Range-Angle Coupling and Near-Field Effects of Very Large Arrays in mm-Wave Imaging Radars

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Abstract—In order to improve the resolution of imaging radars, electrically large arrays and a high absolute modulation bandwidth are needed. For radar systems with simultaneously high range resolution and very large aperture, the difference in path length at the receiving antennas is a multiple of the range resolution of the radar, in particular for off-boresight angles of the incident wave. Therefore, the radar response of a target measured at the different receiving antennas is distributed over a large number of range cells. This behavior depends on the unknown incident angle of the wave and is, thus, denoted as range-angle coupling. Furthermore, the far-field (FF) condition is no longer fulfilled in short-range applications. Applying conventional signal processing and radar calibration techniques leads to a significant reduction of the resolution capabilities of the array. In this article, the key aspects of radar imaging are discussed when radars with both large aperture size and high absolute bandwidth are employed in short-range applications. Based on an initial mathematical formulation of the physical effects, a correction method and an efficient signal processing chain are proposed, which compensate for errors that occur with conventional beamforming techniques. It is shown by measurements that with an appropriate error correction an improvement of the angular resolution up to a factor of 2.5 is achieved, resulting in an angular resolution below 0.4° with an overall aperture size of nearly 200 λ0.

Index Terms—Calibration, direction-of-arrival (DoA) estimation, far-field (FF) condition, imaging radar, large array, millimeter-wave radar, multiple-input multiple-output (MIMO) radar, short-range radar.

I. INTRODUCTION

IMAGING radar sensors provide accurate measurements of range, velocity, and angle and are used in a variety of civil and military applications [1]–[5]. Due to a large number of applications, there is an increasing demand for low-cost and compact imaging radar sensors with an improved resolution and, thus, a higher separability of closely spaced targets. To separate closely spaced targets, both the range and angular resolution of the radar must be improved, which is achieved by increasing the absolute bandwidth and the aperture size of the array, respectively. To keep the sensor compact, operating frequencies above 100 GHz are employed [6]–[10].

Recently, numerous millimeter-wave frequency-modulated continuous-wave (FMCW) imaging radars above 100 GHz have been published [11]–[15], see Table I. Table I is sorted by increasing virtual aperture size \( A_V \), and thus increasing angular resolution capabilities (\( \Delta \vartheta \): azimuth and \( \Delta \varphi \): elevation).

Since phased arrays or mechanical scanning antennas are expensive, the direction-of-arrival (DoA) is determined by digital delay-and-sum beamforming on the receiver side in a lot of low-cost applications. Typically, the DoA of the target is estimated after a previous range-Doppler processing and subsequent target extraction [16]. For typical multiple-input multiple-output (MIMO) radars using conventional aperture sizes or modulation bandwidths, the difference in path length of the incident wave at the receive antennas does not noticeably exceed the range resolution of the radar, see [11]–[13].

However, in case of both a large aperture size and a high absolute bandwidth, the difference in path length between the receiving antennas exceeds the range resolution of the radar significantly, especially for targets located at off-boresight angles. Therefore, the radar response of different virtual channels is distributed over a large number of range cells, depending on the incident angle of the signal. Applying conventional signal processing techniques, the system performance is considerably reduced. In addition, large aperture arrays usually violate the far-field (FF) condition in short-range applications. Consequently, the radar calibration and subsequent measurements cannot be performed based on the plane wave approximation.

Similar problems are known from the synthetic aperture radar (SAR). The azimuth-dependent range cell migration originates from the fact that the distance between the radar and the measured target is changing within the synthetic aperture time. Various SAR focusing and correction methods have been presented [17]–[19]. The back-projection and range migration algorithm are two prevalent methods for image reconstruction.
and are used in [14] and [15]. However, the high computational complexity of these algorithms is disadvantageous and makes them unsuitable for low-cost radar applications [19].

This work discusses the performance degradation associated with high-resolution MIMO radars when both large apertures and high bandwidths are used in short-range applications. This article contains the following new key aspects. First, a path-based error correction method is derived, allowing conventional signal processing and calibration techniques to be applied under FF violation. Second, an efficient signal processing is proposed that enables the full exploitation of the angular resolution capabilities of large arrays with high range resolution.

This article is organized as follows. The system concept of very large aperture radars is introduced in Section II. In Sections III and IV, the physical effects of using large arrays with high range resolution and violation of the FF condition are formulated, and a path-based error correction method is derived. A computationally efficient signal processing chain is proposed in Section V. Finally, the reliability of the presented error correction method and its feasibility are proven by measurements in Section VI.

II. SYSTEM CONCEPT

The block diagram in Fig. 1 shows the system concept of an imaging radar employing an electrically large aperture size. The radar system consists of $L$ transmit-receive (TRx) channels and is technically extendable to any number of hardware channels. Furthermore, the overall large aperture is dividable into $N$ smaller subapertures.

In order to realize a MIMO system with an electrically large aperture, signal coherency must be guaranteed across the whole aperture [20]. This is particularly challenging at higher frequencies and comes with an increased hardware effort. For apertures of medium size ($\lambda_0 \approx 70 \lambda_0$), the local oscillator (LO) signal can be distributed at a lower frequency band and multiplied on the monolithic microwave integrated circuit (MMIC) [10], [13], [21]. However, for large apertures, high losses of the distributed signal aggravate a coherent LO distribution concept. Signal coherency can also be achieved for incoherent signal synthesis by using a parasitic coupling path of the radar system [20]. Alternatively, phase synchronization between incoherent signals can be achieved by a joint processing of all bistatic TRx pairs (i.e., $\text{TX}_i\text{RX}_j$ and $\text{TX}_i\text{RX}_i$, $i \neq j$) and the generation of a synthetic beat signal [22].

In the following, it is assumed that all subapertures in Fig. 1 can be individually evaluated using conventional methods without significant performance degradation related to the large aperture and the high bandwidth. The mathematical description of the physical effects thus focuses on the overall aperture with high range resolution and FF violation.

III. RANGE-ANGLE COUPLING EFFECT

In this section, the errors that are caused by the large aperture size and the high bandwidth are mathematically formulated. Afterward, a simple path-based error correction method is proposed.

A. Description of the Range- Angle Coupling Effect

Fig. 2 shows the reference coordinate system with an exemplary transmit ($\text{TX}_i$) and receive ($\text{RX}_j$) antenna pair and the related virtual antennas ($\text{VX}_k,\phi$ and $\text{VX}_k,R$) for a target in the FF located at the distance $R_{\text{Target}}$ and angle $\vartheta$ from the array center $C$. In general, the wave reflected by the target and impinging on the RX antennas is affected by different path lengths at the RX antennas dependent on the incident angle, which causes a phase difference of the RX signals at adjacent antennas. An evaluation of these phase differences allows for the estimation of the DoA. Formally, the signal phases at the individual RX antennas are summarized in the FF steering vector $a_{\text{RX,FF}}$, i.e.,

$$a_{\text{RX,FF}} = \left[ e^{j\frac{2\pi}{\lambda_0} x_1 \sin(\vartheta)}, \ldots, e^{j\frac{2\pi}{\lambda_0} x_j \sin(\vartheta)}, \ldots, e^{j\frac{2\pi}{\lambda_0} x_N \sin(\vartheta)} \right]^T$$

$$= \left[ e^{j\Delta \phi_{\text{RX,FF},1}}, \ldots, e^{j\Delta \phi_{\text{RX,FF},j}}, \ldots, e^{j\Delta \phi_{\text{RX,FF},N}} \right]^T, \quad (1)$$

with the antenna distance $x_j$ from the array center, the phase progression $\Delta \phi_{\text{RX,FF},j} = (2\pi/\lambda_0)x_j \sin(\vartheta)$, the free-space wavelength $\lambda_0$, and the number $N_{\text{RX}}$ of RX antennas. The same applies to the TX steering vector $a_{\text{TX,FF}}$.

In case of a MIMO radar using orthogonal TX signals, the phase $\phi_k$ of the received signal at an exemplary virtual receive antenna $\text{VX}_k,\phi$ is composed of the sum of the signal phases at the corresponding TX and RX antennas. Mathematically, the steering vector $a_{\text{VX,FF}}$ of the virtual array is calculated by

$$a_{\text{VX,FF}} = a_{\text{TX,FF}} \otimes a_{\text{RX,FF}} \quad (2)$$

where $\otimes$ is the Kronecker product. Thus, the location of the $k$-th VX position $x_{\text{VX}_k,\phi}$ is illustratively given by a spatial convolution of the corresponding TX and RX antenna locations $x_{\text{TX}_i}$ and $x_{\text{RX}_j}$ [23].
where $\Delta R_{k}$ of the received signal at the $k$-th virtual channel corresponds to a frequency shift of the beat signal w.r.t. a signal measured at the array center $C$. To obtain overlaying range spectra for all receive channels, as shown in Fig. 3(a), a frequency shift of the measured signal $s_{B,k}$ is performed. In the case of an FMCW radar, for example, the following relationship between modulation parameters and range holds [24]:

$$s_{B,\text{corr},k}(t) = s_{B,k}(t) \exp \left( -j2\pi \frac{2}{c_0} \frac{B}{t_{\text{up}}} t \right),$$  

where $s_{B,\text{corr},k}$ is the signal shifted in frequency, $t \in [0, t_{\text{up}}]$ is the continuous time, $t_{\text{up}}$ the up-chirp duration, $B$ the modulation bandwidth, and $c_0$ the speed of light. According to (3), the frequency shift depends on the unknown DoA $\vartheta$ and the VX location $x_{VX,k,\vartheta}$. The latter is known from the manufacturing data or can be derived from the calibration [25]. The determination of the unknown DoA is discussed in Section V.

Due to the digitization of the measurement data and a subsequent fast Fourier transform (FFT) processing, the error caused by the range-angle coupling can be efficiently corrected by a shift of the range spectra in multiples of the size of a range cell after range-Doppler processing. Thus, a renewed 2-D-FFT processing for each target and angle is avoided. The necessary number of range cells for shifting the range spectra for the $k$-th virtual channel is calculated by

$$n_{\text{shift},k} = \left\lfloor \frac{x_{VX,k,\vartheta} N_{ZP}}{\delta R} + 0.5 \right\rfloor,$$

where $N_{ZP}$ denotes the zeropadding factor, $\delta R$ the range resolution, and $\lfloor x \rfloor$ the floor function. Fig. 4 shows the continuous phase of the beat signal for two adjacent range cells. A range shift according to (5) leads to a phase step if the size of a range cell is not an integer multiple of the wavelength. Therefore, an additional phase correction must be applied to mathematically match with the frequency shift in (4). The required phase correction value $\Delta \phi_{R,k}$ of the $k$-th virtual channel is determined by the ratio of range resolution $\delta R$ and free-space wavelength $\lambda_0$, which is converted to a phase by

$$\Delta \phi_{R,k} = -n_{\text{shift},k} \left( \frac{\delta R}{\lambda_0} \right) \cdot 360^\circ.$$

IV. NEAR-FIELD INFLUENCE

This section deals with phase errors caused by the violation of the FF condition. Starting with a mathematical formulation of the near-field (NF) influence, a path-based error correction method is demonstrated.
A. Description of the Phase Errors Due to an FF Violation

The (Fraunhofer) FF distance $R_{FF}$ is the minimum distance at which the spherical wave becomes a close approximation to the phase front of a plane wave [26]. It is defined as

$$R_{FF} = \frac{2A_{phys}^2}{\lambda_0},$$

(7)

where $A_{phys}$ is the physical aperture size of the array. The FF condition refers to a signal path from the antenna to the target. For MIMO systems, the total phase error is composed of the phase error of the TX and RX signal paths, which doubles the distance to satisfy the FF condition (total error $< \lambda_0/16$).

Fig. 5(a) shows the differences of the path lengths and the related phase relations of a spherical wave in comparison with a plane wave with an incident angle $\vartheta = -40^\circ$. The phase error caused by the spherical wave becomes more pronounced with decreasing target distance, as shown in Fig. 5(b).

The definition of the VX location $x_{VX,\vartheta}$ is based on plane wave fronts (FF condition fulfilled). In this case, the resulting signal phase at the VX location, and thus, its virtual distance are determined by the sum of the signal phases at the respective TX and RX antenna locations [Fig. 5(a)], i.e.,

$$\Delta \phi_{VX,FF,k} = \Delta \phi_{TX,FF,j} + \Delta \phi_{RX,FF,j}.$$  

(8)

Since the phase progression between the antennas only depends on the incident angle and not on the target distance (FF condition is fulfilled), the resulting virtual position is constant. According to (1), the VX position is alternatively given by the slope of the angle-dependent phase progression [25].

However, if the NF influence applies, the VXs that hold in the FF, see (8), are no longer valid, which can be interpreted by a displacement of the VX locations, i.e.,

$$\Delta \phi_{VX,NF,k} \neq \Delta \phi_{TX,NF,j} + \Delta \phi_{RX,NF,j}.$$  

(9)

The displacement due to the FF violation depends on the target distance $R_{TARGET}$ and the incident angle $\vartheta$. This allows the definition of an equivalent VX position, which is given by the derivative (slope) of the angle-dependent phase progression.

B. Determination of the Phase Error

The mathematical description of the correction method for the inequality in (9) is performed individually for the signals of the TX and RX signal paths. The location of a target at the distance $R_{TARGET}$ in the coordinate system of Fig. 5(a) is

$$\hat{R}_{TARGET} = [-R_{TARGET} \cdot \sin(\vartheta), R_{TARGET} \cdot \cos(\vartheta)]^T.$$  

(10)

The phase progression of a spherical wave impinging on an RX antenna is given by the NF steering vector

$$\bar{a}_{RX,NF} = \begin{bmatrix} e^{j\frac{2\pi}{\lambda_0}|R_{TARGET} - \tilde{x}_1|/\lambda_0} \\ ... \\ e^{j\frac{2\pi}{\lambda_0}|R_{TARGET} - \tilde{x}_N|/\lambda_0} \end{bmatrix} = \begin{bmatrix} e^{j\Delta \phi_{RX,NF,1}} \\ ... \\ e^{j\Delta \phi_{RX,NF,N}} \end{bmatrix},$$

(11)

where $\tilde{x}_j = [x_j, 0]^T$ is the location of an RX antenna on the $x$-axis and $\Delta \phi_{RX,NF,j} = 2\pi(|R_{TARGET} - \tilde{x}_j| - |\hat{R}_{TARGET}|)/\lambda_0$ the NF phase progression. The same applies to the TX antennas.

The correction steering vector compensating the NF influence is therefore calculated by

$$\bar{a}_{RX,corr} = (\bar{a}_{RX,NF} \odot (\bar{a}_{RX,FF}^*)^*)^* \begin{bmatrix} e^{-j(\Delta \phi_{RX,NF,1} - \Delta \phi_{RX,FF,1})} \\ ... \\ e^{-j(\Delta \phi_{RX,NF,j} - \Delta \phi_{RX,FF,j})} \\ ... \\ e^{-j(\Delta \phi_{RX,NF,N} - \Delta \phi_{RX,FF,N})} \end{bmatrix},$$

(12)
where $\odot$ is the Hadamard product, and $(\cdot)^*$ the complex conjugate. The same applies to the correction of the TX path. Thus, the corrected steering vector including compensation of the NF effects is calculated by

$$\tilde{a}_{RX,FF} = \tilde{a}_{RX,NF} \odot \tilde{a}_{RX,corr}.$$  \hspace{1cm} (13)

Fig. 6 shows the positioning error between the VX positions in the FF and the equivalent VX positions in case of a FF violation as a function of target distance $R_{\text{Target}}$ and incident angle $\vartheta$. It is derived from the phase progression [25] and shown for an exemplary antenna configuration violating the FF condition. It shows that for antennas far apart from the array center $C$ and at short ranges, the VX positions highly depend on target distance and incident angle.

C. Distance-Independent Calibration

Due to the FF violation, the phase progression becomes distance- and angle-dependent, see Fig. 5(a) and (b). The spherical wave causes a phase error in the calibration, which is corrected by employing the known calibration distance, see Section IV-B.

The compensation of the NF influence for both the calibration and the measurement refers them to the FF and allows performing calibration and measurement at an arbitrary distance and with conventional beamforming techniques. However, to correct the NF error, an additional a priori knowledge of the incident angle is required, which is obtained as shown in the following Section V.

V. OVERALL SIGNAL PROCESSING CHAIN

In order to correct the errors caused by the range-angle coupling (see Section III) and the NF influence (see Section IV), an a priori knowledge about the incident angle $\vartheta$ and target distance $R_{\text{Target}}$ is necessary. The entire signal processing chain for the evaluation of electrically large arrays with high range resolution is shown in Fig. 7. It is subdivided into two parts.

1) Subarray Estimate: Each subaperture is characterized by a sufficiently small aperture size with negligible impact of the range-angle coupling effect and the NF influence on the system performance. Thus, the subarray is evaluated conventionally, as shown in the upper part of Fig. 7. After transforming the time-domain signals into the frequency domain by a 2-D-FFT, the range-Doppler matrix is obtained for each virtual channel. As the error caused by the range-angle coupling is negligibly small, a target appears in the same range-Doppler cell for each channel. Afterward, the range-Doppler matrices are noncoherently accumulated, resulting in a processing gain improving the signal-to-noise ratio (SNR). The targets become visible as high amplitude values in certain range-Doppler cells, each containing one or more target signals with the same range and velocity information but potentially different angular information. After the peak search, the steering vector of each target is extracted and fed into a DoA estimator.

2) Full Array Estimate: In contrast to the subarray, electrically large arrays with high range resolution are highly affected by the range-angle coupling and the NF influence. Thus, these errors have to be corrected to achieve optimal performance. The required a priori knowledge of the incident angle is obtained from the subarray estimate. A frequency shift for correction of the range-angle coupling is then performed for each target according to (4) and (5). Afterward, the range-Doppler matrices are noncoherently accumulated. The target for which the correction was applied appears with increased SNR in comparison to the subarray due to a higher processing gain of all channels. Other targets with a different DoA blur. The position deviation between the global coordinate system (center of the full array) and the center of the subarray leads to a deterministic offset between the range-Doppler cells of the full array and a subarray. The range-Doppler cell assigned to a particular target by the subarray is, therefore, related to the global coordinate system. Afterward, the steering vector is extracted in this particular target cell for all channels of the full array. Consequently, no updated peak search is applied. The NF error is then compensated for the extracted steering vector. If multiple targets are located in the same range-Doppler cell, the high angular resolution of the full array enables a separation of those targets in the angular domain.

By splitting the signal processing into these two parts, this processing chain is capable of resolving multiple targets. The FFTs are only calculated once, and the error caused by the range-angle coupling is corrected for each subarray target by
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Fig. 8. (a) Sketch of the used antenna array with TX antennas (●), RX antennas (●), and VX positions (○). (b) Photograph of the antenna array.

TABLE II
OVERVIEW OF THE RADAR PARAMETERS

| Parameter                          | Value          |
|-----------------------------------|----------------|
| Ramp duration $T$                 | 100 µs         |
| Ramp repetition time $T_r$        | 150 µs         |
| Center frequency $f_c$            | 152.5 GHz      |
| RF bandwidth $B$                  | 10 GHz         |
| Number of clumps $N_c$            | 512            |
| Number of virtual channels $N_{VX}$ (subarray) | $64 = 8 \times 8$ |
| Number of virtual channels $N_{VX}$ (full array) | $256 = 16 \times 16$ |
| Virtual aperture $A_v$ (subarray) | $65 \lambda_0$ |
| Virtual aperture $A_v$ (full array) | $196.5 \lambda_0$ |

*In order to improve the baseband signal quality only 10 GHz are used instead of the full available bandwidth of 20 GHz.

with the virtual aperture size $A_v$. In case of a nonuniform antenna illumination, this lower bound is slightly increased.

B. Influence of the Range-Angle Coupling Effect

To evaluate the DoA estimation performance, measurements are performed for a single target, which is located at the distance of 4.9 m and the angle of 30°. To eliminate the NF influence, the radar is calibrated at the same distance. The large incident angle of $\vartheta = 30°$ leads to a significant influence of the range-angle coupling. To demonstrate the improvement in DoA estimation, the measurement results are compared with state-of-the-art signal processing with the entire array (upper row in Fig. 7) without a frequency and phase correction [16], [30], [31].

The range spectra of all 256 virtual channels are shown in Fig. 9(a). Without correcting the error caused by the range-angle coupling, the radar response of a single target is distributed over seven range cells. After the noncoherent accumulation of the range-Doppler matrices, the target peak appears considerably broadened, and the measured signal strength drops by 3.4 dB [Fig. 9(b), (---)]. Since the phase values of the steering vector are extracted from that single range cell, where the target is detected in the accumulated range-Doppler matrix, a large number of entries in the steering vector are extracted outside the individual main peaks or from noise [Fig. 3(b)]. Hence, the angular resolution is significantly reduced to $0.78°$, see Fig. 9(c). Applying the corrections according to Section III-B, the range spectra from all channels are shifted toward the desired range cell, which provides a sharp target peak in the accumulated range-Doppler matrix, and thus, results in an improved angular resolution. However, range quantization errors cause that some channels are one range cell apart from the desired one. As the SNR does not drop immediately, a correct extraction of the steering vector [Fig. 9(b), (-----)] is still possible.

The full angular resolution capability of the array is verified by measuring the angular separability of two targets with the same reflectivity and an angular distance of $0.4°$ under an incident angle $\vartheta \approx 30°$ (Fig. 10). The correction of the error caused by the range-angle coupling (-----) allows an angular separability close to the theoretical limit of $0.3°$, see (14).
Fig. 9. Measured system performance of a target at \( \theta = 30^\circ \) with correction of the error caused by the range-angle coupling (- - -) and without correction (---): (a) range spectra of all virtual channels, (b) accumulated range spectrum, and (c) angular spectrum.

Without correction (---) of the error caused by the range-angle coupling, the power distribution in the angular spectrum is significantly broadened and does not allow separating both targets. The subaperture estimate (- - -) provides a coarse a priori knowledge of the incident angle, which is sufficient to compensate the errors for both targets at 29.8° and 30.2°. 

C. Influence of the NF Error

The influence of the NF on the DoA estimation is evaluated for a target located at a distance of 1.5 m, whereas the radar is calibrated at a significantly larger distance of 5 m. The measured angular spectra are shown in Fig. 11 for a target in the boresight direction.

Without correction of the NF error described in Section IV-B, the received power of the target in the boresight direction \( (\theta = 0^\circ) \) is spread in the angular domain over two main maxima (at \( \pm 2^\circ \)), which corresponds to slightly different aspect angles related to both subapertures from a short distance. This behavior proves the FF violation (Fig. 6) and the distance dependence of the calibration [Fig. 5(b)]. However, if the NF influence is corrected according to Section IV-B and both calibration and measurement are referred to the FF [Fig. 5(b)], the DoA estimation performance is comparable to a target located at the calibration distance. Fig. 11 shows good agreement between the measurement at 5 m (---) and 1.5 m (-----) in case that the NF influence is compensated. The correction method also works at an off-boresight angle but requires an additional compensation of the range-angle coupling error.

D. Extended Target Scenario

The feasibility of the signal processing chain proposed in Section V (Fig. 7) is demonstrated with a wooden box as an extended target. The box is rotating with a rotational velocity \( v_r = 35^\circ/s \) around its vertical axis. The radar is calibrated at 5 m, whereas the wooden box is located at approximately 1.75 m. First, as shown by Fig. 12(a), the measurement is evaluated conventionally using both subapertures as proposed in the upper part of Fig. 7. For each of the detected targets in the subaperture estimate, a DoA estimation is performed providing an a priori knowledge to compensate for the NF errors and the errors due to the range-angle coupling. Applying the correction method from Section III-B individually to all targets, the received power level for the corrected target increases, whereas targets at other angles are blurred, see Fig. 12(b). Afterward, the full resolution capability of the array is exploited. With the proposed method it is possible to separate two edges of a vertical wooden slat located in the same range-Doppler cell with an angular distance of 0.5°, see Fig. 12(c) (highlighted in green, -----). The other diffraction edges, which are detectable by the radar, are shown in red (-----). As shown by the x-y-diagram in Fig. 12(d), the radar is capable of detecting the most significant diffraction edges, and thus, to determine both the orientation and size of the wooden box in front of the radar.
Fig. 12. Measurement of a wooden box located at off-boresight direction. (a) Range-velocity diagram measured with subaperture 1. (b) Range-velocity diagram for a correction of the error caused by the range-angle coupling using $\theta \approx -21^\circ$. (c) Angular spectrum for the detected wooden slat ($\times$) after correction of the range-angle coupling and the error caused by the violation of the FF condition ($\circ$) in comparison with an evaluation with subaperture 1 ($\cdots\cdots$). (d) $x$--$y$-diagram of all detected targets within the measurement scenario, including a photograph of the box.

VII. CONCLUSION

In this article, the performance degradation in radar imaging using electrically large arrays and high range resolution with a simultaneous violation of the FF condition is discussed. It is shown that the difference in path lengths of the incident wave at the antenna elements significantly exceeds the range resolution of the radar. Depending on the unknown DoA of the target echo, the measured distance of the target at the different receiving channels is distributed over multiple range cells. In addition, due to the violation of the FF condition, the calibration becomes distance-dependent. Based on a mathematical formulation of the physical effects, two path-based correction methods are proposed to compensate for all relevant errors. A signal processing chain is given to provide the unknown a priori knowledge of the incident angle, which is afterward used to exploit the full resolution capability of the array. Measurements of both point-like targets and an extended target scenario prove the feasibility of the proposed error correction method and the related signal processing chain.

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