Localization of passive target based on UWB backscattering range measurement. In *Proceedings of the IEEE International Conference on*

Ultra-Wideband (ICUWB). Vancouver (BC), 2009, p. 145–149. DOI: 10.1109/ICUWB.2009.5288835

[7] KOCUR, D., ŠVECOVÁ, M., ROVŇÁKOVÁ, J. Through-the-wall localization of a moving target by two independent ultra wideband (UWB) radar systems. *Sensors*. Basel (Switzerland), 2013, vol. 13, no. 9, p. 11969–11997. DOI: 10.3390/s130911969

[8] ZHOU, Y., LAW, C. L., GUAN, Y. L., et al. Indoor elliptical localization based on asynchronous UWB range measurement. In *IEEE Transactions on Instrumentation and Measurement*. Jan. 2011, vol. 60, no. 1, p. 248–257. DOI: 10.1109/TIM.2010.2049185

[9] ROVŇÁKOVÁ, J., KOCUR, D. Data fusion from UWB radar network: Preliminary experimental results. In *Proceedings of the 21st International Conference Radioelektronika (RADIOELEKTRONIKA)*. Brno (CZ), 2011, p. 1–4. DOI: 10.1109/RADIOELEK.2011.5936439

[10] RAOL, J. R. *Multi-Sensor Data Fusion with MATLAB*. 1st ed.: CRC Press, Taylor & Francis Group, 2009. ISBN: 9781439800034

[11] ŠVECOVÁ, M., KOCUR, D. TOACOM: A new cooperative method of target localization by UWB radar systems. In *Proceedings of the IEEE 9th International Symposium on Intelligent Signal Processing (WISP)*. Siena (Italy), 2015, p. 1–6. DOI: 10.1109/WISP.2015.7139158

[12] ŠVECOVÁ, M., KOCUR, D., URAMOVÁ, N., et al. TOA complementing method for target localization by UWB radar systems. In *Proceedings of the International Radar Symposium (IRS)*. Dresden (Germany), 2015, p. 949–954. DOI: 10.1109/IRS.2015.7226265

[13] RUDAS, I. J., FODOR, J., KACPRZYK, J. *Towards Intelligent Engineering and Information Technology*, (Through Wall Tracking of Moving Targets by M-Sequence UWB Radar). 1st ed., Berlin (Germany): Springer, 2009. ISBN: 978-3-642-03736-8. DOI: 10.1007/978-3-642-03737-5

[14] DARDARI, D., CONTI, A., FERNER, U., et al. Ranging with ultrawide bandwidth signals in multipath environments. In *Proceedings of the IEEE*. Feb. 2009, vol. 97, no. 2, p. 404–426. DOI: 10.1109/JPROC.2008.2008846

[15] DUTTA, P. K., ARORA, A. K., BIBYK, S. B. Towards radar-enabled sensor networks. In *Proceedings of the Fifth International Conference on Information Processing in Sensor Networks (IPSN 2006)*. Nashville, USA, 2006, p. 467–474. DOI: 10.1109/IPSN.2006.243915

[16] ROVŇÁKOVÁ, J. , KOCUR, D. TOA estimation and data association for through-wall tracking of moving targets. *EURASIP Journal on Wireless Communications and Networking*. vol. 2010, article ID 420767. DOI: 10.1155/2010/420767

[17] EBERLY, D. *Intersection of Ellipses*. Geometric Tools, LLC, 2000, 20 pages. [Online] Available at: http://www.geometrictools.com

[18] ROVŇÁKOVÁ,J. , KOCUR, D. Compensation of wall effect for through wall tracking of moving targets. *Radioengineering*. June 2009, vol. 13, no. 2, p. 189–195. ISSN: 1805-9600

[19] FORTES, J., KOCUR, D. Solutions of mutual shadowing effect between people tracked by UWB radar. In *Proceedings of the IEEE International Conference on Microwaves, Communications, Antennas and Electronics Systems (COMCAS)*. Tel Aviv (Israel), Oct. 2013, p. 1–5. DOI: 10.1109/COMCAS.2013.6685300

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