Abstract—Radar sensors in the 24- and 77-GHz frequency domain will be used to increase comfort and safety in many future automotive applications. In this paper, a radar network with four short-range radars is considered. Each sensor measures individually only the range information of all targets inside the observation area. The Cartesian coordinates of each target are calculated by a trilateration technique based on range measurements selected in a data-association procedure. Estimating a target position based on range measurements is called trilateration. In contrast to this, estimation of a target position based on pure angular measurements is called triangulation.

In automotive applications, situations with multiple targets almost always occur. Therefore, a high-performance data association is very important to separate and to distinguish between these targets. To avoid errors in the data-association step and resulting ghost targets, this paper describes a technique that combines the procedures of data association and position estimation into a single step. This signal-processing technique shows very good results in multitarget situations and reduces the number of ghost targets drastically.

Index Terms—Automotive radar, data association, least mean-square methods, position measurement, radar signal processing, radar target recognition, road vehicle radar, trilateration.

I. INTRODUCTION

RADAR-SENSOR-BASED driver systems for automotive applications are currently under investigation to increase comfort and safety [12]. For adaptive cruise control (ACC) applications, a single 77-GHz far-distance radar sensor, which has a long maximum range of 200 m but covers only a narrow azimuth angle of 15°, is used, for example, in [1]. All targets inside the observation area will be detected and the distance between the relevant object and the host vehicle will be controlled by this single radar sensor.

For many other and additional automotive applications like Stop&Go, PreCrash, or Parking Aid, a completely different observation area is needed. In this case, a maximum range of 30 m, but a wide-azimuth-angle area, is required. For these demanding applications, not a single radar sensor but a radar network consisting of four 24-GHz short-range radar sensors will be considered, as shown in Fig. 1. For reasons of economy, the considered sensors will provide just the range, but no azimuth angular measurements of the detected targets. Using sensors with additional bearing measurements and a wide-azimuth observation area will cause a completely different signal-processing structure.

The objective of this paper is to discuss the signal-processing procedure for a radar network with four distributed radar sensors behind the front or rear bumper like it is used for automotive-radar purposes. Considering short-range automotive-radar applications, mainly situations with multiple targets or even extended targets having multiple reflections will be observed [4], [7]. Therefore, this paper will focus on multitarget handling in the short-range area.

A 24-GHz radar network with four different distributed sensors is assumed for analytic examinations and practical validation based on measurements with the Hamburg University of Technology (TUHH) experimental car [6]. Each individual radar sensor has the capability to measure target ranges up to 30 m with high range resolution (HRR) and accuracy. Azimuth angle and radial velocity will not be measured by a single sensor but by the radar network and the trilateration procedure.

From an analytical point of view, only two radar sensors are needed by the trilateration process to calculate the intersection points and the target positions inside the observation area. However, in multiple-target situations, ambiguities can occur. Therefore, in practical applications, some redundancy is integrated into the radar network and four individual radar sensors are used for data acquisition and range measurement.

Fig. 1. Radar sensors for automotive applications.

Fig. 2 describes the block diagram of the radar network. A number I = 4 of radar sensors (S) measure, independently of each other, the ranges of all objects inside the observation area. These measured data are transmitted, e.g., via controller area network (CAN)-bus, to a central processing unit that has to associate the received information to different targets and has to estimate the particular target positions.
In addition to the pure position estimation, tracking procedures can be used to trace the target positions over time. This process will also increase the accuracy of target range, azimuth angle, and velocity. Furthermore, the tracking procedure bypasses detection losses and provides a possibility to predict the target position for the next measurement cycles.

### II. Trilateration Process

By defining a coordinate system with the origin in the middle of the experimental car’s front bumper shown in Fig. 3, the positions of the four sensors are given in Table I as an example.

For a fixed target position \( T = (t_x, t_y) \) in Cartesian or polar coordinates, respectively, the ranges \( r_i(T) \), which will be measured by each sensor \( s_i = (s_{xi}, s_{yi}) \), can be calculated as follows:

\[
    r_i(T) = \sqrt{(t_x - s_{xi})^2 + (t_y - s_{yi})^2}. \tag{1}
\]

Typically, trilateration techniques are used to determine the target position if pure range measurements are provided \([14]–[16]\). In Fig. 4, the four sensor positions are represented by small boxes at the bottom and the intersection point is calculated on the basis of range measurements from four individual radar sensors. The range measurements are given for the target position \( T = (5 \text{ m}, 0 \text{ m}) \) in accordance to the plot.

In contrast to these ideal considerations, the real measurements \( \hat{r}_i \) are superimposed by the noise term \( n_i \).

\[
    \hat{r}_i = r_i(T) + n_i. \tag{2}
\]

The error values \( n_i \) are assumed to be statistically independent and identically Gaussian distributed with zero mean. In the case of realistic but noisy measurements, least-sum-squared-error techniques are applied for target-position estimation based on the trilateration technique. A good summary of these position-estimation techniques is given in \([5]\).

\[
    E(T) = |\hat{r} - r(T)|^2 = \frac{1}{4} \sum_{i=1}^{4} |\hat{r}_i - r_i(T)|^2 \tag{3a}
\]

\[
    \hat{T} = \arg \min E(T). \tag{3b}
\]

Minimization of \( E(T) \) means to find the target position \( T = (\hat{t}_x, \hat{t}_y) \) that best fits the measured data vector \( \hat{r} \). To calculate the target position \( \hat{T} \), a nonlinear optimization procedure has to be performed \([6], [9]\). The iterative Gauss–Newton algorithm is the common method used to solve this minimization task.

In a single-target situation, the trilateration process can be applied directly. As soon as not a single but \( K \) targets are presented to the radar sensors, every sensor will provide a set of measured ranges

\[
    \mathcal{O}_i = \{\hat{r}_{i1}, \ldots, \hat{r}_{iK_i}\} \tag{4}
\]

where \( K_i \leq K \) corresponds to the number of targets detected by sensor \( i \).

Fig. 5 shows a measurement situation where three human beings are positioned in front of the radar network at a distance of approximately 6 m. This measurement situation is considered in this paper as a typical multitarget situation to study...
Fig. 5. Measurement situation with three persons standing at almost the same distance from the radar sensors.

the trilateration procedure and the target-resolution capability in range and azimuth angle.

The objective of a data-association process is to select all measured ranges for a single target. In a multitarget situation, there are some ambiguities in the possible combinations of measured ranges, which have to be solved before the trilateration process starts. If the measured ranges are associated accordingly, the derived single-target position can be processed in the trilateration procedure independently of each other. But each error in the association process will generate the so-called ghost targets.

If the observed objects in a multitarget situation are located in obviously different range areas, the data-association process is rather simple. The measured ranges can be processed directly in the trilateration process like in a single-target situation. Only in a dense-target situation does the data-association process become extremely important. All errors that will occur in the data-association procedure lead to ghost-target situations at the output of the trilateration process. In other words, a ghost target is the result of the combination of measured ranges that do not belong together.

The multitarget situation shown in Fig. 5 resulted in the following single-shot range measurements and the \( xy \) plot shown in Fig. 6.

As depicted in the range measurements, it is quite obvious that one person is standing at a slightly larger distance (left person) than the others. Here, the data association is rather simple. It is just to take the four measurements with the largest range. For the rest of the measurements, it is not that simple to find groups of range measurements describing the middle and the right person. Furthermore, the trilateration process will lead to position estimates even for a set of wrongly assigned range data (ghost-target generation). A trilateration process based on the measured ranges \( \{\hat{r}_{11} = 6.07\, \text{m}, \hat{r}_{21} = 5.28\, \text{m}, \hat{r}_{32} = 5.57\, \text{m}, \hat{r}_{41} = 5.41\, \text{m}\} \), respectively, leads to a position estimate indicated by the black diamond in Fig. 6, which is obviously a ghost target and not one of the targets present. Therefore, a reliable technique is needed to perform a correct data association even for dense-target situations. For the given example, there are 57 possible data sets that contain measurements from three or four sensors. The trilateration algorithm converges to position estimates for 51 of these sets while only three position estimates correspond to valid targets. All these resulting target positions are described in Fig. 7.

The correct data association is the most important part for a reliable target-position estimation in the case of an automotive radar network. Two classical procedures of data association are given in Section III, before a new and more reliable method for data association is presented in Section IV.

### III. Top-Down Data Association

Each target position is represented unambiguously by four range measurements. The technical challenge in the data-association procedure is to identify the four related range measurements unambiguously in multiple- and dense-target situations [2], which are characteristic of automotive-radar applications.

#### A. Range-to-Range Association

First of all, an algorithm that searches for targets specifically corresponding to four range measurements and combines them to a data set \( \{\hat{r}_1, \ldots, \hat{r}_4\} \) that describes a single target for the trilateration procedure (range-to-range association) can be
implemented. Fig. 8 depicts the signal-processing procedure by a block diagram.

With the example given in Fig. 6, it is obvious to combine the measured ranges \{6.07, 6.12, 6.35, 6.49 m\} to a single target. These four range data will be processed in the trilateration procedure. The resulting target position is \( \mathbf{T} = (5.77\, \text{m}, 2.30\, \text{m}) \), which is the position of the left person. For the remaining range measurements, a range-to-range association will be applied. All signal processing, data association, trilateration, and possible tracking will be processed in a totally independent and separate way.

### B. Range-to-Track Association

To handle more complicated target scenarios, the data-association process can be optimized jointly with the tracking procedure. Therefore, the data-association process uses the output information of a tracking procedure as a reference point to associate the measured ranges to corresponding and already-existing target track positions. At the output of the association process, the measured ranges can be directly used to update the track information (range-to-track association). In this case, no separate target-position-estimation step based on the trilateration procedure is needed. Furthermore, even a single range measurement can be used to update an existing track without any trilateration scheme. This is especially important in situations with low-target-detection probability. The block diagram for the range-to-track association is given in Fig. 9.

As long as the target movement can be modeled as a rectilinear nonaccelerated motion, this method will provide excellent results. In addition, a track-generating technique is needed to establish new tracks. In [13], Oprisan and Rohling give a detailed description of the two mentioned association techniques, explain their capabilities, and compare the quantitative results based on an HRR radar network.

The great advantage of this method is that the output of the tracking procedure can be used as an initial target-position estimate for the position-dependent data association. This reduces the risk of ghost targets caused by misassigned range measurements dramatically. If no tracking information is provided, e.g., when starting a new track, or when the quality of the target prediction is quite poor, the idea of initial target-position estimates has to be generalized to single-scan target measurements.

In contrast to tracking systems, the present paper deals with the single-scan data association, which is necessary in the case of range-only-measuring radar sensors in trilateration networks for target-position estimation. The aim is to reduce the number of ghost targets even in a single scan. Given by the short reaction times in automotive-radar applications, it is very important to have as few ghost targets as possible.

Especially when using a radar sensor with range-only measurements, the risk of ghost targets is very high. Nevertheless, these sensor networks are widely discussed for automotive-radar applications. If sensors with angular measuring capability are used, the circumstances are completely different. In such cases, one of the well-known data-association techniques for tracking, such as that described by Blackman and Popoli [2], should be used. Publications on adapting these techniques for automotive radar have been made, e.g., by Dang et al. [3], Lee and Kim [7], [8], and Möbus et al. [10], [11].

### IV. Bottom-Up Data Association

In this paper, a new and alternative data-association-and-target-position-estimation process is proposed. The position-estimation algorithm is based on a finite set of possible target positions inside the observation area. In the following section, this proposal is derived from the basic principles of data-association and trilateration-based position-estimation techniques.

So far, the target-position estimation process was divided into two main steps, data association and trilateration. To perform the trilateration algorithm (3b), a data association is necessary to find the related range measurements \( \hat{r}_{ia} \) for each sensor \( i \) out of the particular target list \( O_i = \{ \hat{r}_{i1}, \ldots, \hat{r}_{iK_i} \} \) given in (4). It is obvious that the correct data association depends very much on the number of observed and detected targets. Furthermore, any error in data association will always lead to ghost target positions. In Section III, this was called the top-down approach.

If the target position \( \mathbf{T} \) is known in advance, the data-association procedure becomes rather simple. For an assumed target position \( \mathbf{T} \) taken as a reference, it will be shown that an optimal data association could be performed based on a simple minimum-distance calculation. This approach is referred to in this section as bottom-up processing.

In order to obtain reference points for assumed target positions, a grid is utilized in the bottom-up processing over the entire observation area as shown in Fig. 10. All individual grid points \( \mathbf{T} \) are treated as possible target positions and subsequently, this hypothesis is scrutinized. For reasons of practical processing, the observation area is defined as a grid in polar coordinates with a finite number of possible and deterministic
target positions $\hat{T}$. With this quantization, the grid is given by $N$ range bins with a distance $R_{\text{Step}}$ and $M$ azimuth angular bins $\phi_{\text{Step}}$. For quantitative analysis, the system parameters

\[ R_{\text{Step}} = 0.05 \text{ m} \quad (5a) \]
\[ \phi_{\text{Step}} = 2^\circ \quad (5b) \]

have been used for experimental purposes.

For practical calculations, $R_{\text{Step}}$ and $\phi_{\text{Step}}$ should be chosen in accordance with the radar range resolution and the required azimuth-angle accuracy of the radar network. These values can be assumed to be constant in the entire observation area [15].

For a known or assumed target position $T$, the optimal data association is given implicitly by the mmse-based trilateration (3) when changing the minimization variables from $T$ to $\hat{r}_i$.

\[ E(T) = \min_{\hat{r}_i \in O_i} \sum_{i=1}^{4} [\hat{r}_i - r_i(T)]^2 \]
\[ = \sum_{i=1}^{4} \left( \min_{\hat{r}_i \in O_i} (\hat{r}_i - r_i(T)) \right)^2 \quad (6a) \]

\[ = \sum_{i=1}^{4} \left[ \min_{\hat{r}_i \in O_i} (\hat{r}_i - r_i(T)) \right]^2 \quad (6b) \]

The sets $O_i = \{\hat{r}_{i1}, \hat{r}_{i2}, \ldots, \hat{r}_{iK_i}\}$ are for $K_i$ range measurements of each individual sensor $i$ in a multitarget situation.

Instead of the complex data-association procedures needed for the standard top-down processing, with the high risks of ghost targets, the bottom-up procedure considers a simple minimum-distance calculation for assigning the measured range data individually for every sensor. The minimal estimation error for all sensors at the considered grid point $T$ is given by the sum of the minimal single-sensor distances between the predefined geometrical distance $r_i(T)$ and the best fitting measured range $\hat{r}_{i,k}$.

\[ \hat{r}_{i,k} = \arg \min_{\hat{r}_i \in O_i} [\hat{r}_i - r_i(T)]. \quad (7) \]

In general, the error value $E(T)$ defines a function over the two-dimensional observation area, and the final target positions are given by the appropriate local minima. To account for missing detections of a single sensor, the same calculations can be performed using just the best three of four measurements.

This bottom-up procedure has been applied to the multitarget situation described in Fig. 5. The resulting contour plot that describes the error value $E(T)$ for each grid point is given in Fig. 11. The positions of all targets inside the observation area can be found according to the three minima of the depicted function.

V. MEASUREMENT RESULTS

To verify the capability of the described algorithm, it was applied to the measured range data of an automotive radar network [6]. This network consists of four identical pulse radar sensors mounted behind the front bumper of a test vehicle. With this radar network, different target situations were observed and the results of two characteristic multiple-target situations are presented. Even though the algorithm was developed for moving-target scenarios, two stationary-target scenarios are presented without loss of generality.

All results are based on the following system parameters:

- Number of sensors, $I = 4$
- Range resolution, $\Delta r = 0.15 \text{ m}$
- Range accuracy, $\sigma = 0.03 \text{ m}$. \quad (8)

The range accuracy is used as a standard deviation $\sigma$ to describe the measurement error.

A. Measurement Situation With Three Persons

The known target situation of three persons, all standing at approximately 6 m from the sensors, is used to demonstrate that point targets can be separated in azimuth angle. The measured radius values of the four sensors

\[ O_1 = \{6.07 \text{ m}\} \quad (9a) \]
\[ O_2 = \{5.28 \text{ m}, 5.53 \text{ m}, 6.12 \text{ m}\} \quad (9b) \]
\[ O_3 = \{5.25 \text{ m}, 5.57 \text{ m}, 6.35 \text{ m}\} \quad (9c) \]
\[ O_4 = \{5.41 \text{ m}, 6.49 \text{ m}\} \quad (9d) \]
are visualized in Fig. 12. The four boxes near the origin of each graph denote the positions of the radar sensors, whereas the circular arcs represent the measured ranges between sensor and target. It has to be mentioned that only two sensors (numbers 2 and 3) have measured three different radius values and sensor number 1 has measured only one. Since the person on the left is standing at a slightly greater distance, one can identify an intersection of four circular arcs in the upper left part.

The results of the simple range-to-range (top-down) processing is given in the upper part [Fig. 12(a)] and the respective bottom-up processing results are given in the lower part [Fig. 12(b)]. While the upper figure is already known from the aforementioned details, the lower part is finally giving the correct results for the position estimates of the three persons standing in front of the sensors. The bottom-up signal processing was able to identify the correct three position estimates out of the 51 possible trilateration results.

In Table II, the assigned correct range measurements as well as the corresponding target-position estimates are given. The outer left person shows up as an intersection of four circular arcs in the upper left part.

B. Measurement Situation With Four Persons

As a second measurement example, a situation with four standing persons is considered. Two persons are arranged in front of the sensors at distances of 2 and 6 m, respectively. The other two persons are both standing at approximately 4 m away, but at different aspect angles. The set of measurements for this scenario is given below.

\[
\begin{align*}
O_1 &= \{2.28 \text{ m}, 4.42 \text{ m}, 4.85 \text{ m}, 6.60 \text{ m}\} \\
O_2 &= \{2.15 \text{ m}, 4.18 \text{ m}, 4.56 \text{ m}\} \\
O_3 &= \{2.12 \text{ m}, 4.42 \text{ m}, 4.71 \text{ m}, 6.38 \text{ m}\} \\
O_4 &= \{2.26 \text{ m}, 5.01 \text{ m}, 6.61 \text{ m}, 7.33 \text{ m}\}.
\end{align*}
\]

In Fig. 13, the results of the signal processing are visualized. From the plot in Fig. 13(a), it is obvious that this setup causes a lot of possible ghost targets in the center area of the two 4-m targets. In contrast to this, the bottom-up processing leads to the four correct target positions without any additional ghost targets. In addition to the plots, the actually estimated target positions and the accordant data association are given in Table III. Again, one range measurement has been correctly assigned to two targets.

VI. PERFORMANCE ANALYSIS IN COMPARISON TO STANDARD RANGE-TO-RANGE ASSOCIATION

To validate the benefit of the derived bottom-up data-association method in comparison with the classical top-down approach, the second-mentioned target scenario with four individual targets is again considered. For this setup, 100 consecutive measurement cycles were recorded with an update rate of 20 ms.

Based on the recorded range measurements from the four sensors, target positions are calculated with two different methods. First, with a classical range-to-range data association and following the trilateration procedure, and second, with the grid-based technique derived in Section IV. Since a stationary setup is considered, all 100 measurement cycles are describing exactly the same situation. Based on these estimates, the number
Fig. 13. Results of simple range-to-range and bottom-up processing. (a) Twenty-four position estimates with range-to-range (top-down) processing. (b) Four correct position estimates with bottom-up processing.

TABLE III
DATA ASSOCIATION FOR THE FOUR-PERSON SITUATION

<table>
<thead>
<tr>
<th>Target</th>
<th>front (m)</th>
<th>left (m)</th>
<th>right (m)</th>
<th>rear (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor 1</td>
<td>2.28</td>
<td>4.42</td>
<td>4.85</td>
<td>6.60</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>2.15</td>
<td>4.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor 3</td>
<td>2.12</td>
<td>4.71</td>
<td>4.42</td>
<td>6.38</td>
</tr>
<tr>
<td>Sensor 4</td>
<td>2.26</td>
<td>5.01</td>
<td>-</td>
<td>6.61</td>
</tr>
<tr>
<td>Association</td>
<td>1111</td>
<td>2332</td>
<td>3320</td>
<td>4043</td>
</tr>
<tr>
<td>x-Position</td>
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<td>4.09</td>
<td>4.15</td>
<td>6.46</td>
</tr>
<tr>
<td>y-Position</td>
<td>-0.05</td>
<td>2.16</td>
<td>-1.74</td>
<td>-0.14</td>
</tr>
</tbody>
</table>

of ghost targets that appeared was counted. Results are given in Fig. 14 and Table IV.

It can be seen from Fig. 14 that the number of ghost targets is not constant over time. This is due to fluctuations within the radar measurement. Furthermore, the range-to-range association obviously leads to more ghost targets, whereas the bottom-up technique outperforms the previous one and gives just a few ghost targets. While the number of ghost targets for range-to-range processing is three times higher than the number of true targets, the bottom-up processing leads to just a few ghost targets on the average.

VII. CONCLUSION

In this paper, a method for target-position estimation using range-only-measuring radar sensors in a radar network is presented. The main idea behind the approach is to overcome the common data association before estimating the target positions in multitarget situations. This is done by applying a new bottom-up estimation technique that does not estimate a position for an associated set of trilateration measurements, but rather finds matching measurements for an assumed position estimation. Therefore, the data-processing complexity is in contrast to common-data-association techniques constant with the number of targets.

The bottom-up processing significantly reduces the number of ghost targets and has a high position accuracy even in symmetric multitarget situations. Processing results with measured data have been presented to validate the analytical results.

REFERENCES


Florian Fölster received the Dipl. Ing. degree in electrical engineering from the Hamburg University of Technology (TUHH), Germany, in 2001. He visited Luleå Tekniska Universitet (LTU), Sweden, in a student exchange program. Since 2002, he has been working towards the Ph.D. degree with the Department of Telecommunications, TUHH. His research interests include various aspects of signal processing, target detection, position estimation, and handling of extended targets for future automotive applications.

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