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**Abstract**—This paper presents an approach to estimate the true direction of motion and the velocity of a target within a single measurement snapshot. This is achieved by using a single radar sensor in combination with an active repeater element that is operated as a displaced virtual sensor. Coherency between sensor and repeater tag is only obtained by signal processing; on a hardware level both operate incoherently. This setup provides the necessary multi-perspective view on the target at low effort and large freedom of placement. The results of simulations and measurements in the 77 GHz band with one radar sensor and two repeater elements are presented to validate the theory.

## I. INTRODUCTION

Modern millimeter-wave radar sensors provide high resolution measurements of relative velocities and ranges at small mechanical dimensions of the sensor. Especially the ability to measure the radial velocity of a target directly due to the Doppler-shift is a major advantage over other sensor types like video cameras or laser sensors. The reduction in dimensions and partly cost of modern millimeter-wave radars fuels the ongoing trend of sensor networks consisting of multiple spatially distributed radar sensors [1].

Such a network enables additional capabilities due to the difference in perspective onto a mutual target object. In [2] the true velocity and direction of a target object was estimated with a sensor network, based on the different projections of the motion vector for each sensor. In [3], the joint evaluation of multiple sensor nodes for high-level target tracking and velocity estimation of extended objects was presented.

The use of sensor networks comes with the downside of increased hardware effort to achieve simultaneous triggering and signal processing as well as data storage for each sensor node. Substantially more effort is needed to utilize the bistatic target response between different sensors, which demands at least a clock distribution for coherent coupling of the sensor nodes to achieve signal coherency. Even then, noise coherency is not achieved, which leads to high phase noise and therewith a poor detection performance [4].

These issues do not arise, if instead of multiple sensors only one sensor and one or more active repeater elements are used, which relay the transmitted signal back to the sensor. Because the processing of the bistatic path is performed back at the original sensor, there is virtually no signal or noise decorrelation due to the local oscillator of the transmit signal being used again for downconverting the received signal. Therefore, a hardware connection between the nodes of the

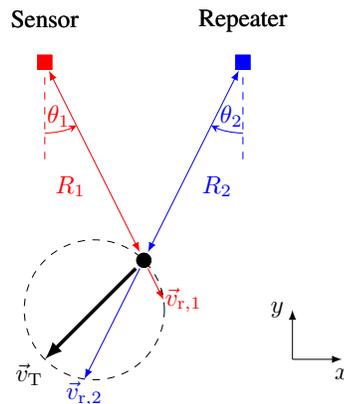


Fig. 1. Network with one sensor, one repeater, and a target with velocity vector  $\vec{v}_T$ . The ranges and the radial velocities of the target seen from the sensor or repeater are given as  $R_1$ ,  $R_2$  and  $v_{r,1}, v_{r,2}$  respectively.

network is not needed and the repeater elements [5] only require a power supply.

The paper is organized as follows: First, the theoretical background of true velocity estimation using a radar network build on repeater elements is explained. Based on the theory, simulations are presented to show that the direction and magnitude of the target velocity can be acquired. Finally, the simulations are verified with real measurements to show the viability of the proposed method.

## II. SYSTEM MODEL

In the following, the system model of the network is derived. Fig. 1 shows the geometrical relationship between the actual motion vector  $\vec{v}_T$  and the measured radial velocities  $\vec{v}_{r,1}$  and  $\vec{v}_{r,2}$  for a network consisting of one sensor and one repeater element.

### A. Velocity components and geometry

The basis for the proposed method is the fact that all possible radial velocity vectors  $\vec{v}_r$  measured by a radar sensor at a certain position for a target with a given velocity vector  $\vec{v}_T$  are located on a circle whose center is the midpoint between the base and the tip of  $\vec{v}_T$  and whose diameter is the length of the vector. If this circle can be derived from the measured data, the real  $\vec{v}_T$  can be determined.

To construct a circle at least three points located on the circle path have to be known. With  $\vec{v}_{r,1}$  and  $\vec{v}_{r,2}$  and the target

position, a circle going through the tips of the radial velocity vectors and the target point can be spanned. The diameter of this circle is the estimated target velocity, and the velocity direction is determined from the target point to the opposite side of the circle where the distance is the diameter of the circle, as can be seen on Fig. 1.

The sensor acquires the range and radial velocity of the target as  $R_1$  and  $v_{r,1}$ . Additionally, the sensor receives bistatic target information via the repeater element. The bistatic received information is the superposition of the monostatic one and of what a sensor at the position of the repeater would see. Therefore, the bistatic range is given as

$$R_{21} = R_1 + R_2 \quad (1)$$

and the bistatic velocity as

$$\vec{v}_{r,21} = \vec{v}_{r,1} + \vec{v}_{r,2}. \quad (2)$$

With millimeter-wave radar sensors only sign and magnitude of velocities can be measured [6]. Therefore, the available target information is given as  $R_1$  and  $v_{r,1}$  for the sensor and  $R_{21}$  and  $v_{r,21}$  for the repeater. To be able to calculate the complete target velocity, the angle  $\theta_1$  between sensor and target and the angle  $\theta_2$  between repeater and target have to be known. The necessary angles can be calculated if the target position can be estimated. As the positions of the sensor and the repeater are known, this can be done either by means of multi-channel direction-of-arrival (DoA) estimation at the sensor or by using multilateration. If the angle information is available, the radial velocity vector seen from the target  $\vec{v}_{r,1}$  can be calculated as

$$\vec{v}_{r,1} = \begin{pmatrix} v_{r,1,x} \\ v_{r,1,y} \end{pmatrix} = \begin{pmatrix} v_{r,1} \sin(\theta_1) \\ v_{r,1} \cos(\theta_1) \end{pmatrix}. \quad (3)$$

The same way,  $\vec{v}_{r,21}$  can be calculated as

$$\vec{v}_{r,21} = \begin{pmatrix} v_{r,21,x} \\ v_{r,21,y} \end{pmatrix} = \begin{pmatrix} v_{r,21} \sin(\theta_2) \\ v_{r,21} \cos(\theta_2) \end{pmatrix}. \quad (4)$$

With  $\vec{v}_{r,21}$  and  $\vec{v}_{r,1}$  known,  $\vec{v}_{r,2}$  can be acquired in a similar way. As  $\vec{v}_{r,21}$  is given as the summation of  $\vec{v}_{r,1}$  and  $\vec{v}_{r,2}$ , the radial velocity seen from the repeater has to be calculated with

$$\vec{v}_{r,2} = (\vec{v}_{r,21} - \vec{v}_{r,1}) \cdot \begin{pmatrix} \operatorname{Re} \left\{ e^{1j\angle(\vec{v}_{r,1}, \vec{v}_{r,21})} \right\} \\ \operatorname{Im} \left\{ e^{1j\angle(\vec{v}_{r,1}, \vec{v}_{r,21})} \right\} \end{pmatrix}. \quad (5)$$

With  $\vec{v}_{r,1}$ ,  $\vec{v}_{r,2}$ , and the target position being available, the target velocity can be calculated. In [7], this method is applied to estimate the velocity of a moving object with multiple single-channel radar sensors.

### B. Bistatic repeater responses and modulation frequencies

In the previous section the calculation of  $\vec{v}_{r,2}$  was discussed. To get knowledge about  $\vec{v}_{r,2}$ , the bistatic target range and velocity have to be extracted. In order to acquire this bistatic information from the repeaters, the frequency of

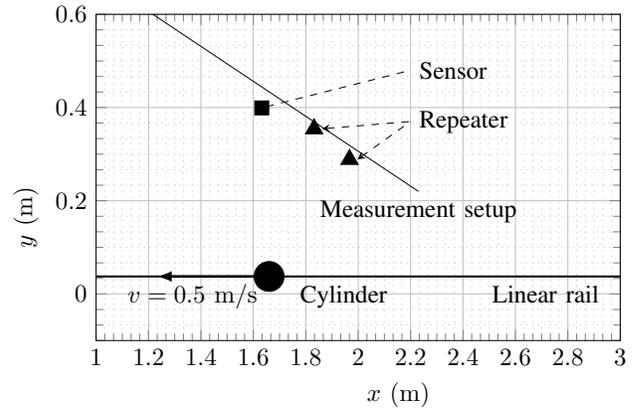


Fig. 2. Simulation and measurement setup of the network consisting of one sensor and two repeater elements.

the incoming signal is shifted by  $f_{\text{mod}}$ . The sensor receives this frequency-shifted signal, from which the bistatic target information can be extracted. The shift of the frequency in the repeater directly translates into a shift of the intermediate frequency signal at the receiver, which results in a target range offset of

$$R_{\text{shift}} = \frac{f_{\text{mod}} T_{\text{rep}} c}{2B}.$$

The velocity is also shifted because the modulation signal of the repeaters is not synchronized with the sensor ramps. This shift is static because it is only dependent on the modulation frequency  $f_{\text{mod}}$  and the chirp repetition time  $T_{\text{rep}}$  and can be calculated as

$$f_{D,\text{shift}} = \operatorname{mod} \left( f_{\text{mod}}, \frac{1}{2T_r} \right),$$

which results in a velocity offset of

$$v_{\text{shift}} = \frac{f_{D,s} c}{2f_c}.$$

This makes it possible to account for the shift in range and velocity, so that the monostatic target information can be discerned from the bistatic one later.

Table 1. Radar parameters for simulation and measurements

Parameter	Value	Parameter	Value
$f_c$	76 GHz	Target position	$\begin{pmatrix} 1.68 \text{ m} \\ 0.06 \text{ m} \end{pmatrix}$
$B$	3 GHz	Target velocity	-0.55 m/s
$T_c$	256 $\mu$ s	Sensor position	$\begin{pmatrix} 1.63 \text{ m} \\ 0.40 \text{ m} \end{pmatrix}$
$T_{\text{rep}}$	$T_c + 72 \mu$ s	Repeater positions	$\begin{pmatrix} 1.83 \text{ m} \\ 0.35 \text{ m} \end{pmatrix}, \begin{pmatrix} 1.97 \text{ m} \\ 0.29 \text{ m} \end{pmatrix}$
$f_s$	1 MHz	Repeater modulation frequencies $f_{\text{mod}}$	201.7 kHz, 262.67 kHz
$N_{\text{chirp}}$	128		

## III. SIMULATIONS

Simulations are carried out to validate the proposed concept. For the simulation one radar sensor and two repeaters

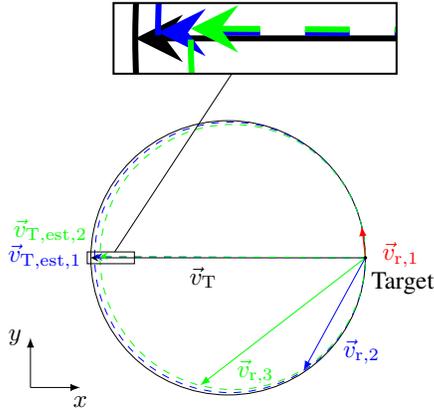


Fig. 3. Reconstructed velocity vector drawn as dashed arrows. The target position is estimated as intersect point of the range circles around sensor and repeater elements. The true target velocity and the corresponding velocity circle are drawn as solid lines.

are used. The bistatic informations are therefore denoted as  $R_{21}$ ,  $\vec{v}_{r,21}$ , and  $\vec{v}_{r,2}$  for repeater element one and  $R_{31}$ ,  $\vec{v}_{r,31}$ , and  $\vec{v}_{r,3}$  for repeater two. The simulated scenario can be seen in Fig. 2 and the chosen parameters are given in Tab. 1. The global coordinate system is aligned to the linear rail. The  $x$ -axis is placed parallel to the rail and  $y=0$  is at the lower edge of the rail. The bistatic target peaks are extracted as described in Section II. The position of the target is determined by intersecting the range circles stemming from the monostatic and the bistatic responses. This results in a determined target position at  $(x_{T,est}, y_{T,est}) = (1.671 \text{ m}, 0.060 \text{ m})$ , which fits the defined target position quite accurately. Additionally to the target position, the radial velocity  $\vec{v}_1$  for the sensor as well as  $\vec{v}_{r,2}$ ,  $\vec{v}_{r,3}$  for the repeaters are determined. Based on these radial velocities, the reconstructed target velocity is calculated for the pair  $\vec{v}_{r,1}$ ,  $\vec{v}_{r,2}$  as  $\vec{v}_{T,est,1}$  and again for the pair  $\vec{v}_{r,1}$ ,  $\vec{v}_{r,3}$  as  $\vec{v}_{T,est,2}$ . The resultant values for the vector components are shown in Tab. 3. The estimated velocity vector according to Section II is visualized in Fig. 3.

Table 2. Estimated radial velocities

Parameter		Nominal value	Simulation	Measurement
$\vec{v}_1$	$v_{1,x}$	-0.012 m/s	-0.007 m/s	-0.014 m/s
	$v_{1,y}$	0.082 m/s	0.064 m/s	0.091 m/s
$\vec{v}_2$	$v_{2,x}$	-0.114 m/s	-0.124 m/s	-0.111 m/s
	$v_{2,y}$	-0.223 m/s	-0.227 m/s	-0.217 m/s
$\vec{v}_3$	$v_{3,x}$	-0.337 m/s	-0.331 m/s	-0.329 m/s
	$v_{3,y}$	-0.268 m/s	-0.256 m/s	-0.262 m/s

#### IV. MEASUREMENTS

The setup introduced in Fig. 2 is now evaluated by measurements. The measurement setup is identical to the previously defined simulation scenario depicted in Fig. 4. The measurement parameters can be found in Tab. 1. In the scenario, a cylinder target is moving along a linear rail in front of the measurement equipment. The sensor and repeater elements are attached to another rail, which is tilted relative



Fig. 4. Measurement setup consisting of one sensor and two repeater elements mounted on a linear rail. The target is also placed on a linear rail and is moved with 0.5 m/s along the rail.

Table 3. Estimated target velocity

Parameter		Nominal value	Simulation	Measurement
$\vec{v}_{T,est,1}$	$v_{T,est,1,x}$	-0.55 m/s	-0.542 m/s	-0.553 m/s
	$v_{T,est,1,y}$	0 m/s	0.002 m/s	0.009 m/s
$\vec{v}_{T,est,2}$	$v_{T,est,2,x}$	-0.55 m/s	-0.532 m/s	-0.545 m/s
	$v_{T,est,2,y}$	0 m/s	0.003 m/s	0.010 m/s

to the rail for the moving target. The measurement is initiated after the cylinder passes a trigger switch, and then multiple measurement snapshots are captured. Since the simulation and measurement setup are the same, the results can directly be compared. For a meaningful comparison, the target position of the evaluated measurement frame is selected to be equal to the simulated target position.

At first, the monostatic and bistatic target peaks of the simulation and measurement are compared in Fig. 5. For the determined target position, both the monostatic and the two bistatic  $Rv$ -bins are at the expected positions. The artifacts seen on the right  $Rv$ -plot of Fig. 5 originate from multiple reflections between arbitrary combinations of the sensor, repeater and linear rail.

To further show that the bistatic received  $Rv$ -bins are correct, an  $Rv$ -plot for several of the captured radar snapshots is presented in Fig. 6, where the bistatic bins are connected by a white line. It is possible to capture the bistatic target information for both repeaters for multiple target positions on the rail. The responses fit the range-velocity profile of a linearly moving target.

The measurement frame of Fig. 5 is used to determine the velocity vector of the target. Before the radial velocities of the sensor and the repeaters can be calculated as vectors, the target position is determined by means of multilateration with the available range information. The so estimated target position is at  $(x_{T,est}, y_{T,est}) = (1.683 \text{ m}, 0.063 \text{ m})$ .

Now, with the target position known, the radial velocity vectors for the target point can be constructed. The measured value of the radial velocities after removing the offset coming

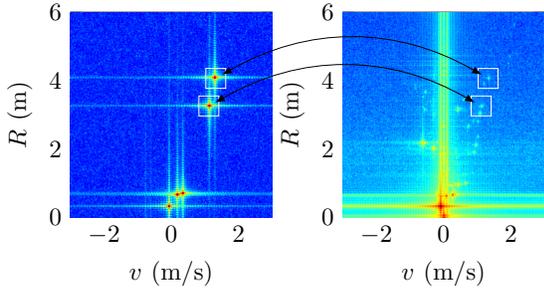


Fig. 5. Comparison between simulated  $Rv$ -domain plot (left) and measured  $Rv$ -domain plot (right). The modulation peaks from the repeaters generate targets at the expected positions.

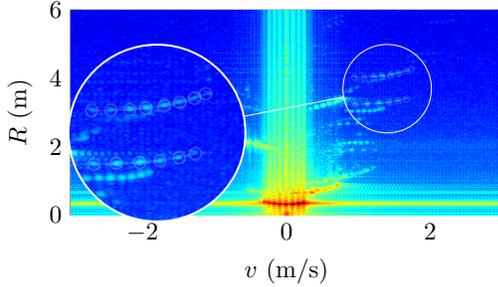


Fig. 6. Measured  $Rv$ -plot of the sensor including the responses of the two repeater elements over several frames. The frame information is superimposed by non-coherent integration. The bistatic repeater responses are marked with white circles and magnified.

from the repeater modulation and the subtraction of the monostatic velocity component is shown in Tab. 2. With this information, the circle for the true target velocity can be spanned, which is visualized in Fig. 7. By visual inspection of Fig. 7 it is already apparent, that the reconstructed target velocity vector deviates only slightly from the ground truth. By comparing the results of the measurements with the ground truth value in Tab. 3, the estimated target velocity matches the theoretical value of  $-0.55$  m/s closely.

The error in  $y$ -direction is marginal with the reconstructed  $y$ -velocity components of  $v_{T,est,1,y} = 0.009$  m/s and  $v_{T,est,2,y} = 0.010$  m/s, which translates to very small unwanted inclination angles of  $1.05^\circ$  and  $0.93^\circ$  relative to the true movement direction.

## V. CONCLUSION

In this paper, the instantaneous velocity vector of a target is determined within a single measurement snapshot. To acquire the velocity in a single snapshot, a radar network is used. The network consists of one sensor and two repeaters, which operate coherently. This novel networking concept enables the use of a coherent bistatic path between the sensor and the repeater without wiring between the nodes. The repeaters can be distributed freely and are acting as a stand-alone system with a power supply as only requirement.

This approach provides a cost- and time-effective velocity estimation, as the measurement network neither needs to

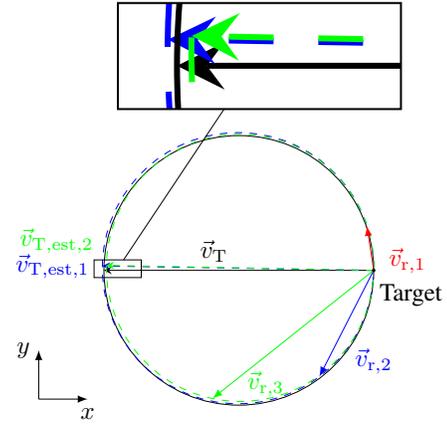


Fig. 7. Reconstructed velocity vector drawn as dashed arrows. The target position is estimated as an intersection of the range circles around the sensor and repeater elements. The true target velocity and the corresponding velocity circle are drawn as solid lines.

be synchronized nor requires knowledge over multiple measurement snapshots. Simulations were conducted to prove the proposed system concept. Measurements with a cylinder target moving on a rail were carried out to support the simulations. The evaluation showed that the bistatic information from the repeaters can be extracted and evaluated and that the true velocity of the target could be gathered with a high accuracy.

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## REFERENCES

- [1] A. Frischen, J. Hasch, and C. Waldschmidt, "A Cooperative MIMO Radar Network Using Highly Integrated FMCW Radar Sensors," *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 4, pp. 1355–1366, Apr. 2017.
- [2] S. Uematsu, "Determination of Volume of Arterial Blood Flow by an Ultrasonic Device," *Journal of Clinical Ultrasound*, vol. 9, no. 5, pp. 209–216, Jun. 1981.
- [3] D. Kellner, M. Barjenbruch, J. Klappstein, J. Dickmann, and K. Dietmayer, "Instantaneous Full-Motion Estimation of Arbitrary Objects using Dual Doppler Radar," in *IEEE Intelligent Vehicles Symposium Proceedings*, Jun. 2014, pp. 324–329.
- [4] A. Frischen, J. Hasch, and C. Waldschmidt, "Performance degradation in cooperative radar sensor systems due to Uncorrelated Phase Noise," in *11th European Radar Conference*, Oct. 2014, pp. 241–244.
- [5] M. S. Dadash, J. Hasch, P. Chevalier, A. Cathelin, N. Cahoon, and S. P. Voinescu, "Design of Low-Power Active Tags for Operation With 77–81-GHz FMCW Radar," *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 12, pp. 5377–5388, Dec. 2017.
- [6] V. Winkler, "Range Doppler detection for automotive FMCW radars," in *European Microwave Conference*. IEEE, 2007, pp. 1445–1448.
- [7] M. Steiner, O. Hammouda, and C. Waldschmidt, "Ego-Motion Estimation using Distributed Single-Channel Radar Sensors," in *IEEE MTT-S International Conference on Microwaves for Intelligent Mobility (ICMIM)*, Apr. 2018.