Near-Field Compensation for Coherent Radar Networks

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***Abstract*—With radar networks, the resolution of critical radar parameters like Doppler and angle can be improved compared to a single radar sensor. As the network's aperture is considerably larger than the one of a single radar, a much higher angular resolution is achieved. However, with a large aperture, range-dependent phase deviations, i.e. near-field effects, occur and affect the angle estimation. In this work, these near-field effects are evaluated exemplarily for a coherent network. Furthermore, a new strategy to compensate those network near-field effects is proposed and demonstrated based on measurements. The benefits of the near-field compensation are emphasized by comparing the networks angle-estimation capabilities with and without compensated near-field effects.**

***Index Terms*—radar, network, repeater, near-field, multistatic, coherency, aperture, compensation**

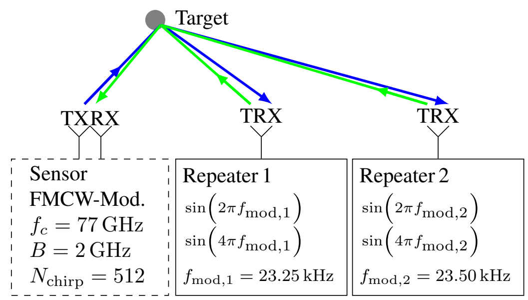

Fig. 1. Schematic representation of used radar-repeater network. Depicted are exemplary signal paths between a target and the network nodes. Each repeater is fed by two sine signals. Blue color denotes paths from radar to repeater, green color denotes the reverse paths from repeater to radar.

I. Introduction

The trend in modern radar systems goes towards radar networks [1], [2], [3], [4], as they allow for better scene coverage, frame rates, robustness, and angular estimation performance, among other benefits. Coherent radar networks feature phase coherency between the nodes yielding superior angle estimation performance. The coherency in the network is conserved either via the hardware setup or via signal processing techniques. In this work, a coherent network is realized as radar-repeater network [5], [6] without loss of generality, i.e. as a radar node supported by multiple repeater nodes. The repeater hardware consists of amplifiers and a mixer, where modulation signals can be fed into, similar to [7]. In order to achieve a successful calibration and measurements with an extended radar network, near-field effects [8] have to be considered. The near-field effects describe the deviation of the receive phase from the plane wave assumption. The larger the aperture and the closer the target, the bigger the impact on the angle estimation. Previous work includes the compensation of the near-field for polarimetric MIMO radars [9] and for electrically large apertures of a single radar [10]. In contrast, in case of this coherent sensor network, the near-field calibration is a two-step process. First, the target's range and position are estimated by the radar node, which, due to its small aperture, is not largely influenced by the near-field effect. This way, a geometric model is constructed based on the radar's measurements. The near-field influence from target to the network nodes is then calculated and compensated by means of this model.

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The paper is structured as follows: After the introduction of the system and description of the near-field effect in Section II, the near-field compensation for the network nodes is derived in Section III. In Section IV, the simulative investigation of the near-field is performed. Finally, measurements are featured in Section V to validate the concept.

II. System

A. System Setup

The investigated coherent network is built as radar-repeater network ([5], [6]), which consists of a radar sensor and one or multiple additional repeaters. In this work, the radar uses the frequency-modulated-continuous-wave (FMCW) modulation [11], but other radar modulation forms, e.g. orthogonal-frequency-division-multiplexing (OFDM) are also possible [6]. The repeaters act as additional network nodes via modulation and retransmission of the emitted radar signal back to the sensor. All signals are received and processed at the radar node. The repeater modulation enables the radar to differentiate between monostatic and bistatic received signal paths featured in Fig. 1. No downmixing is done within the repeaters and thus, phase coherency is preserved without tedious and costly RF cabling. Also, the phase noise remains correlated, therefore, the bistatic signal still profits from the range-correlation effect [12].

B. Signal Model

An ideal radar steering vector [13] for a target at angle θ and a sensor with a single transmit and M receive antennas can be described as

$$\mathbf{y}\left(\theta\right) = \left(\mathrm{e}^{\mathrm{j}2\pi \frac{x_1}{\lambda}\sin(\theta)}, \ldots \mathrm{e}^{\mathrm{j}2\pi \frac{x_M}{\lambda}\sin(\theta)}\right) , \qquad (1)$$

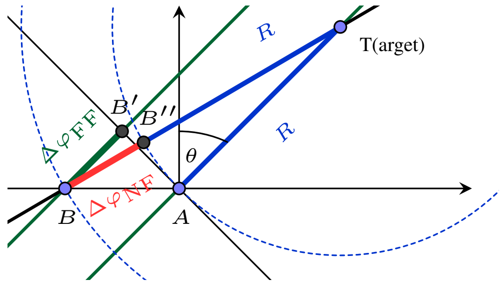
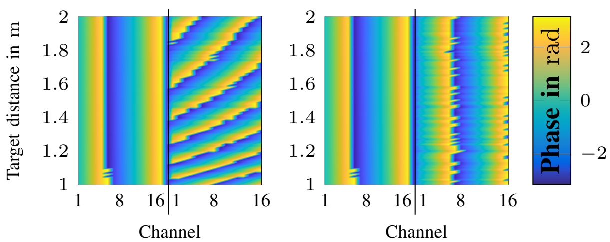


Fig. 2. Phase progression between the network nodes A and B for a target in the far-field (green) and a target in the near-field (red).



(a) Without near-field compensation (b) With near-field compensation

Fig. 3. Simulated target phase without and with near-field compensation. Depicted is the receive phase over 16 antennas for two repeater elements.

where λ is the signal wavelength and x_m with $m = 1, \ldots, M$ are the positions of the antenna elements. The steering vector contains the information about the target's angle of incidence relative to the radar. In case of a coherent radar network, where the distance between nodes in the network is large in terms of λ, a large aperture results. For targets in the near-field of this network aperture the phase progression deviates from (1). The resulting implications of this deviation are discussed in the next section.

III. Near-Field Compensation

The coherent network introduced in Fig. 1 is now investigated in terms of phase deviation to the plane-wave model (1). The near-field can lead to a severe degradation of the network angle estimation capability. To counteract this degradation, the near-field can be compensated as a two-step procedure. First, the near-field influence on the network is calculated based on the target angle information from a single radar sensor. Then, the network near-field is compensated, and the angle estimation for the complete coherent network can be performed.

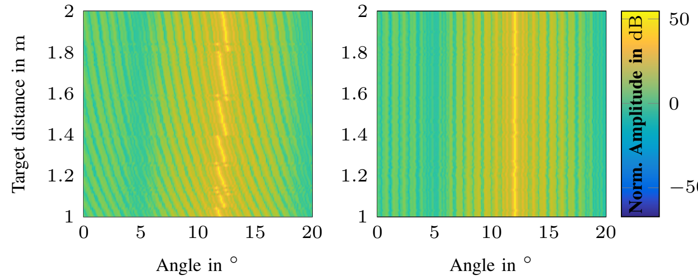
A. Near-Field Compensation for Monostatic Array

The Fraunhofer far field region [8], [14] gives the relation between far-field distance R and maximal antenna aperture D,

$$R > \frac{2D^2}{\lambda}\,. \tag{2}$$

For a target in the near-field, the corresponding radar receive phase can be calculated geometrically. The near-field range of a target in reference to the m-th antenna element is given by

$$R' = \sqrt{\Delta d_{\mathrm{m}}^2 + R^2}\,, \tag{3}$$



(a) Without near-field compensation (b) With near-field compensation

Fig. 4. Estimated target angle without and with near-field compensation after compressed sensing reconstruction (simulative setting).

where d_{m}^2 is the distance of the m-th antenna element to the center of the array. The near-field phase can then be calculated by

$$\Delta R_{\mathrm{NF},m} = R' - R \Rightarrow \varphi_{\mathrm{NF}} = \frac{2\pi}{\lambda}\Delta R_{\mathrm{NF},m} \tag{4}$$

and thus can be compensated.

B. Network Near-Field Compensation

The compensation of the near-field effect in the network depends on the target position relative to the network nodes. In Fig. 2 the far-field phase difference $\Delta\varphi_{\mathrm{FF}}$ between points A and B for a target at angle θ is given as green line. If additionally the range is considered, the near-field phase difference between the points A and B is given as $\Delta\varphi_{\mathrm{NF}}$ in red. The target's angle θ and range R are defined relative to the reference point A located in the geometric middle of the monostatic radar aperture. Therefore, these target parameters can be estimated via the monostatic radar response. With known position $(x_{\mathrm{A/B}}, y_{\mathrm{A/B}})$ and the target position (x_T, y_T) acquired via the radar, the phase for network node B in the near-field can be calculated as

$$\Delta\varphi_{\mathrm{NF}} = \exp\left(\mathrm{j}\frac{2\pi}{\lambda}\overline{BB''}\right), \tag{5}$$

$$\begin{aligned} \text{where } \overline{BB''} &= \overline{BT} - R \qquad (6)\\ &= \sqrt{(x_{\mathrm{T}} - x_{\mathrm{B}})^2 + (y_{\mathrm{T}} - y_{\mathrm{B}})^2} - R\\ &= \sqrt{(R\sin\theta - x_{\mathrm{B}})^2 + (R\cos\theta - y_{\mathrm{B}})^2} - R\,. \end{aligned}$$

The compensation phase is computed as

$$\begin{aligned} \Delta\varphi_{\mathrm{comp}} &= \Delta\varphi_{\mathrm{NF}} - \Delta\varphi_{\mathrm{FF}} \qquad (7)\\ &= \exp\left(\mathrm{j}\frac{2\pi}{\lambda}\overline{BB''}\right) - \exp\left(\mathrm{j}\frac{2\pi}{\lambda}\overline{BB'}\right). \qquad (8) \end{aligned}$$

The phase $\Delta\varphi_{\mathrm{comp}}$ can be subtracted from the received phases to eliminate the near-field influence. The quality of $\Delta\varphi_{\mathrm{comp}}$ depends on the radar's measurement of R and θ. Small variations in the estimation of these parameters can lead to small deviations in $\Delta\varphi_{\mathrm{comp}}$. Particular attention needs to be paid in the case of a radar-repeater network, as the phase $\Delta\varphi_{\mathrm{comp}}$ has to be subtracted twice. This stems from the fact that, as the radar signal travels both to and from the repeater via the target, it is influenced twice by the near-field.

IV. Simulations

Simulations are carried out to validate the assumed near-field model for targets in a close distance of $1\,\mathrm{m}$ to $2\,\mathrm{m}$ and at an angle of $12°$ to the radar. A radar with one transmit and 16 receive antennas is assumed. Two repeaters are used, which are placed at $25\,\lambda$ and $56\,\lambda$ to the right of the center of the radar's receive aperture. To evaluate the receive phases of the repeater nodes in reference to each other, all phases are normalized to the first receive phase of the left repeater. The resulting phases for the repeaters in the network as well as the angle estimation are depicted in Fig. 3 and Fig. 4, respectively. Here, the generalized formula (8) for the calculation of the near-field range is used, with a geometry as in Fig. 2. To get the angle of arrival, the phase information of the receive channels of radar and repeaters are evaluated via Compressed Sensing evaluation using the *Iterative Method with Adaptive Thresholding* (IMAT) [15] algorithm and subsequent FFT-processing. As shown in Figs. 3 and 4, the phase and angle after applied near-field compensation do no longer feature a range dependency. Consequently, the assumed geometric model and the calculated near-field phases are included correctly.

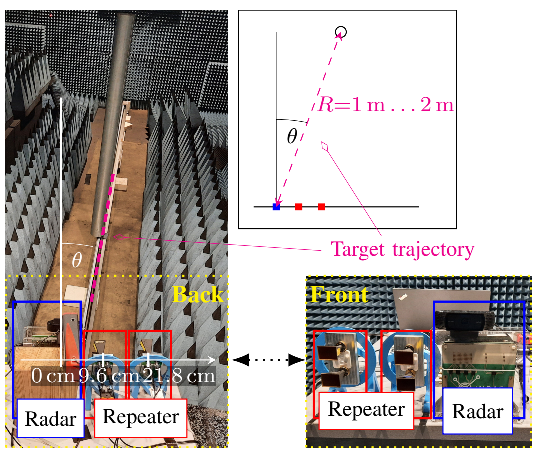
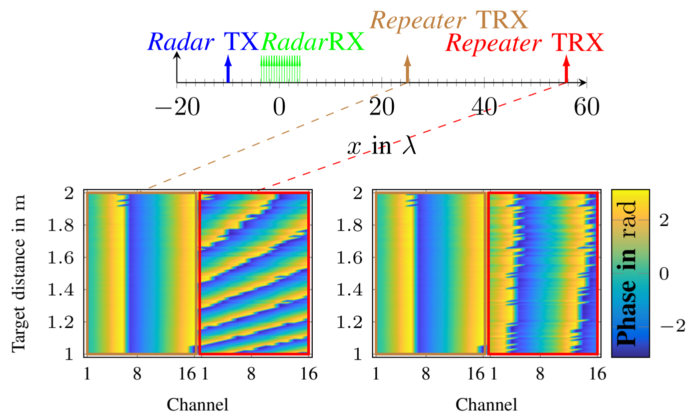


Fig. 5. Coherent network setup of one radar and two repeater elements. The radar consists of a patch antenna array (HPBW: $51°$) with linear $\lambda/2$ spacing; the repeater elements have horn receive and transmit antennas (HPBW: $13°$). The cylindrical target is moved in steps of $1\,\mathrm{cm}$ from $1\,\mathrm{m}$ to $2\,\mathrm{m}$.

V. Measurements

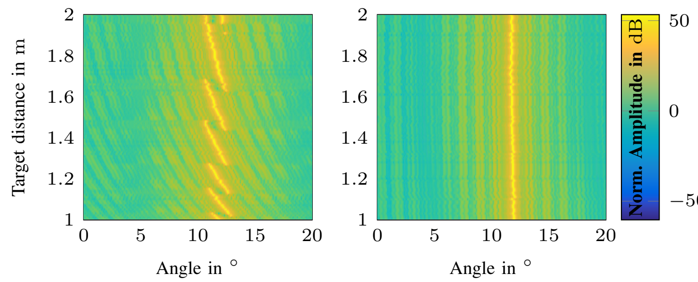
In this section the preceding observations regarding the network near-field effects will be validated by measurements. The measurement setup can be seen in Fig. 5, which features a radar sensor in combination with two repeater elements. The network nodes are placed according to the described simulation settings, and a cylinder target is placed in varying distances at an angle of $\theta{=}12°$. Subsequently, the near-field compensated phases are investigated in conjunction with the angular detection performance. In Fig. 6 the antenna configuration and the receive phases for the measurement target at $12°$ are presented, both without and with applied near-field compensation. By comparison of the phase plots of Fig. 6, the range-dependent change in the receive phase can be observed for the uncompensated phase plot, which vanishes after the applied compensation. The corresponding angle estimation plots based on the phases of Fig. 6 are featured in Fig. 7. The angle plot in Fig. 7(b) with compensated near-field influence shows a constant estimated angle, with a standard deviation of only $0.0925°$. Therefore, the near-field compensation was successful. The compensation can also be applied to a coherent radar-repeater network in a multi-target scenario as in [5], [6] to get rid of near-field-related angle distortions.

(a) Schematic representation of physical antenna positions



(b) Without near-field compensation (c) With near-field compensation

Fig. 6. Measured target phase without and with near-field compensation. The near-field compensated phase progression (c) is range-independent.



(a) Without near-field compensation (b) With near-field compensation

Fig. 7. Measured target angle without and with near-field compensation after compressed sensing reconstruction.

VI. Conclusion

In this work, the near-field effect in a coherent network was investigated. First, a signal model was introduced to describe the near-field effect in the network, afterwards, simulations and measurements were carried out to quantify the influence of the near-field effect on a target in close distance to the network. Via the simulations and measurements the successful compensation of the near-field influence was demonstrated. The measurements showed that, even for close target ranges, a range-independent angle estimation is provided after the near-field compensation is applied.

VII. Acknowledgment

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