Multiple People Detection & Localization with Multistatic UWB Radar in Vehicle Cabin

Fioranelli, Francesco; Rufas, Elisabet; Yarovoy, Alexander

DOI
10.1109/iWAT57102.2024.10535859

Publication date
2024

Document Version
Final published version

Published in
2024 IEEE International Workshop on Antenna Technology, iWAT 2024

Multiple People Detection & Localization with Multistatic UWB Radar in Vehicle Cabin

Francesco Fioranelli
Microwave Sensing Signals & Systems
Dept. Microelectronics, TU Delft
Delft, the Netherlands
f.fioranelli@tudelft.nl

Elisabet Rufas
Microwave Sensing Signals & Systems
Dept. Microelectronics, TU Delft
Delft, the Netherlands
e.rufastalamas@studelft.tudelft.nl

Alexander Yarovoy
Microwave Sensing Signals & Systems
Dept. Microelectronics, TU Delft
Delft, the Netherlands
a.yarovoy@tudelft.nl

2024 IEEE International Workshop on Antenna Technology (iWAT) | 979-8-3503-1475-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/iWAT57102.2024.10535859

***Abstract*—The problem of detection and localization of multiple people using a network of Ultra-Wide Band (UWB) radar nodes in the cabin of a vehicle is addressed in this paper. Specifically, an algorithm for decentralized vital signs detection is proposed, based on the analysis of a novel model for radar signatures of vital signs. Additionally, a centralized association processing block is used to fuse the detections from all radars in the network using a dedicated cost-matrix computation. The performance of the proposed processing pipeline is tested experimentally with a multistatic radar network, and a simulation framework is also developed to evaluate the performance in alternative topologies of the radar network beyond the experiments. It is shown that the detection and localization of humans within the car environment is possible with the proposed processing pipeline, with localization Root Mean Square Error (RMSE) of 16cm for both single and double target scenarios. Moreover, the distribution of multiple radars and the introduction of bistatic geometries enhance the detection and localization.**

***Index Terms*—Ultra Wide-Band Radar, Multistatic Radar, Vital Signs Estimation, Multiple People Localization**

I. Introduction

Detecting people and estimating their vital signs has many applications for healthcare and safety, including sleep pattern recognition, assisted living, in-cabin monitoring of drivers and child presence detection (CPD) in vehicles, amongst others [1], [2]. For these applications, Ultra Wide Band (UWB) radar systems offer solutions for contactless detection and remote vital signs extraction, operating at relatively large bandwidths that result in fine range resolution. This enables the detection of humans, and particularly the detection of small movements such as the displacements of the chest due to breathing or heartbeat, enabling the use-case of contactless human vital-sign extraction [3]–[5].

A variety of processing pipelines have been proposed in the literature for the detection of people and monitoring of their vital signs with radar systems, where both UWB radars operating in the lower 6-10 GHz frequency range and mm-wave systems have been proposed. Different techniques address different steps such as pre-processing the signal for denoising [6], localization of the range bins containing the signatures of humans [7], and vital signs estimation [8]. However, it appears that many published works rely on several assumptions that are not easily compatible with the constraints of automotive vehicle cabins. These are for instance the fact that the number of people and their size & positions inside the vehicle are not known a priori, and that the vehicle itself is a cluttered and multipath-dense environment, which makes localization challenging using only a single radar placed at a specific position. To address these limitations, in this paper a network of UWB radars is proposed for the detection and localization of multiple subjects in vehicle cabin, leveraging on the additional capabilities provided by multiple spatial view points on the complex scene of interest [9]. Specifically, an algorithm for decentralized vital signs detection is proposed, together with a centralized association processing block to fuse detections from all radars in the network using a dedicated cost-matrix computation. By fusing the detections obtained by the multiple multistatic sensors, the overall system can become more reliable and provide increased detection probability. The performance of the proposed processing pipeline tested with a multistatic radar network is validated with simulations and experiments, showing promising results with Root Mean Square Error (RMSE) of about 16 cm for both single and double subject scenarios.

The rest of the paper is organized as follows. Section II presents the proposed processing pipeline. The simulation framework for the multistatic UWB radar network with the corresponding experimental setup are discussed in Section III, with experimental results reported in Section IV and conclusions in Section V.

II. Proposed Processing Pipeline

The proposed processing pipeline consists of two blocks: the detection block and the association block, as shown in Fig. 1 [9]. In the detection block, the data from every radar receiver is independently evaluated and a detection matrix is provided for each of the Rx in the network. In the data association block, information is combined to provide a final localization estimate, discarding ghost targets.

A. Detection block

A detection algorithm operating on 30s of CIR (Channel Impulse Response) data is formulated to determine the number of people detected at each radar Rx, their position

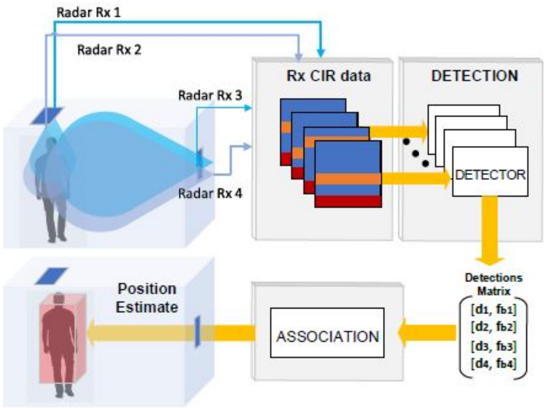

Fig. 1. Block diagram of the proposed processing pipeline with generation of Channel Impulse Response data from each UWB radar, followed by detection and data association processing blocks.

with respect to the Rx, and their breathing frequencies. Firstly, the CIR data is band-pass filtered to select the signal in the frequency range 0.1-0.8 Hz where human vital signs are expected. Secondly, an FFT is applied in the slow-time dimension for all range bins to compute a Range-Doppler map, and a 2D Constant False Alarm Rate detector (CFAR) is applied to select the cells with human signature. As the signature of each human is distributed in multiple consecutive range & Doppler bins, the detections returned by the CFAR are first clustered, and their weighted-average range-frequency information is classified as possible humans in the environment. Their weight is established with respect to the energy of the echoes in the cluster.

The final output of the detector block for a specific radar receiver denoted by m is the detection matrix $\mathbf{D_m}$ as defined in Equation (1). This contains the range and the estimated breathing frequency $[d_n, f_{bn}]$ of the $n = 1, 2, ...N$ detected targets for each of the $m = 1, 2, ..M$ receivers considered.

$$\mathbf{D_m} = \left[(d_1, f_{b1}), (d_2, f_{b2}), ..., (d_N, f_{bN})\right] \tag{1}$$

B. Data association and localization block

The data association block is needed to associate the separate detections from M receivers to possible humans in the scene, and then perform localization in 3D space. Poor data association will lead to ghost targets [10]. The number C of combinations in between the N_m detections for each of the M radar nodes can be expressed as seen in Equation (2):

$$C = \prod_{m=1}^{M} (N_m + 1) \tag{2}$$

where M is the total number of radar receivers used and N is the number of detections obtained by each radar. A novel association algorithm inspired by [11], [12] is proposed, where a cost is assigned to each of the C possible combinations between radars, denoting the likelihood that a given hypothesis corresponds to a real target. This depends on both the range at which a human is detected and the detected breathing frequency.

1) Cost calculation for association algorithm: The cost associated to each combination consists of 3 contributions. Firstly, the cost given by range estimation is computed for each receiver m by estimating the error in localization $d_{Pos,m}$ as:

$$d_{Pos,m} = |\mathbf{d_m} - \mathbf{\hat{d}_m}| = |\mathbf{d_m} - distances(\mathbf{\hat{p}_m})|, \tag{3}$$

where $\mathbf{d_m}$ is a vector consisting of the ranges that form the hypothesis, and $\mathbf{\hat{d}_m}$ are the estimated distances from the hypothetical target coordinates to the radar receivers. In case of a true target, these vectors ought to be similar. The estimated position based on $\mathbf{d_m}$ is obtained with a localization algorithm in which the 3D space is divided into cells as defined in [9] and the kNN algorithm is used to find the cell whose distance $\mathbf{d_c}$ to the receivers is the closest to $\mathbf{\hat{d}_m}$.
Assuming that different humans will have different breathing rates, the second cost item is defined by the error in breathing frequency for each receiver m as:

$$d_{Breath,m} = \sum_{n=1}^{N} f_{b,m,n} - mean(\mathbf{f_{b,n}}) \tag{4}$$

where $\mathbf{f_{b,n}}$ is the vector containing the breathing frequencies of the hypothesis.
Finally, a cost item is defined to account for missed detections in the hypothesis. If we rely on complete detections from the detector, it can be established that a hypothesis which considers a missed detection from a radar will have a higher cost than a hypothesis which considers a full combination of detections. This cost can be computed as in [11]:

$$d_{miss,m} = log_{10}\left(\left(\frac{P_d}{P_{fa}}\right)^{N_{miss,m}}\right) \tag{5}$$

where $N_{miss,m}$ is the number of accounted missed detections in a particular hypothesis, and P_d, P_{fa} probability of detection and false alarm, respectively. The final cost can be expressed as in Equation (6) as the sum of the 3 contributions:

$$C(m) = d_{Pos,m} + d_{Breath,m} + d_{miss,m} \tag{6}$$

To identify the minimum cost $C(m)$, an assigning function based on Lagrangian relaxation is used to solve the problem [11].

2) Target localization: Finally, the 3D positioning and estimated breathing frequencies of the humans in the environment are presented as the identified minimum-cost hypothesis after association. Additionally, accounting for the fact that ghost targets may appear as a result of incorrect associations, a 'Probability of target' is defined.

Assuming that ghost targets may result from missed detections & false alarms in the processing block, and that the association algorithm can account for these, some identified hypothesis can be assigned a higher probability, i.e., those considering more miss-detections are more likely to be ghost targets. Thus, an additional threshold could be defined to determine that low-probability targets are not considered [9].

III. Radar network simulation & experimental setup

A realistic simulation of CIRs from different Rxs in the multistatic radar network is developed to evaluate the performance of the proposed processing pipeline. This allows to evaluate the effect of different topologies of the radar nodes, and different locations and vital signs parameters of different people in the scene of interest, which may be cumbersome and not always practical to realize in actual experiments. For simulations in this context, most available literature would simulate only the signature created by a human breathing model. However, for this study, static objects in the environment and the multipath components caused by these have been also included in the developed framework [9], inspired by [13]. It should also be noted that the fluctuation due to human breathing is modelled not just in the signal phase, as conventionally done to generate Doppler signatures, but also in the radar echoes' amplitude, due to the modifications of the torso shape (for simplicity modelled as an ellipsoid, whose RCS can be computed analytically).

The experimental setup consists of a multistatic radar network realized with NXP UWB NCJ29D5 chips and omnidirectional Decawave Spline antennas. Each NCJ29D5 board can be flexibly programmed to work as Tx or Rx, and synchronized by a given clock. To establish a monostatic radar setup, the transmitter and receiver boards are co-located, whereas in bistatic operations the receiver boards are placed at distances comparable to the distance of the targets from the transmitters. For the specific setup of this work, the radar network consists of six boards organized as 2 multistatic radar anchors. An anchor is defined as a Tx board synchronized with 2 Rx boards positioned accordingly to create a monostatic and bistatic radar. Frequency division multiplexing was used to separate the anchors' transmissions, with center frequencies f_{c1} = 6.5 GHz and f_{c2} = 7.5 GHz, respectively. A picture of the boards in the TU Delft anechoic chamber is shown in Fig. 2, whereas the sketch of their actual deployment in a vehicle cabin is shown in Fig. 3. The Tx of one anchor is placed at the rear mirror of the vehicle, looking inwards, whereas the Tx of the other anchor is placed on the ceiling of the back seats, looking downwards. The respective monostatic Rxs are placed next to each transmitter, and the bistatic Rx boards are placed close to the opposite Tx boards. Various people were seated in the areas denoted by A & B in Fig. 3, both individually or together at the same time.

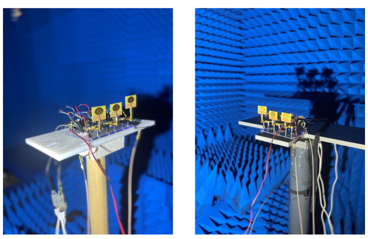

Fig. 2. UWB boards in the anechoic chamber: Tx2 , Rx2 monostatic, Rx1 bistatic (left), and Tx1, Rx1 monostatic, Rx2 bistatic (right).

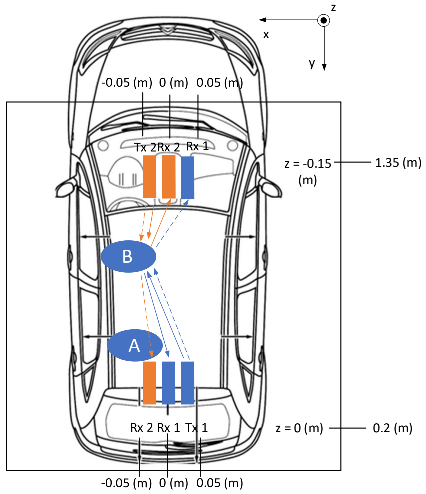

Fig. 3. UWB radar boards positions in vehicle cabin measurements; A & B are the target positions (left back seat and driver seat, respectively).

IV. Results

Results for single persons are shown in Fig. 4 and 5. It can be seen how most radars can detect the person with a localization error of about 10cm. It should be noted that the monostatic radar on the ceiling above the back seat performed noticeably worse, most likely because the breathing motion used for detection happens almost orthogonally to its line of sight. Results of two people simultaneously sitting at positions A and B in the vehicle are shown in Fig. 6. As expected, the detection capabilities drops compared to single-person measurements. This is likely caused by monostatic radars struggling to detect both targets at the same time. The achieved localization RMSE is about 16cm, similar to single-person measurements; however, an increased presence of ghost targets is seen, which can be linked to worse detection from monostatic radars in this more complex scenario.

Summarizing, single persons can be successfully detected by all radars in the network, even in complex environments with multipath such as the vehicle cabin. When multiple people are present, monostatic radars struggle to locate both people, at least in the tested network topology. Bistatic radars, however, can detect both people even if these are at close ranges, by distinguishing their different breathing frequencies. The importance of properly positioning the radars is showcased by the fact that some people cannot be detected by monostatic radars, e.g., the radar placed on the ceiling of the back seat.

For this reason, two different radar network topologies are evaluated, leveraging on the simulation framework mentioned in Section III. In the first extra topology (denoted as '*Sep*'), the radar boards are spaced 15cm outwards in the X direction with respect to the experimental setup of Fig. 3 (denoted as '*Orig*'), to gain additional spatial diversity. In the second topology (denoted as '*Low*'), the boards on the ceiling are moved to the back of the center-back seat, i.e., observing the people from their lower back in the original experimental setup of Fig. 3. For both cases, 100 Monte Carlo simulations are performed with two people whose breathing frequencies and chest displacement amplitudes are sampled from uniform distributions between [0.1-0.8] Hz and [5-15] mm, respectively. From the results in Table I, it is seen that the extra topologies can improve the metrics of number of detected real (*NTarg*), ghost (*NGhost*), and missed (*NMiss*) targets after association, and the localization error (*LocErr*).

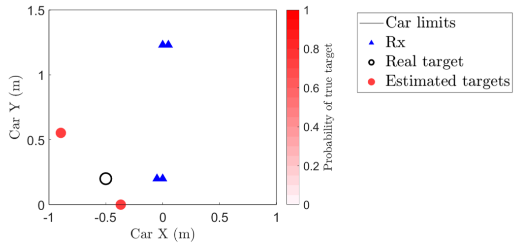

Fig. 4. Localization of sitting person in vehicle, position A (back-left seat)

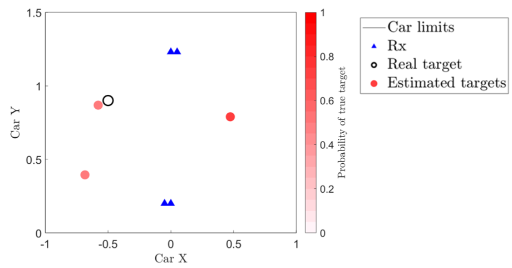

Fig. 5. Localization of sitting person in vehicle, position B (driver's seat)

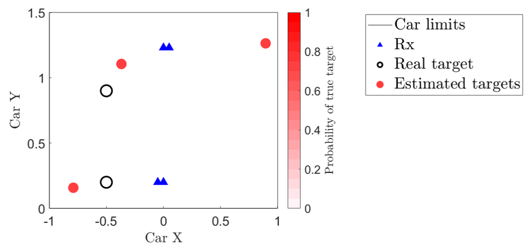

Fig. 6. Localization of two sitting people in vehicle at both positions A-B

TABLE I

DATA ASSOCIATION PERFORMANCE COMPARISON BETWEEN ORIGINAL EXPERIMENTAL RESULTS (*ORIG*) AND 2 EXTRA RADAR TOPOLOGIES (*SEP* & *LOW*) SIMULATED WITH 100 MONTE CARLO REPETITIONS FOR DIFFERENT SUBJECTS.

ID	Ntarg	NGhost	Nmiss	LocErr 2 Targets [cm]
Orig	2.22	1.05	1.21	[10,8]
Sep	2.01	0.25	0.86	[4.8,1.6]
Low	2.69	1.38	0.92	[7.6,2.9]

V. CONCLUSIONS

The detection & localization of multiple people in a vehicle is addressed with a network of UWB radars. A novel processing pipeline is formulated with decentralized detection at each radar, followed by centralized data association based on a cost-matrix computation. The performance is tested experimentally with a multistatic UWB radar network, and a simulation framework is also developed to evaluate alternative topologies of the network beyond the experiments.

The detection & localization of humans in a vehicle is achieved by the proposed pipeline, with localization RMSE of about 16cm for single and double person scenarios. A significant effect of the network topology is also shown, with the best results obtained with bistatic geometries providing multiple concurrent views on the people to be detected.

ACKNOWLEDGMENT

The authors thank R. Roovers, K. Brink, & S. Tertinek of NXP Semiconductors for supporting the internship and MSc thesis work of E. Rufas, from which this paper originated.

REFERENCES

[1] Y. Han, A. Yarovoy, and F. Fioranelli. An approach for sleep apnea detection based on radar spectrogram envelopes. In *2021 18th European Radar Conference (EuRAD)*, pages 17–20, 2022.

[2] Xinming Huang, Ling Sun, Tian Tian, Zeyan Huang, and Edward Clancy. Real-time non-contact infant respiratory monitoring using uwb radar. In *2015 IEEE 16th International Conference on Communication Technology (ICCT)*, pages 493–496, 2015.

[3] Sohee Lim, Seongwook Lee, Jaehoon Jung, and Seong-Cheol Kim. Detection & localization of people inside vehicle using impulse radio ultra wideband radar sensor. *IEEE Sensors Journal*, 20(7):3892–3901, 2020.

[4] Takato Koda, Takuya Sakamoto, Shigeaki Okumura, and Hirofumi Taki. Noncontact respiratory measurement for multiple people at arbitrary locations using array radar and respiratory-space clustering. *IEEE Access*, 9:106895–106906, 2021.

[5] Dingyang Wang, Sungwon Yoo, and Sung Ho Cho. Experimental comparison of ir-uwb radar and fmcw radar for vital signs. *Sensors*, 20:1–22, 11 2020.

[6] Kuo-Kai Shyu, Luan-Jiau Chiu, Po-Lei Lee, Tzu-Han Tung, and Shun-Han Yang. Detection of breathing and heart rates in uwb radar sensor data using fvpief-based two-layer eemd. *IEEE Sensors Journal*, 19(2):774–784, 2019.

[7] Faheem Khan, Asim Ghaffar, Naeem Khan, and Sung Ho Cho. An overview of signal processing techniques for remote health monitoring using impulse radio uwb transceiver. *Sensors*, 20:2479, 04 2020.

[8] Kuo-Kai Shyu, Luan-Jiau Chiu, Po-Lei Lee, and Lung-Hao Lee. Uwb simultaneous breathing and heart rate detections in driving scenario using multi-feature alignment two-layer eemd method. *IEEE Sensors Journal*, 20(17):10251–10266, 2020.

[9] Elisabet Rufas Talamas. Multiple people detection and localization with multistatic uwb radar in multipath environments for the automotive industry. *TU Delft MS3 group*, MSc Thesis, August 2022.

[10] A. Samokhin, I. Ivashko, and A. Yarovoy. Algorithm for multiple targets localization and data association in distributed radar networks. In *2014 15th International Radar Symposium (IRS)*, pages 1–6, 2014.

[11] Lucas Giroto de Oliveira, Mohamad Basim Alabd, Benjamin Nuss, and Thomas Zwick. Range association and fusion in a network of single-channel monostatic ofdm radars. In *IEEE MTT-S International Conference on Microwaves for Intelligent Mobility*, pages 1–4, 2020.

[12] ChangKyeong Kim and Joon-Yong Lee. Toa-based multi-target localization and respiration detection using uwb radars. In *EURASIP Journal on Wireless Communications and Networking*, 2014.

[13] Jakob Möderl, Franz Pernkopf, and Klaus Witrisal. Car occupancy detection using ultra-wideband radar. In *2021 18th European Radar Conference (EuRAD)*. IEEE Xplore, 2021.