UWB Radar Signal Processing for Positioning of Persons Changing Their Motion Activity

Jana Rovňáková, Dušan Kocur

Department of Electronics and Multimadia Communications,
Faculty of Electrical Engineering and Informatics, Technical University of Košice,
Park Komenského 13, 041 20 Košice, Slovak Republic
jana.rovnakova@tuke.sk, dusan.kocur@tuke.sk

Abstract: In many applications of ultra-wideband (UWB) radar a character of target motion is a priori not known and naturally can differ within a group of multiple targets. Usually a signal processing aimed at the positioning of only moving persons or only static persons leads to a loss of information. To solve this task, the utilization of combined processing based on detection of non-stationary signal components in the time domain and human respiratory motions in the frequency domain is proposed in this paper. The results of such processing are more reliable and robust with respect to motion activity of all monitored persons, which is demonstrated by processing of measured UWB radar signals.

Keywords: Moving targets; positioning; signal processing; static targets; UWB radar

1 Introduction

The positioning of persons by an ultra-wideband (UWB) radar has a vast number of practical applications. The examples include the tracking of people in dangerous environments (for the purposes of fire fighters and/or policemen), through rubble localization following an emergency (e.g. an explosion or earthquake) or interior monitoring (for unauthorized intruders, or for aged people, helping to ensure their health and safety). In such applications, the UWB radars have advantages over other systems due to their high spatial resolution, the usage of harmless radio waves and the ability of their stimulation signals to penetrate through different materials or obstacles [28].

Radar signal processing for the purpose of person positioning differs with respect to the target motion activity. In the case of living human beings, we can basically distinguish between moving persons whose limbs (legs, hands, head, trunk) are in motion and static persons whose limbs are motionless, but inner organs (lung, heart) still cause geometric alterations of the human body shape discernible by a high resolution UWB radar. The positioning of moving targets is usually based on monitoring of non-stationary signal components in the time domain. The target positions are then calculated analytically by localization techniques [16], [5], [12], or targets are seen as radar blobs in gradually generated radar images (radar imaging techniques, [14], [8], [6]). Commonly, the positioning is followed by a complex tracking system enabling the monitoring of changing target positions during observation time [2], [26], [17]. In the positioning of static persons, target detection is very challenging by itself. It is based on the periodical nature of the breathing or heartbeat that makes it possible to distinguish it from noise and clutter components. In the literature, most of the radar signal processing techniques are aimed at searching for the body variations caused by respiratory motions [15], [22], [11], but few of them are oriented also to cardiac-induced radar signatures [27], [3].

In our previous works [18], [9], a complete signal processing procedure for through wall tracking of multiple moving targets was introduced and tested on radar data acquired by a pseudo-noise UWB radar equipped with one transmitting and two receiving antennas [30]. The processing results have proved the ability to track a single person moving in a complex environment, such as inside fully furnished rooms, behind thick walls with high relative permittivity or even behind more walls. Successful tracking of multiple moving targets was achieved in the cases when persons did not shadow each other [10]. If during measurement an effect of mutual shadowing occurred, only a person moving nearby the radar antennas could be tracked (an effective solution is e.g. in application of UWB sensor network [19]). Experimental measurements with static persons were also realized. By using the same procedure, a motionless person breathing behind a wall could be revealed as well, but only when nobody else was moving inside the monitored area. A decreased reliability of processing results was also obtained for persons changing their motion activity, e.g. when a walking person stops for a longer time and becomes a part of the background.

As in many rescue, surveillance or security operations a character of target motion is a priori not known and naturally can differ within a group of multiple targets, an application of the procedure for positioning of only moving persons or only static persons can lead to a loss of information. Therefore, we suggest the utilization of a proper combination of both procedures. This idea is simple, but to our best knowledge its results have not yet been presented in the UWB radar literature. For that purpose, the description of the combined signal processing procedure for positioning of persons with unknown or changing motion activity represents the core of this paper. It is introduced in Section 2. The performance of the proposed procedure is demonstrated by the processing of UWB radar signals acquired for the typical scenario of moving and static target mix. It is outlined and analyzed in Section 3. Finally, some advantages and drawbacks of the introduced radar signal processing are discussed in the conclusions.

2 UWB Radar Signal Processing

In what follows, the effective procedures for the positioning of moving persons and static persons by means of UWB radar will be firstly separately described. Within them, the significance of the particular signal processing phases together with the specific methods providing stable, good and robust performance for the considered application will be outlined. Finally, a fusion principle of both procedures resulting in a combined signal processing procedure for the positioning of persons with unknown or changing motion activity will be introduced.

The radar signal processing described in this section was originally designed for signals provided by the pseudo-noise UWB radar system using the maximum-length-binary-sequence (M-sequence) as the stimulus signal [23]. As the signals acquired by the M-sequence UWB radar have a form of the impulse responses of the environment through which the stimulus signals are propagating, the same processing procedures can also be directly applied for signals obtained by means of some other kinds of UWB radars, e.g. impulse UWB radars.

2.1 Procedure for Positioning of Moving Persons

The chosen signal processing procedure [18] consists of phases responsible for the elimination of stationary clutter (methods of background subtraction), the decision about the target presence or absence (methods of detection), the estimation and association of distances from the same target (methods of time-of-arrival (TOA) estimation), the estimation of target positions (methods of localization) and finally the monitoring of target motion over time (methods of tracking). If target detection and tracking by UWB radar is realized through the walls with known parameters (thickness and relative permittivity of the wall), the phase of wall effect compensation is added between the phases of TOA estimation and target localization. The detailed description of the particular phases of radar signal processing together with the corresponding mathematical formulas is provided in [18]. The phase significance and recommended methods of signal processing are summarized below.

2.1.1 Background Subtraction

Raw radar signals can be interpreted as a set of impulse responses of surrounding through which the signals emitted by the radar were propagated. The first task of radar signal processing is to improve the signal to noise ratio. This is done by background subtraction, which especially rejects the stationary and correlated clutter, such as antenna coupling, impedance mismatch response and ambient static clutter, and allows the response of moving targets to be detected. Exponential averaging was chosen from a variety of background subtraction methods because of its robust performance and low complexity [29].

2.1.2 Target Detection

Detection represents a class of methods that on the basis of a statistical decision theory determine whether a target is absent or present in the examined radar signals. Between detectors able to provide good and robust results in the case of multi-target through wall detection by UWB radar, a constant false alarm rate (CFAR) detector can be assigned. It is based on the Neymann-Person optimum criterion providing the maximum probability of detection for a given false alarm rate. In the considered radar signal processing, the CFAR detector that assumes a Gaussian clutter model has been applied [4].

2.1.3 TOA Estimation

Binary data representing the detector output form a noticeable trace of the moving targets. It represents the time of arrival (TOA) of the electromagnetic waves reflected by the target for the particular instants of the observation time. As the range resolution of UWB radars is considerably high with regard to the physical dimensions of the targets to be detected, the targets are usually represented by more TOA values in the detector output. In order to simplify the target localization, such distributed targets are replaced by simple targets; i.e. the target position in every observation time instant is given by only one TOA. This phase of radar signal processing is referred to as the TOA estimation. For its realization, a novel algorithm entitled TOA association has been proposed in [20]. It further enables the combining of the TOAs estimated from both receiving antennas into couples from which the positions of the potential true targets can be computed during localization phase. This part of algorithm represents a data-association phase and is responsible for the de-ghosting task solution.

2.1.4 Wall Effect Compensation

The propagation of electromagnetic waves through a wall results in a delay time of signals reflected by targets moving behind the wall. This means that the TOA estimated by the previous phase of radar signal processing are time shifted because of the wall presence. Their correction can be achieved by the subtraction of the mentioned delay time, whereas its estimation is the task of the wall effect compensation phase. The method referred to as the target trace correction of the 2nd kind [21] provides promising results in this area. To use this method, the wall parameters, such as the permittivity, permeability and thickness of the wall, must be known in advance, or they can be estimated very effectively with the same M-sequence UWB radar by using the method described in [1].

2.1.5 Target Localization

The aim of the localization phase is to determine the target coordinates in the defined coordinate systems whereby the target locations estimated in consecutive time instants create the target trajectory. As the input of this radar signal processing phase, the estimated and corrected TOA couples are used. Because the considered UWB radar system consists of one transmitting and two receiving antennas, only the non-iterative direct method of localization can be employed. In this case, the target coordinates are simply calculated by trilateration methods as intersections of two ellipses formed on the basis of the estimated TOA couples and known coordinates of the transmitting and receiving antennas [16].

2.1.6 Target Tracking

The particular locations of the targets are estimated with certain random error usually described by its probability distribution function. Taking into account this model of target position estimation, the target trajectory can be further processed via tracking algorithms. They provide a new estimation of the target location based on the previous positions of the target. Usually, the tracking results in a decrease in the target trajectory error and includes trajectory smoothing. In the case of multiple targets, track filtering must also deal with track maintenance and with the problem of determining which measurements to associate with which targets being tracked. From a wide spectrum of tracking algorithms, the multiple target tracking (MTT) system using a linear Kalman filtering has been chosen as the method to enclose the complex procedure of the UWB radar signal processing applied for through wall tracking of the multiple moving targets [7].

2.2 Procedure for Positioning of Static Persons

The basis of the signal processing procedure for static persons positioning was originally introduced in [24]. It is quite close to the procedure described in Section 2.1 except that body movements are markedly restricted. Therefore, the signal to clutter ratio will further decrease and the only feature to distinguish the persons from static objects is their small movement due to breathing. There are few features that serve as a basis for methods to enhance the response from a breathing person:

- Human breathing can be considered as periodical motion over a certain interval of time. The frequency of breathing can change slowly with time, but it should always be within a frequency band of about 0.2-0.5 Hz.
- The geometrical variations of the thorax caused by breathing are usually quite a bit less than the range resolution of the radar.

- The echo due to a breathing person is extremely weak, all the more so when the static person is behind an obstacle (e.g. rubble, wall, snow) that strongly attenuates the sounding waves.
- The distance from antennas to the breathing persons does not change during the measurement.

Taking into account these features, the phase of background subtraction is supplemented by a breathing enhancement and followed by transformation of the radar signals into the frequency domain. Consequently, the estimation of power spectral density is used for the breathing detection task. The remaining processing phases, i.e. the TOA estimation, wall effect compensation and target localization, are the same as in the procedure for the positioning of moving persons, but they are applied now on an essentially reduced data set, the size of which corresponds to the number of detected static persons.

It is useful to mention that the UWB radar device applied for the positioning of static persons has a great influence on the success of breathing detection. It can be explained as follows. As the detection of small movements is based on observing the variations of steep signal flanks, the noise should be as small as possible there. It is known that the jitter provokes additional noise on the signal flanks and, therefore, the short time stability of the radar device is of major importance for such applications (the considered M-sequence UWB radar behaves excellently with respect to this point) [25].

2.2.1 Background Subtraction and Breathing Enhancement

The method of exponential averaging recommended for background subtraction in Section 2.1.1 can be used to advantage also in this case [29]. However, the weighing factor controlling the amount of averaging in the background estimation should be set now in such a way as to smooth out high frequency variations and reveal long term trends in the background estimation (i.e. it provides low-pass narrow band filtering). It is done by choosing a longer fraction of the previous estimate of impulse response with subtracted background and a smaller fraction of the actual measured impulse response.

In order to further improve the signal-to-noise ratio of a static target echo, the impulse response with subtracted background is applied to a so-called range filter before the target detection [13]. The range filter helps to improve the signal-to-noise by reducing the clutter residue and noise resulting from the de-correlation of any radio frequency interference due to pseudo-random code transmitted by the radar.

Additionally, breathing as a narrow band process can also be enhanced by the use of low-pass filtering. Here, a low-pass filtering with a cut-off frequency higher than the highest frequency of breathing (e.g. higher than 1 Hz) can be applied along the observation time axis for each propagation time instant to suppress high-frequency noise [24].

2.2.2 Estimation of Power Spectral Density

To extract the breathing rate, a horizontal Fast Fourier Transform (FFT, along the time observation axis for each propagation time instant) is applied on the radar signals after background subtraction and breathing enhancement. The frequency of breathing can change with the observation time. However, the bandwidth of breathing from one person under observation with radar is likely to be considerably less than a priory bandwidth as determined for the whole range of respiratory activity for all individuals. Thus, the total energy contained within the frequency window can serve as an indicator as to whether breathing is present. Finally, the FFT-based Welch periodogram is used for estimating the power spectral density (PSD) of the radar signals in the direction of the observation time [24].

2.2.3 Target Detection

For the detection of static persons, the CFAR detector mentioned in Section 2.1.2 or a simpler threshold detector can be advantageously used [4]. The detector is applied on the data set represented by the estimated PSD. If a breathing person is present in the monitored area, the detector binary output should gain values “1” between frequencies 0.2-0.5 Hz corresponding to the expected breathing rate of human being. If more static persons are situated inside the area, values “1” should occur in more propagation time instants. In order to later estimate for every detected target only one spatial position, the frequency responses from interval 0.2-0.5 Hz are simply summed to one frequency response. Such a response represents then the input to the TOA estimation phase.

2.2.4 TOA Estimation

The TOA estimation phase is realized via the TOA association method (Section 2.1.3) [20]. The estimated TOA for every detected static target represents a round trip time between the transmitting antenna – the target – and the receiving antenna. The TOA multiplied by the light propagation velocity gives the distance between them.

2.2.5 Wall Effect Compensation

Instead of the target trace correction of the 2nd kind outlined in Section 2.1.4, the simpler target trace correction of the 1st kind can be used. The approximate delay time is calculated from the elementary equation given in [21].

2.2.6 Target Localization

If both receiving antennas detect the presence of a breathing person, its position will be calculated as the intersection of the ellipses given by the couple of the TOAs associated during the TOA estimation phase and corrected during the wall effect compensation phase (as long as the wall parameters are known) [16]. If only one receiving antenna confirms a target presence, at least the incomplete positioning of the static person based on the distance from this antenna can be used. The possible locations of the person are then given by the half-ellipse situated inside a monitored area.

2.3 Combined Procedure for Positioning of Persons with Unknown or Changing Motion Activity

The combined procedure exploits the parallel processing of measured radar signals via the procedure for the positioning of moving persons (PPMP) and the procedure for the positioning of static persons (PPSP) described in the previous sections. The procedure flowchart is depicted in Figure 1. It can be seen that PPMP runs consecutively as soon as the impulse responses (IRs) are acquired from the two receiving channels. This results from the fact that the low complex methods of PPMP are always applied only on the actual couple of the IRs (IR from receiving antenna Rx1, IR from receiving antenna Rx2). On the other hand, PPSP requires for proper functioning a larger set of IRs to be able to distinguish periodical breathing from noise and clutter components.

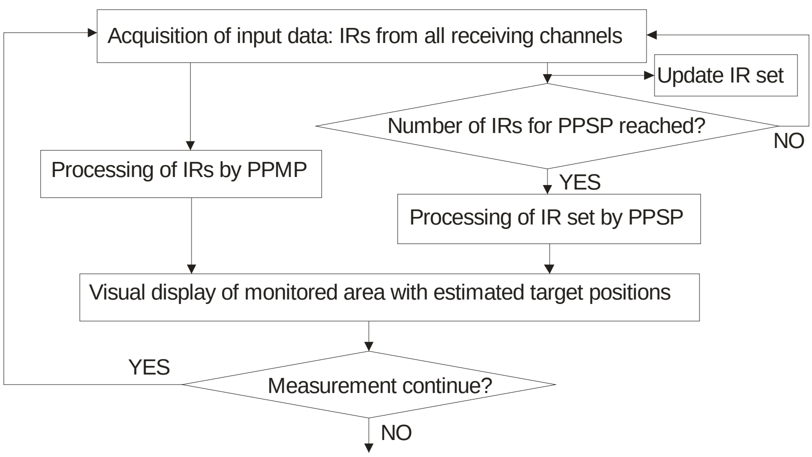


Figure 1
The flowchart of the combined procedure for positioning of persons with unknown or changing motion activity

The processing of the IR set in the frequency domain is also more time consuming. Therefore, the information about static person positions comes in at slower time intervals. Subsequently, the outputs of PPSP are depicted on the same visual display of the monitored area as the PPMP outputs (Figure 1). Although the information about static person positions are delayed compared to the true target positions, they make the radar processing results more reliable and robust with respect to the motion activity of all monitored persons.

3 Experimental Results

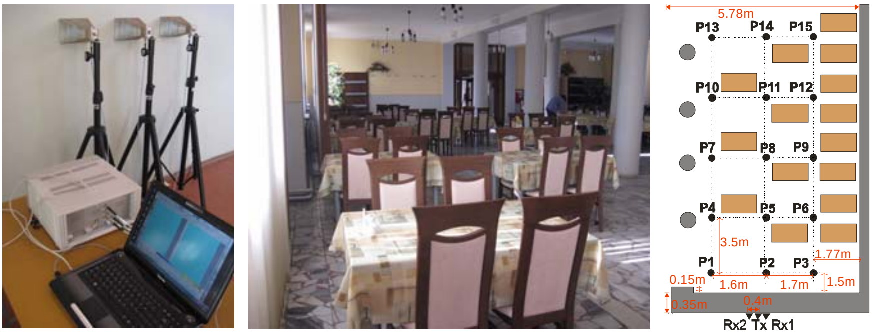
The performance of the proposed combined PPMP and PPSP procedure is demonstrated by the processing of UWB radar signals acquired for a measurement scenario with one static person and one moving person changing his motion activity during measurement. In the next sections, the applied UWB radar device, chosen scenario and obtained processing outputs are described in detail.

3.1 UWB Radar Device

An experimental version of the M-sequence UWB radar system equipped with one transmitting and two receiving horn antennas was utilized for the measurement (Figure 2(a)) [23]. The system clock frequency of the radar device is about 4.5 GHz, which results in an operational bandwidth of about DC-2.25 GHz. The M-sequence order emitted by the radar is 9; i.e. the impulse response covers 511 samples regularly spread over 114 ns. This corresponds to an observation window of 114 ns leading to an unambiguous range of about 17 m. The measurement speed reaches approximately 13.5 impulse responses per second.

3.2 Measurement Scenario

A part of a school dining room of a size approximately 6 m x 17 m was chosen for the monitored area. As can be seen from photo in Figure 2(b), the room was furnished with high wooden chairs and tables with metallic legs. Within the analyzed scenario, two persons, labeled as target A and target B, were present inside the monitored area. Target A was at first walking around tables according a rectangular trajectory given by the reference positions P1-P13-P15-P3-P1 depicted in the measurement scheme in Figure 2(c). Afterwards, the person remained at position P1 until the end of measurement.



(a) (b) (c)

Figure 2
Measurement setup: (a) M-sequence UWB radar located behind the wall, (b) interior of the monitored area, (c) scenario scheme with the positions of radar antennas and the reference positions

Target B was sitting motionless during whole measurement (2 min 36 s) at position P5.

The M-sequence UWB radar system (Figure 2(a)) was located behind a 0.35 m-thick brick wall, depicted in Figure 2(b). All antennas were placed along a line with the transmitting antenna Tx in the middle of Rx1 and Rx2, with the distances between adjacent antennas set at 0.4 m (Figure 2(c)). There was no separation between radar antennas and the wall (Figure 2(a)).

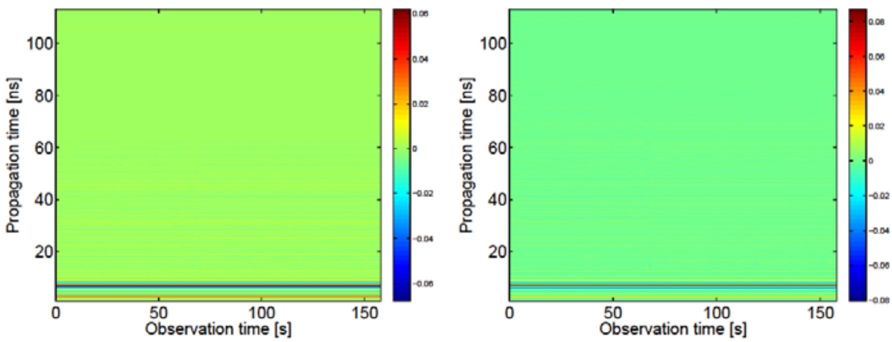
3.3 Signal Processing Outputs

As was explained in Section 2.3, the combined procedure exploits parallel processing of the measured radar signals by PPMP and PPSP. Therefore, in what follows, the outputs from every processing phase are shown at first for PPMP, then subsequently for PPSP, and finally for the combined procedure.

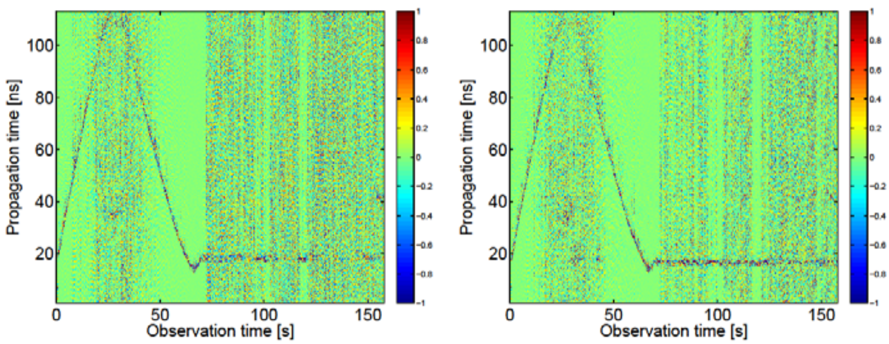
The raw radar signals corresponding to the measurement scenario and obtained by the receiving channels Rx1 are Rx2 are depicted in Figure 3(a) and 3(b), respectively. They have the form of a radargram, i.e. a two dimensional picture in which the vertical axis is related to the propagation time of the impulse response and the horizontal axis is related to the observation time. In these radargrams, only a cross-talk signal and the reflections of the emitted electromagnetic wave from the wall can be viewed, as they are very strong in comparison with the weak signals scattered by the persons.

This situation is changed after the phase of background subtraction, when the primary trace of target A has arisen in the radargrams (Figure 3(c)-3(d)). The trace shape corresponds with the target motion; i.e. at first, the person is retreating from the radar antennas, then approaching them and finally remaining at approximately the same distance from the radar. Target A was not totally motionless while standing (movements with hands and head, turning about) and therefore the primary target trace is partially noticeable also in the second half of radargrams depicted in Figure 3(c)-3(d). The presence of target B is not observable from these figures because this was evaluated as a static background and subtracted from the data.

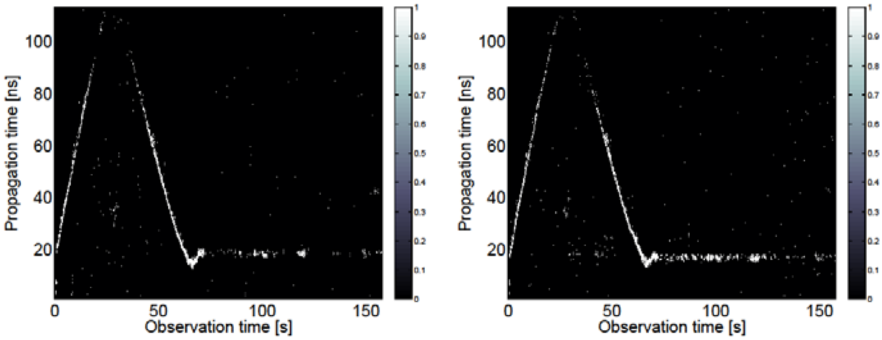
The CFAR detector outputs are shown in Figure 3(e)-3(f). The false alarm rate was adjusted to higher values in order to detect also targets from noisy signals. This results in a greater probability of target detection but also in a higher number of the false alarms (randomly distributed points in Figure 3(e)-3(f)). By comparing Figure 3(e) and Figure 3(f), it can be seen that channel Rx1 has received weaker reflections from the standing person. This is caused by the fact that the standing person position (the reference position P1) was located nearer to antenna Rx2.



(a) (b)



(c) (d)



(e) (f)

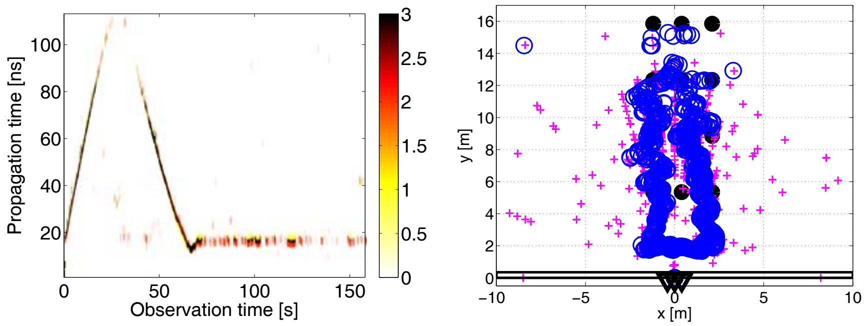
Figure 3

Signal processing results from PPMP: Part I. Radargram depictive raw radar signals: (a) channel Rx1, (b) channel Rx2; Radargram depictive signals with subtracted background: (c) channel Rx1, (d) channel Rx2; Radargram depictive detector outputs: (e) channel Rx1, (f) channel Rx2

A similarity of radargrams obtained by both receiving channels can be seen in Figure 4(a), where the TOA couples belonging to the same target are highlighted in black. This similarity results from the symmetric and small distance between the antennas. In Figure 4(a), the TOA estimated from channels Rx1 and Rx2 are outlined in yellow and red, respectively, and both are artificially widened for better visibility. Their conjunction implies that both receiving channels captured the relevant reflections from the same target. Not associated TOA are considered to be false alarms. In this way ghost generation is avoided.

As the relative permittivity of the wall was not measured for this scenario, the wall effect compensation phase has been omitted from the processing. The outputs of the localization phase are depicted in Figure 4(b) with magenta crosses. They were computed based on the TOA couples from Figure 4(a). Because at further distances the reflections of the moving target were captured only alternately by the receiving channels, the target locations could not be estimated in these observation time instants (around 20-40 ns in Figure 4(a)). Similarly, the positions of the standing person were computed in only a few observation time instants, when the person moved his hands or turned about.

The final result from PPMP is illustrated in Figure 4(b) with circles. The circles create a target track estimated by the MTT system. In comparison with the target positions estimated in the localization phase ("+"), the track is more smoothed and complemented about missing positions, if it was possible. The estimated track corresponds well with the true rectangular trajectory of moving target A except for at the furthest areas, in which the reflection from the person was very weak. While standing at the same position, target A was detected too, but only in a few observation time instants (left down corner of the rectangular track in Figure 4(b)). The sitting target B was not detected at all by PPMP.



(a) (b)

Figure 4

Signal processing results from PPMP: Part II. (a) Radargram depictive artificially widened TOA estimated from Rx1 (values 1) and Rx2 (values 2) , values 3 indicate associated TOA couples; (b) Monitored area depictive the positions of target A estimated in the localization phase (crosses) and in the tracking phase (circles), full circles – reference positions, triangles – radar antennas, lines - wall

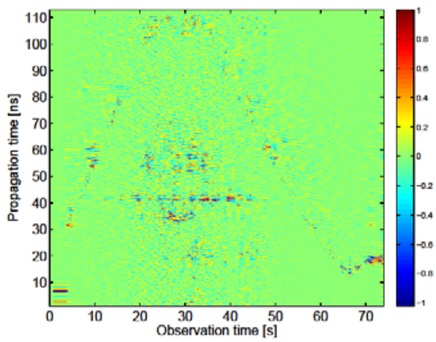
As was mentioned in Section 2.3, to function properly, PPSP requires a larger set of IRs in order to be able to distinguish periodical breathing from noise and clutter components. The size of the IR set for PPSP processing was set to approximately 1000 IRs on the basis of experimental testing. As the measurement rate of the used M-sequence UWB radar is around 13.5 IRs per second, such amount was reached roughly after 75 s. The signal processing outputs of PPSP from the first set of IR, i.e. from the observation time interval 1 s - 75 s, are shown in Figure 5, and from the second set of IR, i.e. from the observation time interval 75 s - 150 s, are shown in Figure 6.

The raw radar signals are at first processed by the phase of background subtraction and breathing enhancement (Figure 5(a)-(b)). In the obtained radargrams, the components pertaining to the moving target A are suppressed, and in contrast, the components pertaining to the motionless target B are enhanced. The primary trace of target B has the shape of a discontinuous line occurring around the propagation time 40 ns.

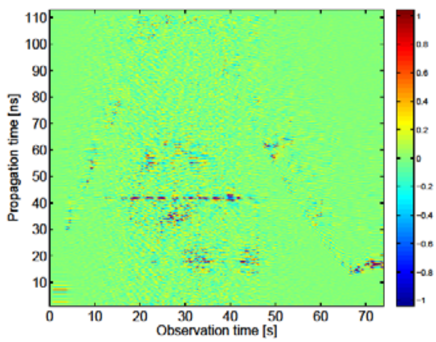
The estimation of PSD for both channels is depicted in Figure 5(c)-(d). It serves for the extracting of the breathing rate. As can be observed from these figures, a few values are highlighted in the frequency window 0.2-0.5 Hz, which corresponds to the typical breathing rate of human beings.

The application of the threshold detector correctly designates a presence of one static person (Figure 5(e)-(f)). His breathing rate reached values of around 0.25-0.3 Hz.

The signal processing outputs from the phase of TOA estimation and localization are given in Figures 5(g) and (h), respectively. The summation of the frequency responses from interval 0.2-0.5 Hz to one frequency response allows us to estimate only one couple of the TOA (Figure 5(g)) and one target location (Figure 5(h)) for every detected person. From the first IR set, the PPSP correctly detected and localized the sitting person. As could be expected, the moving target A was not detected by PPSP.



(a)



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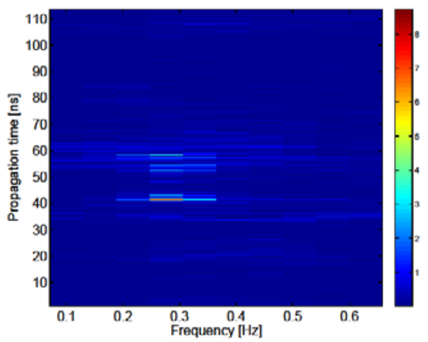

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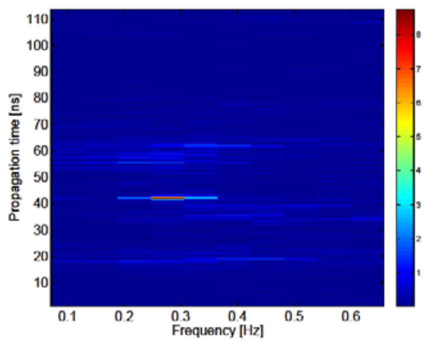

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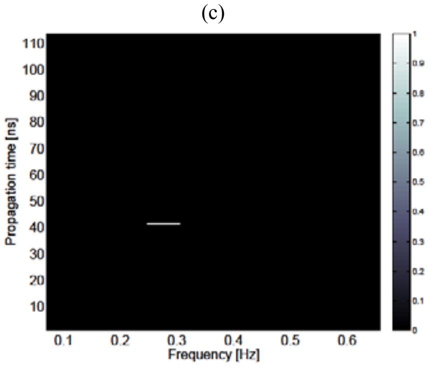
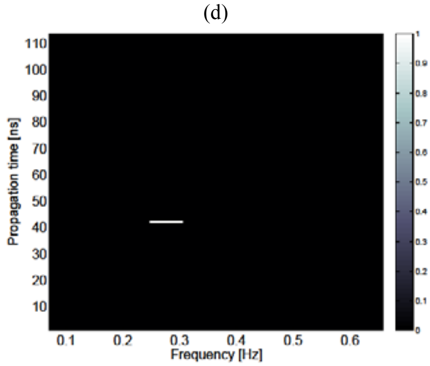


(e)



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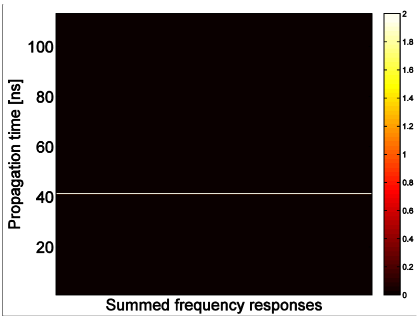
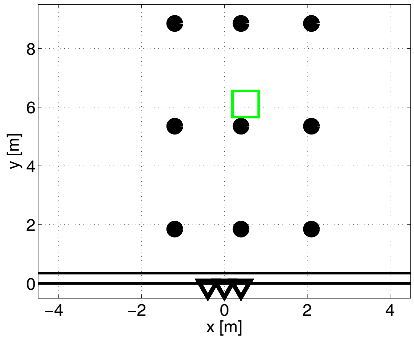


(g)

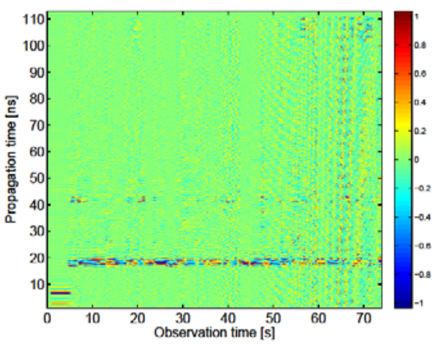


(h)

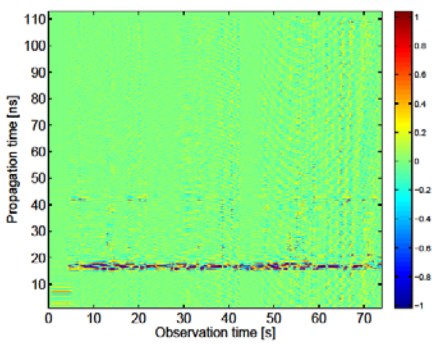
Figure 5

Signal processing results from PPSP: Part I. Signals with subtracted background and enhanced breathing: (a) channel Rx1, (b) channel Rx2; Estimated PSD: (c) channel Rx1, (d) channel Rx2; Detector output: (e) channel Rx1, (f) channel Rx2; (g) Estimated TOA couple (the values from both channels are very close each other); (h) Estimated position of a static target (square), circles – reference positions, triangles – radar antennas, lines - wall

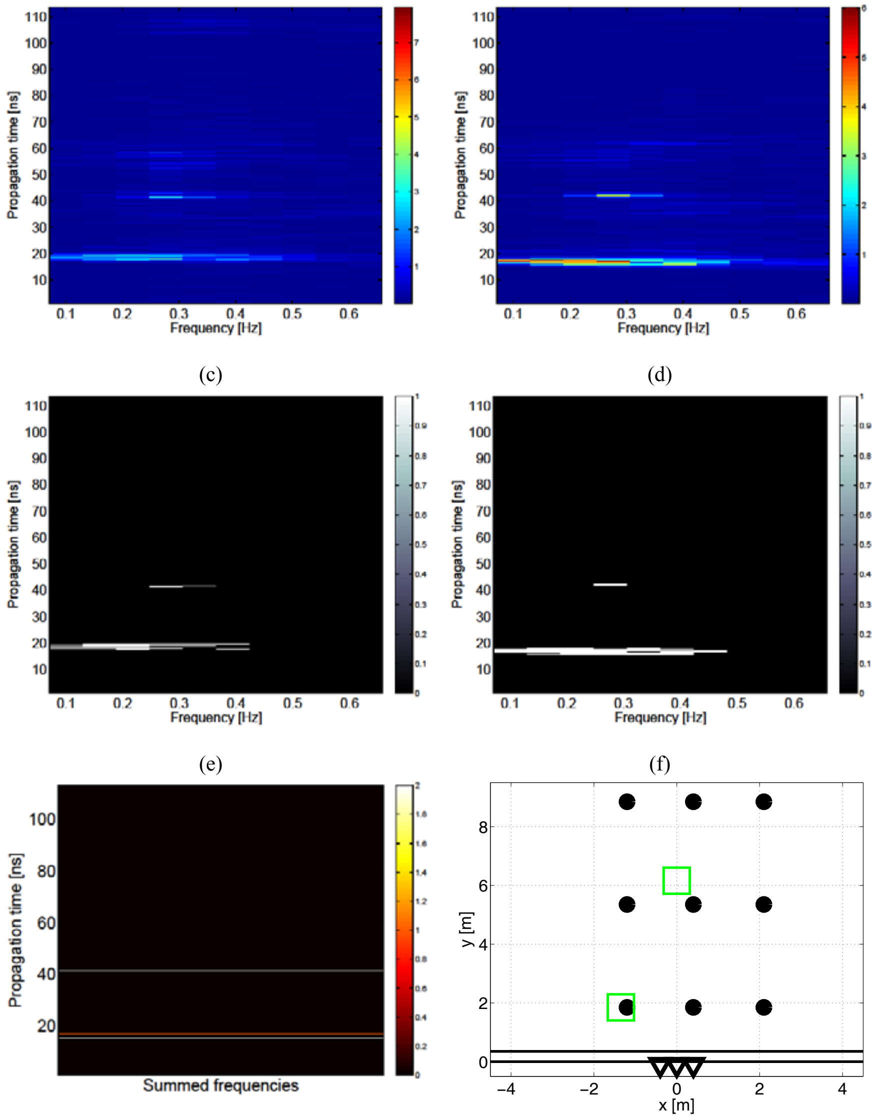
After acquiring the second IR set of 1000 IRs from the observation time interval 75 s - 150 s, the same signal processing steps were realized. The results are depicted in Figure 6. The PPSP detected and localized the standing target A in addition to the sitting target B (Figure 6(e)-(h)). The breathing rate of target A includes more components due to the motion activity of this person (Figure 6(c)-(f)). It can be explained by the fact that it took some time to slow down breathing after walking and the person was also not totally motionless at his position. During the TOA estimation phase, two couples of TOA were associated (Figure 6(g)), which resulted in the computation of two final target locations (Figure 6(h)). As can be seen from this figure, the estimated positions correspond very well with the true target positions.



(a)



(b)



(c) (d)

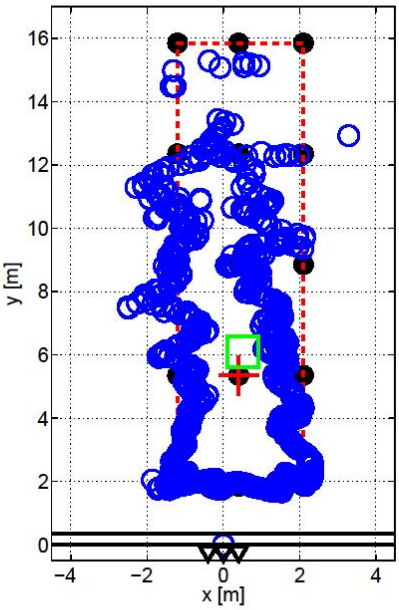
(e) (f)

(g) (h)

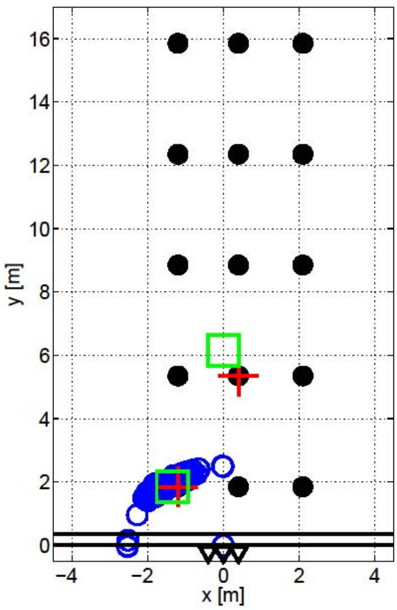
Figure 6

Signal processing results from PPSP: Part II. Signals with subtracted background and enhanced breathing: (a) channel Rx1, (b) channel Rx2; Estimated PSD: (c) channel Rx1, (d) channel Rx2; Detector output: (e) channel Rx1, (f) channel Rx2; (g) Estimated TOA couples; (h) Estimated positions of static targets (squares), circles – reference positions P1-P9, triangles – radar antennas, lines - wall

The final signal processing outputs from the combined procedure are obtained by fusion of results from PPMP and PPSP (Figure 7). During the first part of the measurement scenario, PPMP correctly tracks the moving person but only thanks to processing by PPSP can the motionless sitting person be detected and localized (Figure 7(a)). The imprecision between true and estimated target positions is caused by the complexity of the real environment (mainly the presence of the wall and furniture and the shadowing of target A by target B). The results for the second part of the measurement scenario are illustrated in Figure 7(b). The PPSP accurately detected and localized both static persons, but such output was available only after acquiring and processing the required IR set. Till then, PPMP was providing information about the negligible movements of standing person.



(a)



(b)

Figure 7
Final signal processing results from combined procedure: obtained for (a) the first part of the measurement scenario (observation time interval 1 s - 75 s), (b) the second part of the measurement scenario (observation time interval 75 s - 156 s); Red crosses / dashed line – true target position / trajectory, blue circles – target positions estimated by PPMP, green square – target positions estimated by PPSP, black full circles – reference positions, black triangles – radar antennas, black lines - wall

Conclusions

The presented experimental results, as well as the results obtained by the processing of similar measurement scenarios, demonstrate the ability of the proposed combined processing procedure to obtain from the same measured set of UWB radar signals more extensive and more precise information about the positions of monitored persons located behind an obstacle. This advantage is reached at the expense of higher computational complexity and time consumption. The optimalization of software and hardware can reduce this disadvantage. From the point of view of software, the procedure for the positioning of static persons should be especially improved. The current version utilizes very simple methods which can be replaced by more advanced approaches known from the latest research works. From the point of view of hardware, an adequate increase in the measurement rate can be very conducive for decreasing the delay in processing the results.

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