Th2F-4

Array Calibration and Digital Predistortion Training Using Embedded Near-Field Feedback Probes and Orthogonal Coding for Enhancing the Performance of Millimeter-Wave Beamforming Arrays

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Outline

- Motivation
- Theory
- Measurement Results
- Conclusions
- Acknowledgements

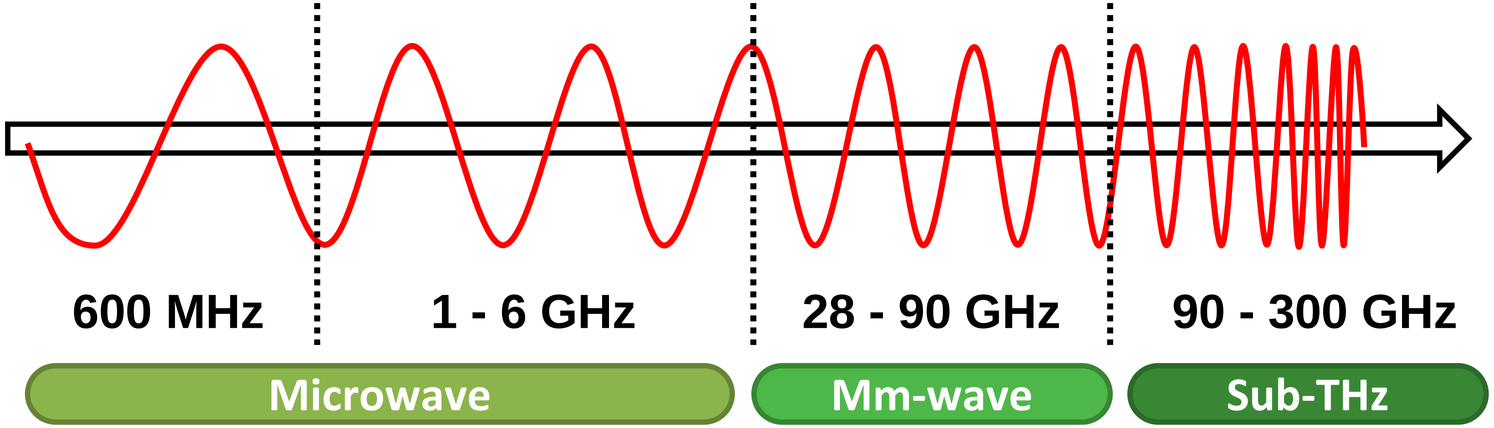
Motivation

- Mm-wave and sub-THz frequencies will play a critical part in enabling future communication systems

✓ Available Spectrum ⟺ **High Data Rate**

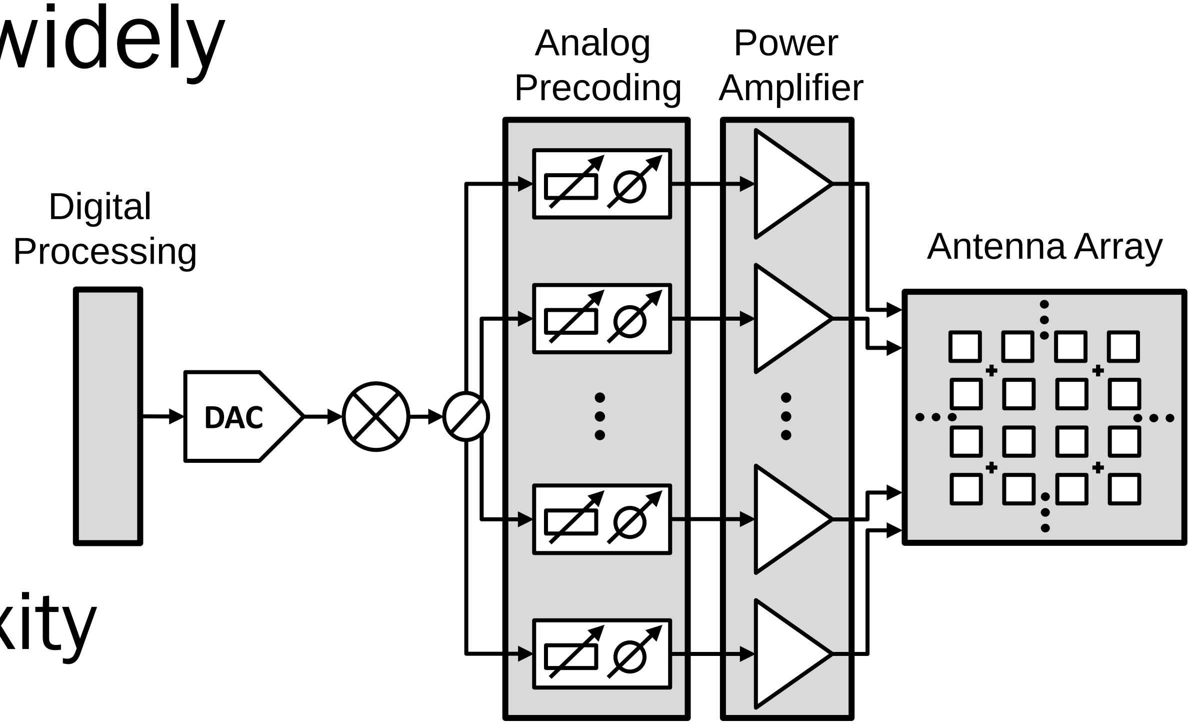
✓ Wideband Signals

✗ High Propagation Losses ⟹ **Phased Arrays**



Motivation

- RF beamforming has been widely adopted at millimeter-wave frequencies
  - Increase Effective Isotropic Radiated Power (EIPR)
  - Low implementation complexity



Motivation

- Nevertheless, RF beamforming arrays suffer from a multitude of nonidealities
  - Linear nonidealities (i.e., phase and gain errors) → **Radiation Pattern** !
    - **IC level** (e.g., phase and gain control circuitries)
    - **Board level** (e.g., assembly errors, routing)
  - Nonlinear nonidealities → **Signal Integrity** !
    - **Power amplifiers**

To compensate for these nonidealities **array calibration** and **digital predistortion (DPD)** techniques need to be deployed

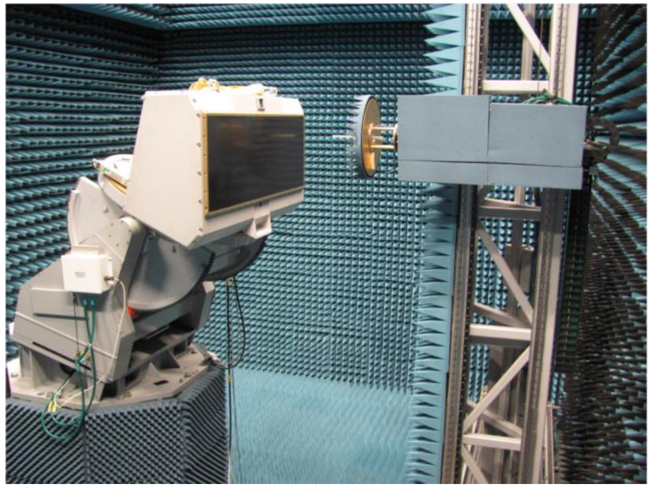
Motivation

- Different array calibration and DPD techniques have been discussed in the literature
- Existing array calibration techniques can be classified into:

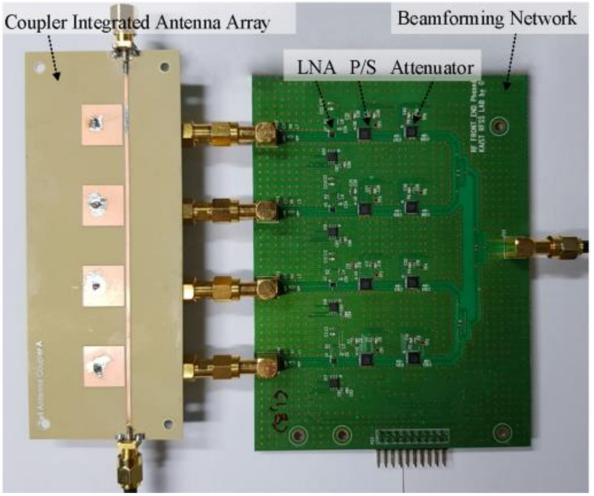
Element-wise array calibration [1-3]	**Active array calibration [4-5]**
Can calibration for phase and magnitude Errors versus beamformer settings (+)	Cannot calibrate for phase and magnitude Errors versus beamformer settings (-)
Are slow and cannot correct for errors due to heating and current loading (-)	Are fast and can correct for errors due to heating and current loading (+)

Motivation

Element-Wise Array calibration

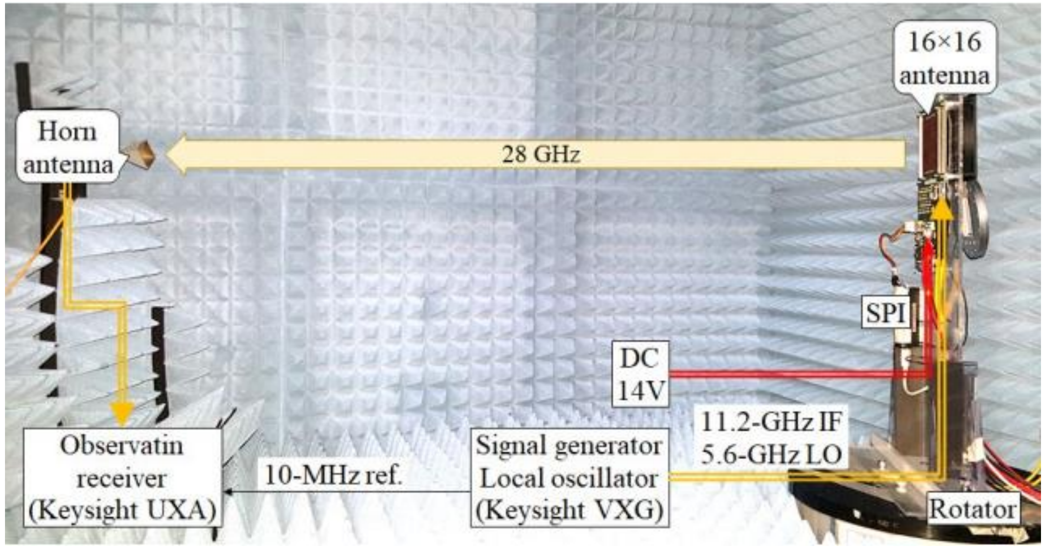


[1] Park and Probe



[2] Integrated coupler

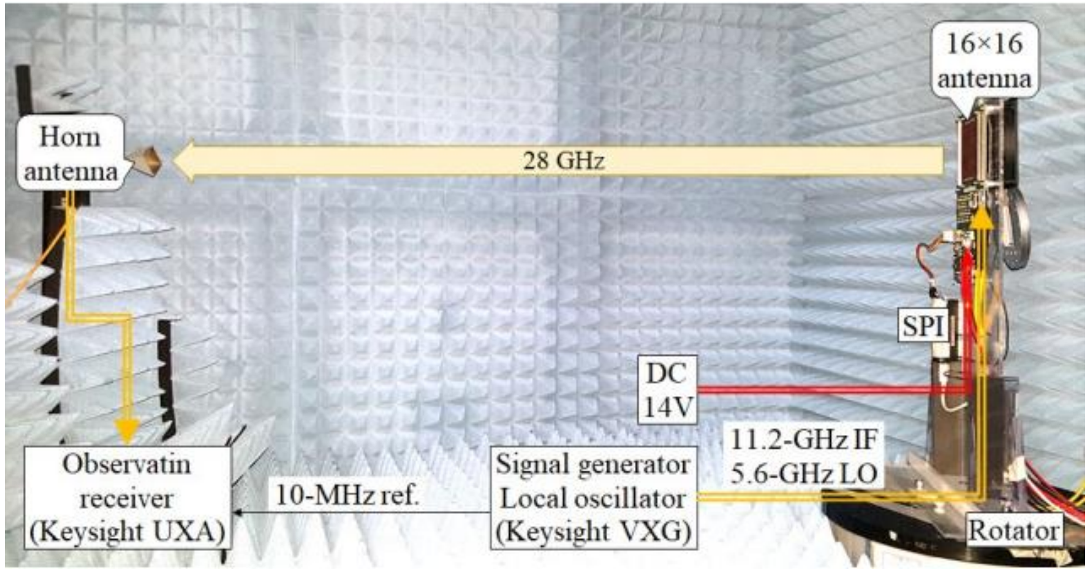
Active Array calibration



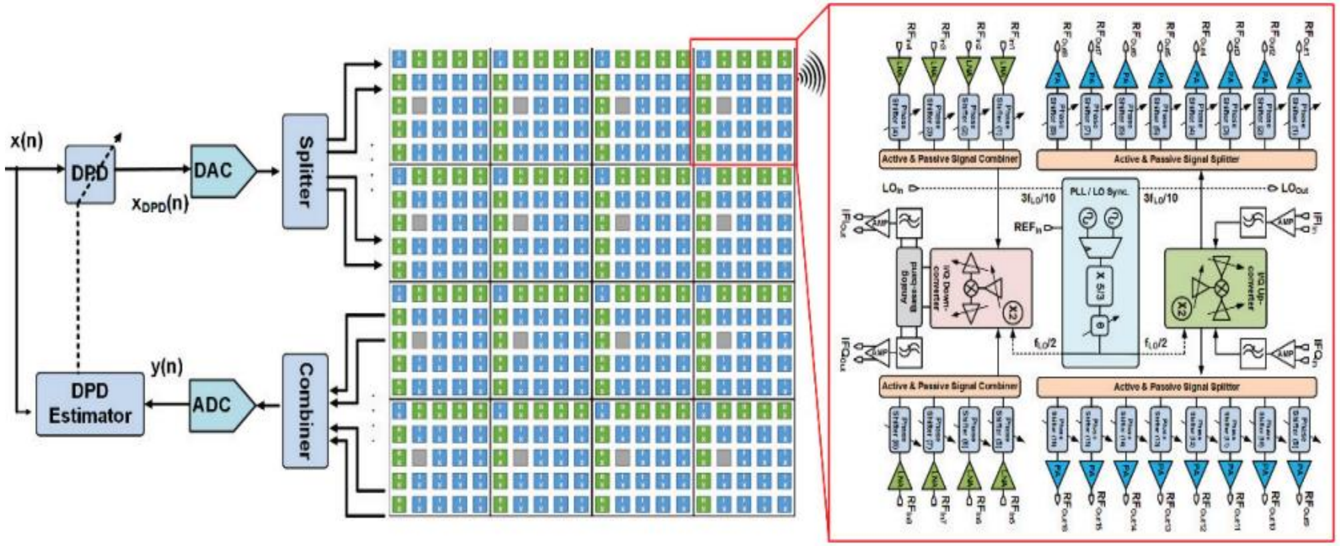
[3] Over-the-air feedback

Motivation

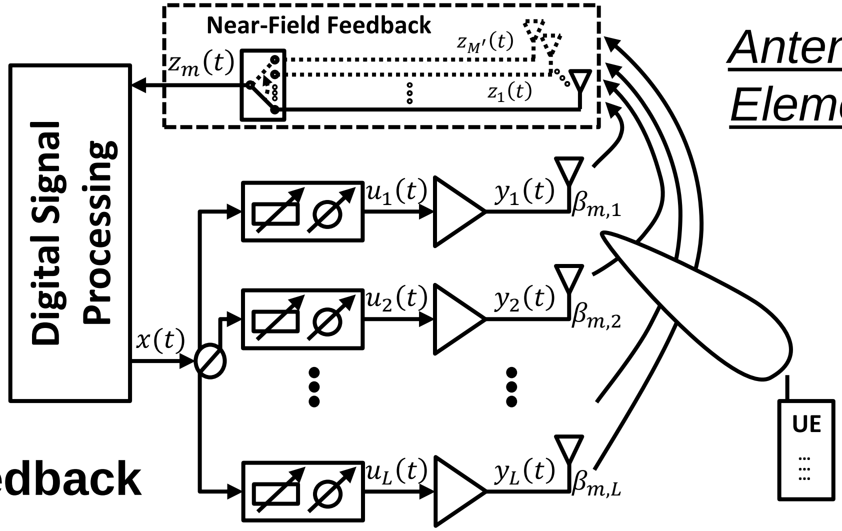
- For DPD training



[3] Over-the-air feedback

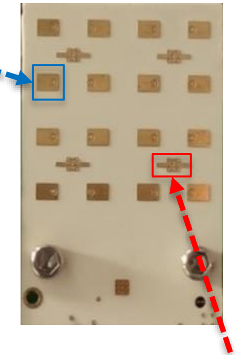


[4] Near-Field feedback



[5] Near-Field feedback

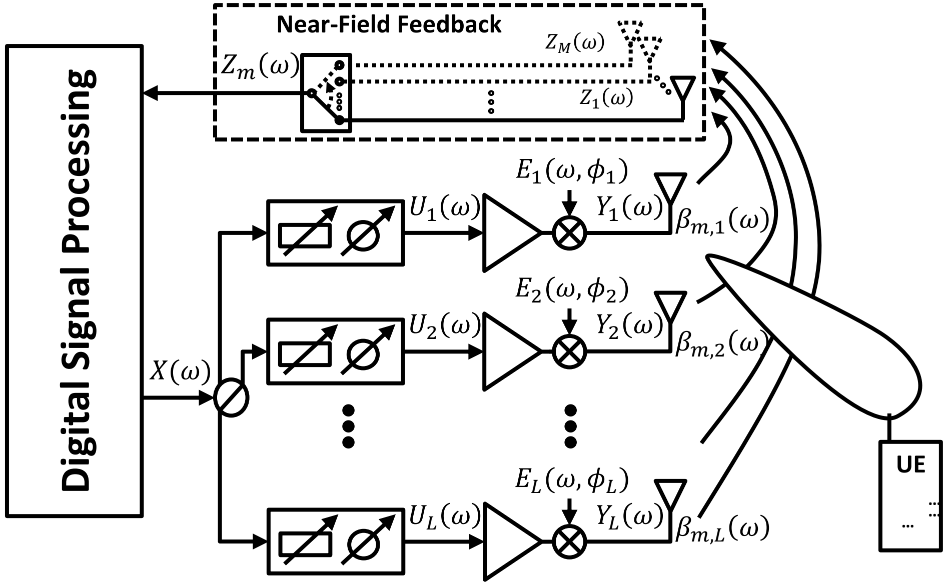
Antenna Element



NF Probe

Theory

- In this work we propose **an active array calibration** and **DPD** training methods that use near-field probes as feedback
- The **proposed active array calibration** enable phased **dependend phase and magnitude error correction**
- The **proposed DPD training method** **relaxes** the contains on the **near-field feedback frequency response**

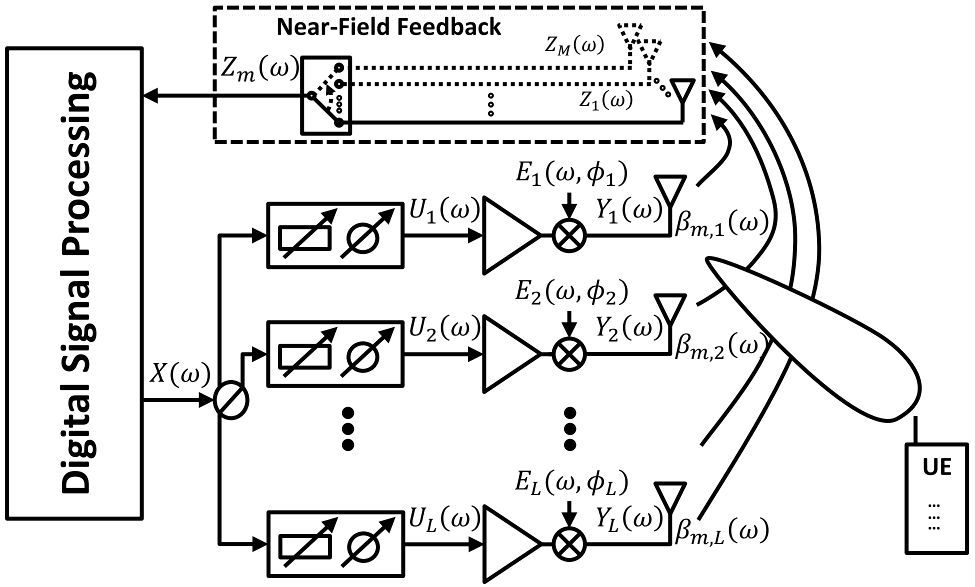


Theory

- Let E_ℓ be the complex valued error at the ℓ'th antenna element.
- To allow for the calibrating of the phase shifter dependent error, $E_\ell(\omega, \phi_\ell)$, in the following derivation, we assume that

$$E_\ell(\omega, \phi_\ell) \approx E_\ell(\omega, \phi_\ell + \pi) \ (1)$$

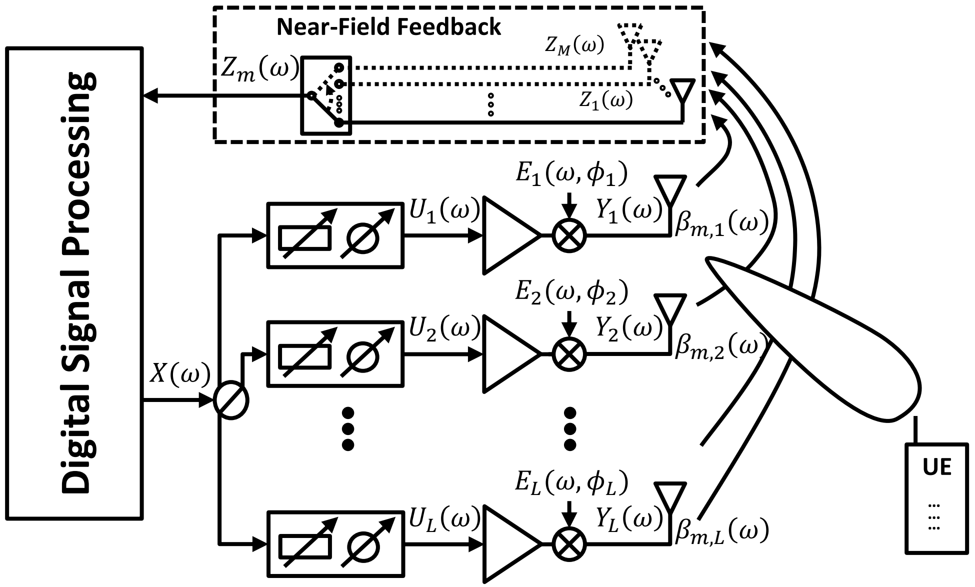
- The assumption in (1) was validated experimentally on different beamforming ICs



Theory

- Consequently, the received signal at the m'th near-field probe can be expressed as follows,

$$Z_m(\omega) = \sum_{\ell=1}^{L} G\beta_{m,\ell}(\omega)X(\omega)e^{i\phi_\ell}E_\ell(\omega,\phi_\ell) \quad (2)$$



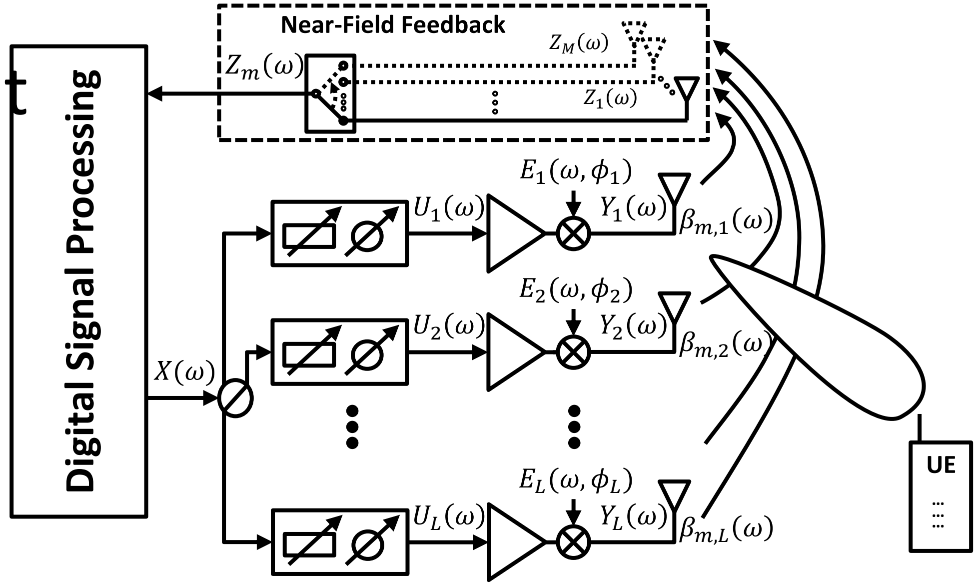
Where $\beta_{m,\ell}$ is the coupling coefficient be ℓ'th antenna element and the m'th near-field probe

- The objective is to estimate $E_\ell(\omega,\phi_\ell)$ using the near-field received signals.

Theory

- Using multiple measurements with different phase settings ϕ_ℓ, we can solve for E_ℓ
- Note, E_ℓ is ϕ_ℓ dependent ➔ E_ℓ should remains constant across the different measurements, i.e.,

$$E_\ell(\phi_\ell) = E_\ell\left(\phi_{\ell,k}\right)\ \forall\ k = 1 \ldots K \text{ and } K \geq L \text{ (3)}$$



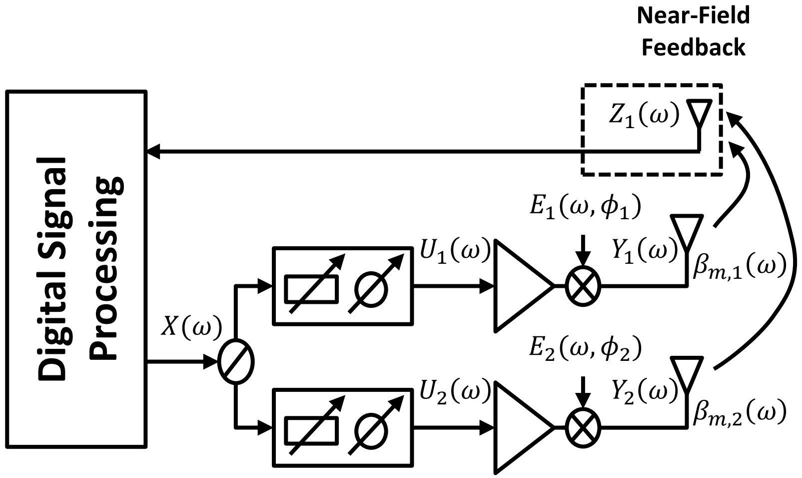
- In this work, we make use of the assumption in (2), i.e., $E_\ell(\omega,\phi) \approx E_\ell(\omega,\phi+\pi)$
- It can be shown that selecting the different phase measurements based of the Walsh-Hadamard matrix H, satisfies (2) and (3), where,

$$\mathbf{H}_n = \begin{bmatrix} \mathbf{H}_{\frac{n}{2}} & \mathbf{H}_{\frac{n}{2}} \\ \mathbf{H}_{\frac{n}{2}} & -\mathbf{H}_{\frac{n}{2}} \end{bmatrix}, \mathbf{H}_1 = 1, \mathbf{H}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \text{ (4)}$$

Theory

- Consider a two-antenna array with one near-field probe, using phase measurements based of **the Walsh-Hadamard** matrix, H, we have,

$$Z_{1,1}(\omega) = GX(\omega)\left(\beta_{1,1}e^{j\phi}E_1(\omega,\phi) + \beta_{1,2}e^{j\phi}E_2(\omega,\phi)\right)$$
$$Z_{1,2}(\omega) = GX(\omega)\left(\beta_{1,1}e^{j\phi}E_1(\omega,\phi) + \beta_{1,2}e^{j\phi+\pi}E_2(\omega,\phi)\right)$$
$$\Rightarrow E_1(\omega,\phi) = \frac{Z_{1,1}(\omega) + Z_{1,2}(\omega)}{2GX(\omega)\beta_{1,1}}, E_2(\omega,\phi) = \frac{Z_{1,1}(\omega) - Z_{1,2}(\omega)}{2GX(\omega)\beta_{1,2}}$$



- In general, using M near-field probes and L/M measurements the different $E_\ell(\omega,\phi)$ errors can be solved for using the following equation and least squares fitting,

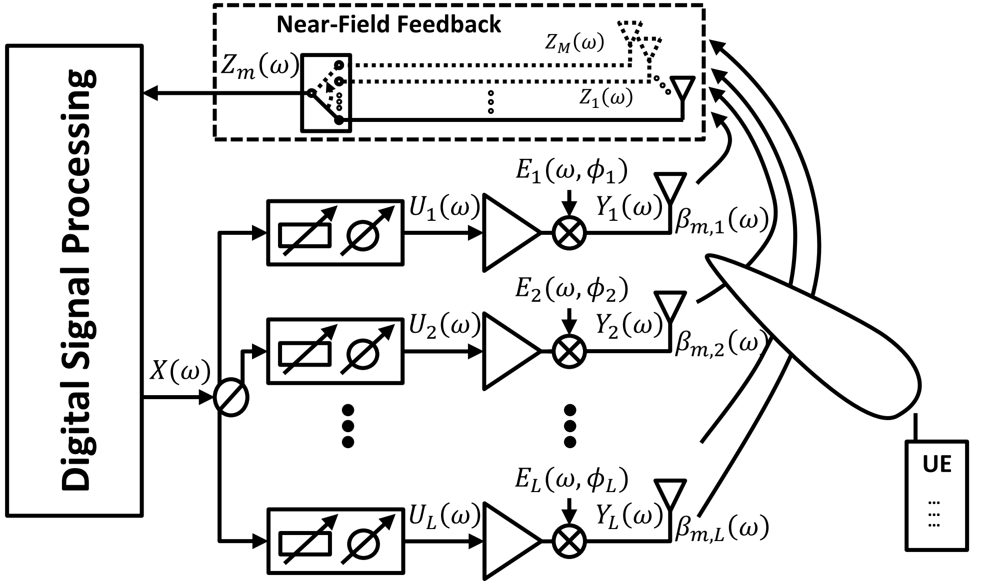
$$\begin{bmatrix}\mathbf{Z}_1(\omega)\\ \vdots \\ \mathbf{Z}_M(\omega)\end{bmatrix} = GX(\omega)e^{j\phi}\begin{bmatrix}\mathbf{HB}_1(\omega)\\ \vdots \\ \mathbf{HB}_M(\omega)\end{bmatrix}\begin{bmatrix}E_1(\omega,\phi)\\ \vdots \\ E_L(\omega,\phi)\end{bmatrix} \quad (5)$$

Theory

- With array now calibrated and operated in its nonlinear region, the ℓ'th PA output can now be modeled as,

$$Y_\ell = GV_\ell(\omega)e^{j\phi_\ell} \quad (6)$$

Where $V_\ell(\omega) = X(\omega) + N_\ell(\omega)$, and $N_\ell(\omega)$ is the ℓ'th PA nonlinear additive error.



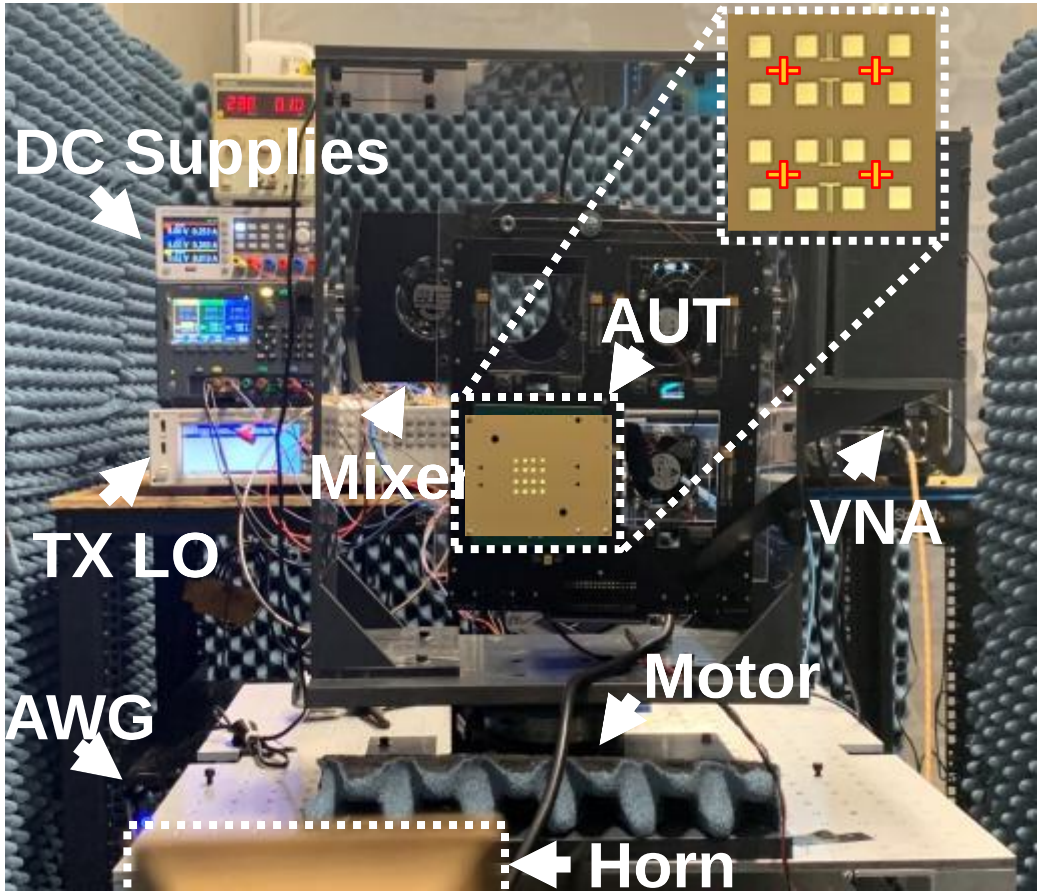
- The received signal at the m'th near-field probe can be expressed as

$$Z_m(\omega) = G\mathbf{\Phi}\mathbf{B}_m\mathbf{V}(\omega) \quad (7)$$

- Using a series if L/M measurements (with phases devised from $\mathbf{H}$), we have

$$\mathbf{Z}(\omega) = G\mathbf{\Phi}\begin{bmatrix}\mathbf{HB}_1(\omega) \\ \vdots \\ \mathbf{HB}_M(\omega)\end{bmatrix}\mathbf{V}(\omega) \quad (8)$$

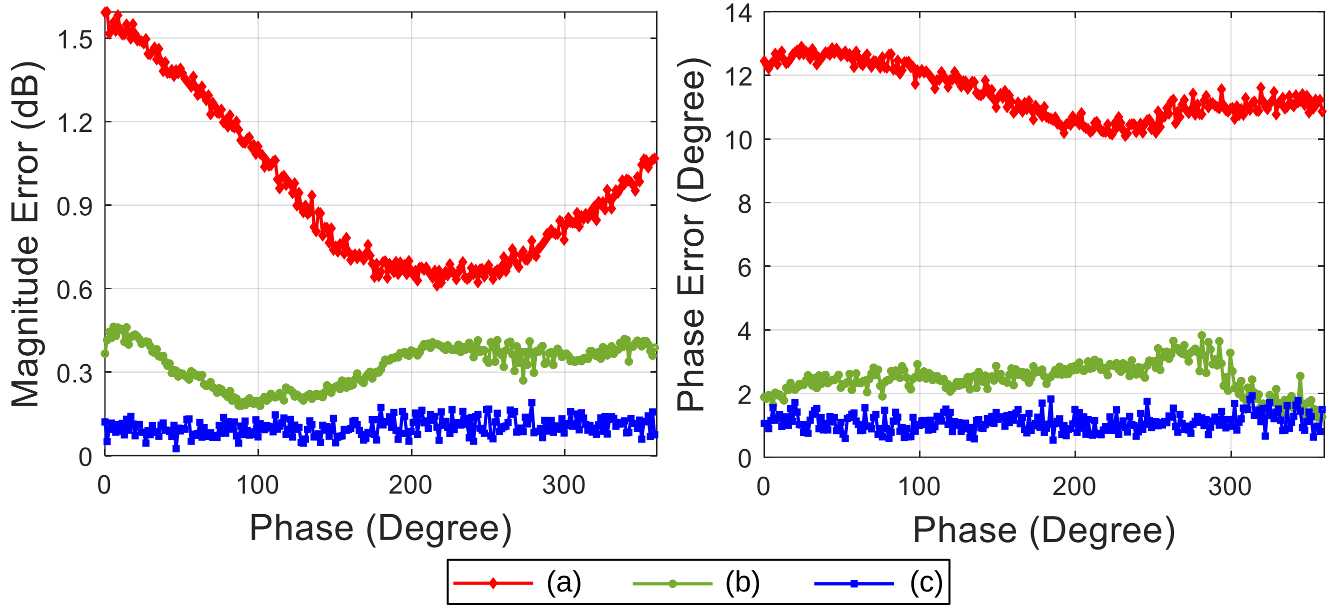
Measurement Results



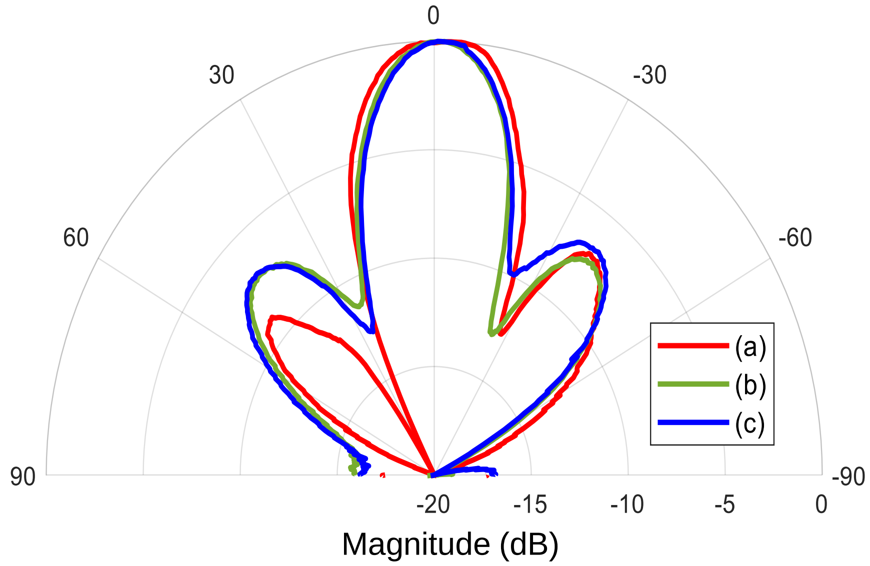
DUT	Custom built 4x4 Huixin Jin
Frequency	37.5 GHz
Signal Modulation BW	400 MHz
Signal Modulation Scheme	256 QAM, OFDM
Sub Carrier Spacing	120 kHz
Cyclic prefix Length	1/16 the FFT Length
Linearization Bandwidth	2 GHz
PAPR	9 dB
# Coefficients	35
Phase settings using in near-field DPD	Walsh-Hadamard matrix

Coupling Coefficients are estimate over a span of 3 GHz with tone spacing of 2MHz

Measurement Results

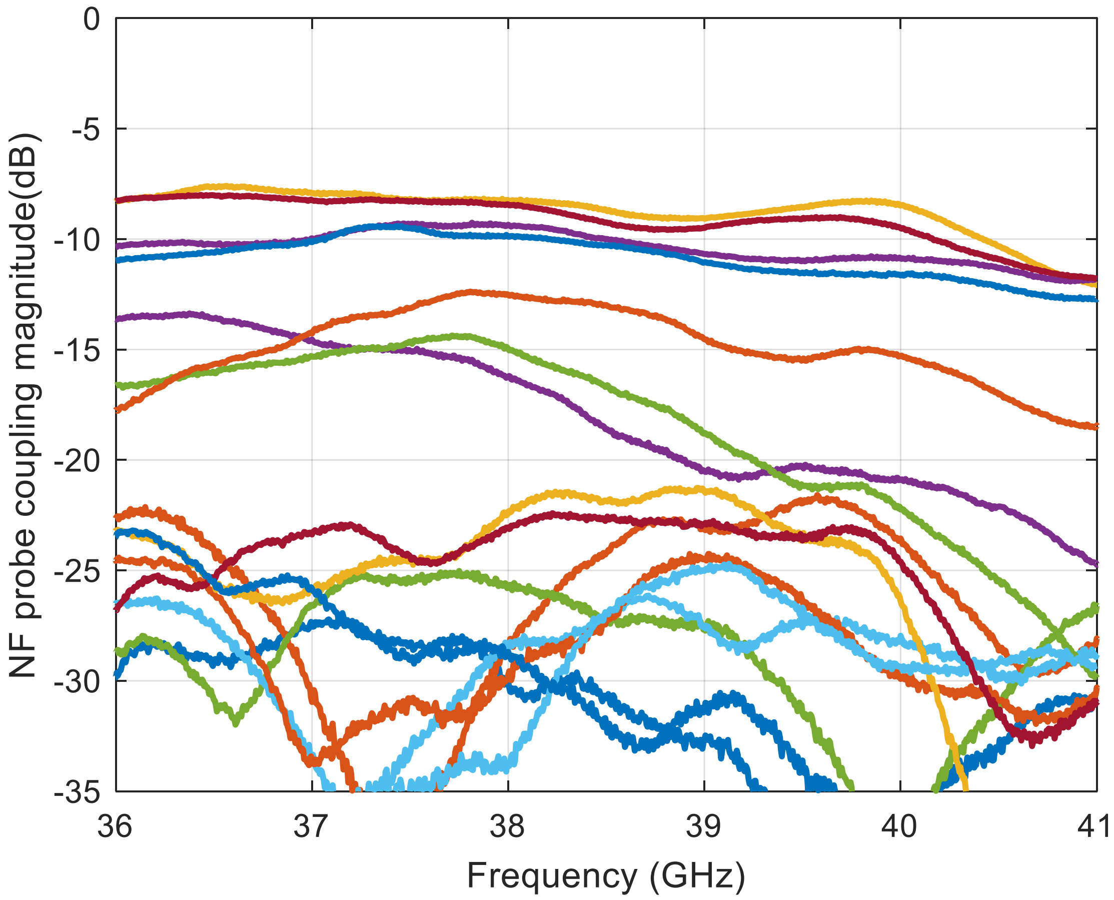


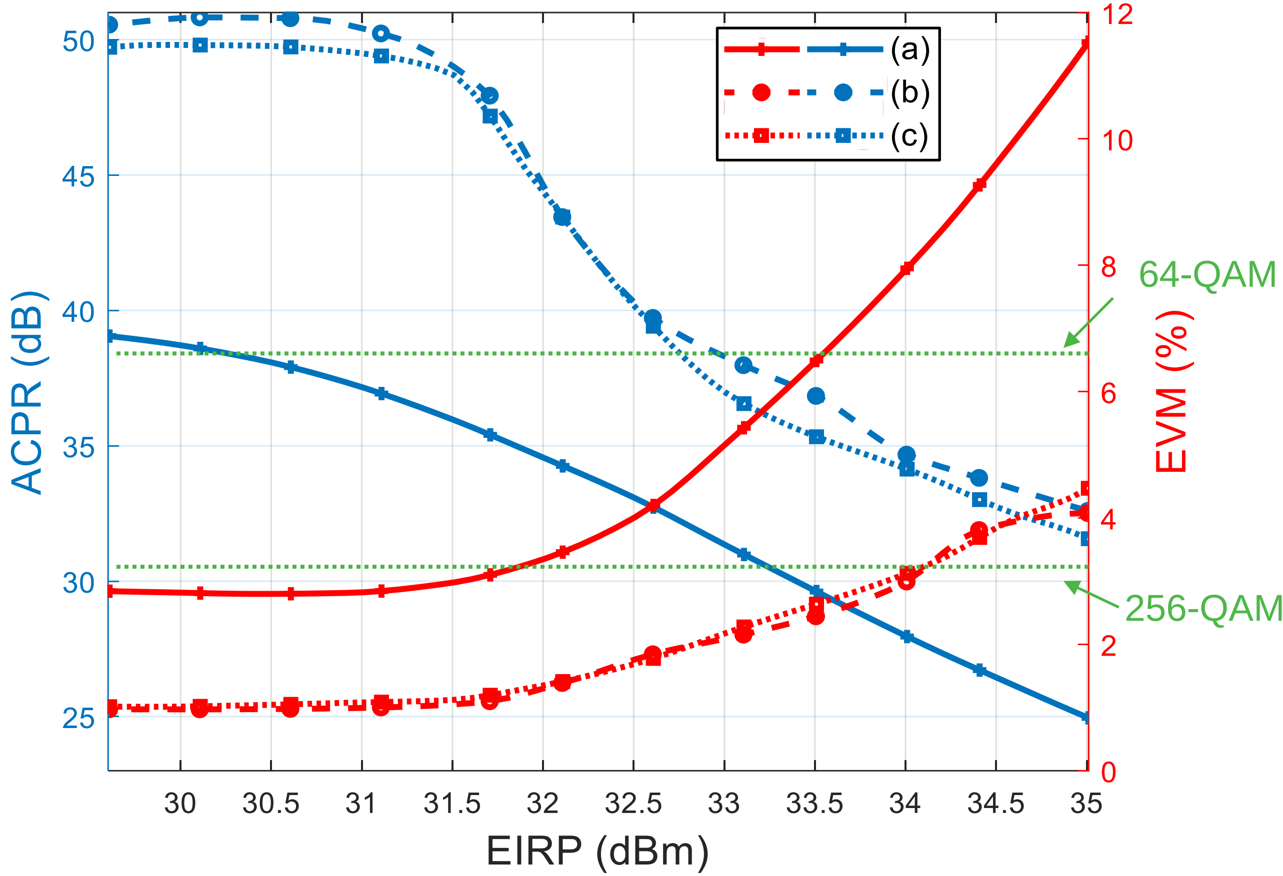
Measured rms magnitude (Left) and phase (right) errors versus phase shifter settings (8-bits): (a) before calibration, (b) after proposed calibration using NF probes, and (c) after element-wise calibration using a FF probe.



Measured radiation pattern with the array driven with a 400 MHz OFDM signal and the beam electrically steered from −90◦ to 90◦: (a) before calibration, (b) after proposed calibration using NF probes, and (c) after element-wise calibration using a FF probe.

Measurement Results





For 256-QAM signal, the application of DPD allowed for an increase of 2.5 dB in EIRP

Conclusions

- In this work, an active array calibration technique and DPD training method that uses near-field probes have been presented
- The proposed calibration method can calibrate for beamforming-dependent errors in the array (i.e., phase dependent errors)
- The proposed calibration method was able to reduce the imbalance in the radiation pattern side-lobes by up to 2 dB and achieve comparable performance to element-wise far-field-based calibration
- The proposed near-field based DPD training method does not impose stringent requirements on the coupling flatness and can achieve similar linearization performance as far-field based DPD training

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Thank you!

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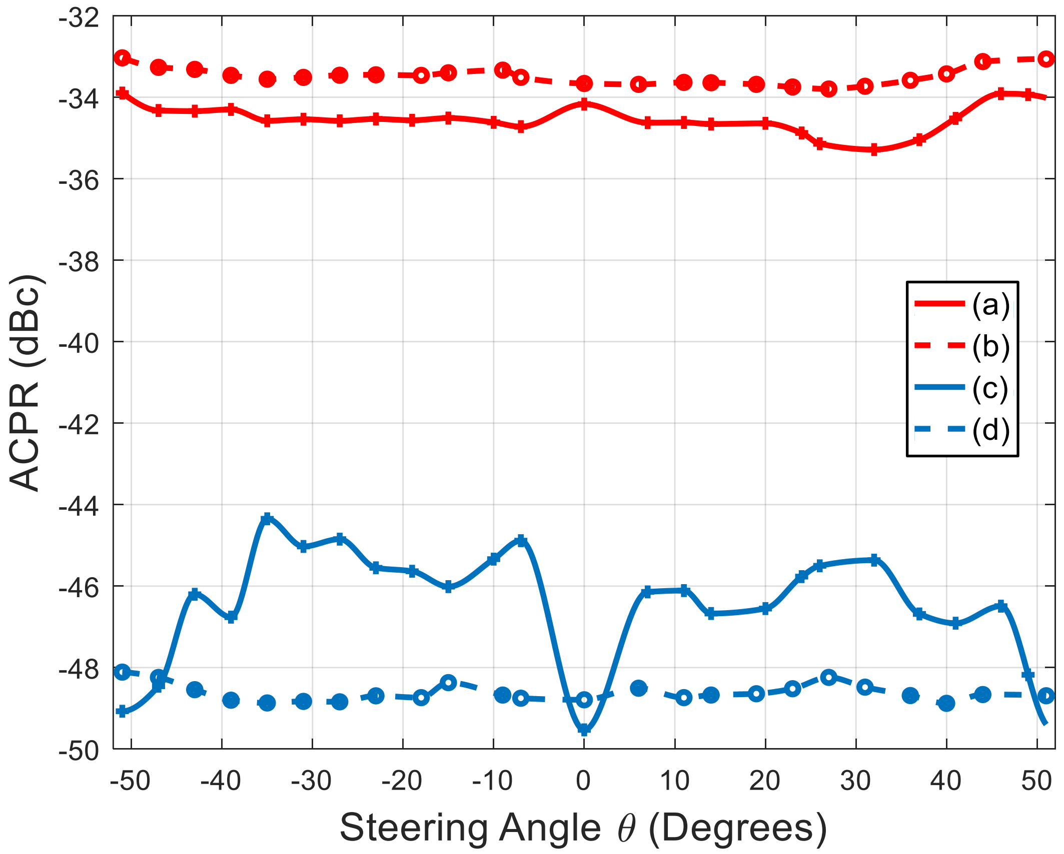
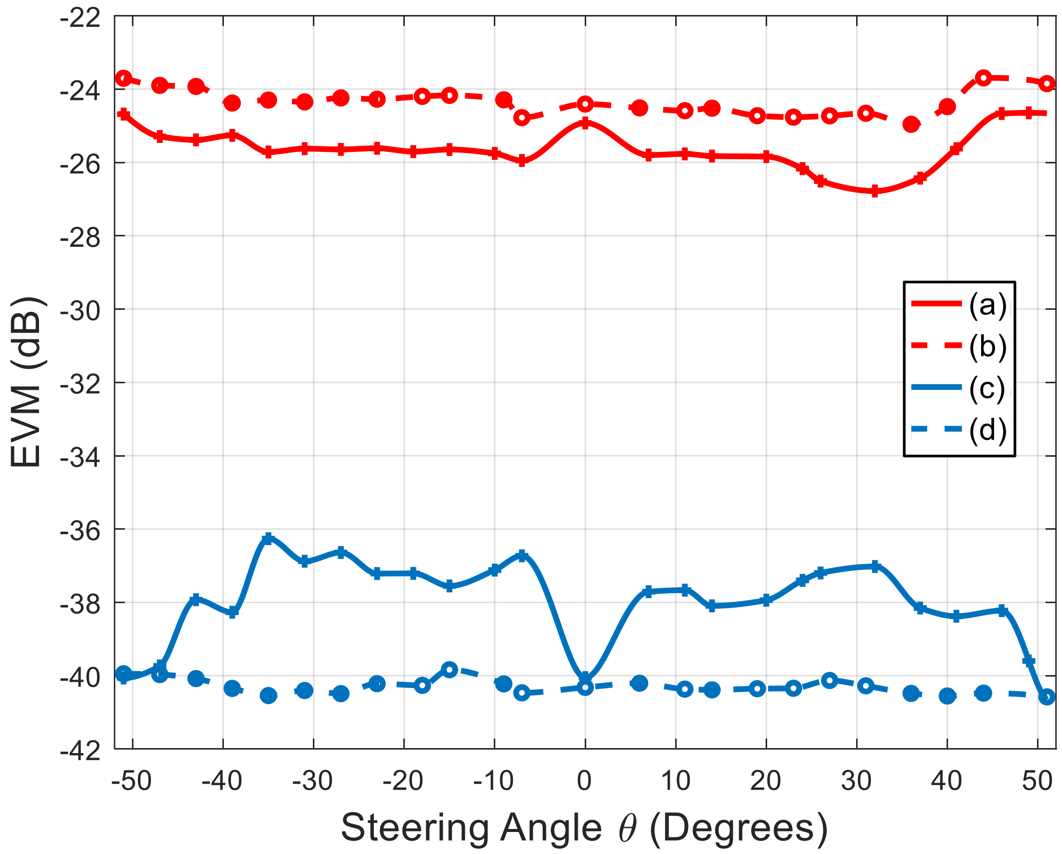
Additional Slides





A. Ben Ayed, P. Mitran and S. Boumaiza, "Novel Algorithm to Synthesize the Tapering Profile for Enhanced Linearization of RF Beamforming Arrays Over a Wide Steering Range," in *IEEE Transactions on Microwave Theory and Techniques*, doi: 10.1109/TMTT.2023.3248151.