QUEEN'S UNIVERSITY BELFAST | ECIT THE INSTITUTE OF ELECTRONICS COMMUNICATIONS AND INFORMATION TECHNOLOGY

# 5G Beamformers: Resetting Connectivity Performance

## Welcome ☺

**The webinar will start at 12:00 PM EST**

**IEEE Young Professionals**
Montreal Section Affinity Group
Ottawa Section Affinity Group
INRS IEEE student branches
Polytechnique MTL

**Muhammad Ali Babar Abbasi**
Lecturer (Assistant Prof.)
go.qub.ac.uk/dr-abbasi

Fri, 5 February 2021 12:00 – 1:00 PM EST

# Content and Structure

- Thank you note
- What is in this Webinar **For You?** (~10 minutes)
  - Important definitions
  - Why do we need beamformers?
- **Beamformer Classifications** (~30 minutes)
  - Latest trends in beamformers
  - Future prospects of beamformers
  - Intermediate Q&A

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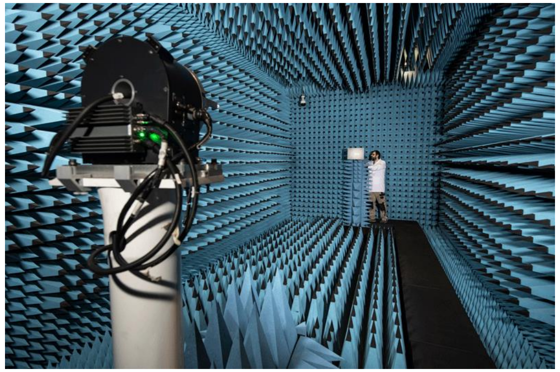
# What is in this Webinar for YOU?


Together, we will:

- understand the role of antenna beamformers in 5G and beyond networks
- review the latest trends and applications, and will
- forecast future beamformers design for our hyper-connected world.




**Our Vision**

**UNDERPINNING TECHNOLOGIES FOR MOBILE, MEDICAL AND SPACE**

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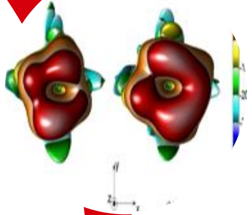
# Centre for Wireless Innovation



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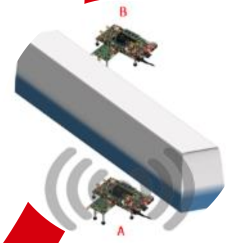

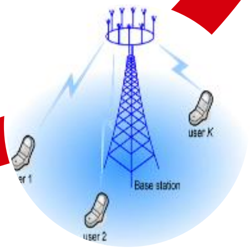


**Millimetre Wave Enabling Technology**

- mmWave antennas & filters (ESA, Airbus – MetOp2)
- Self-steered and retro-directive antennas
- Self-tracking SatComms (ESA)
- Sub-wavelength imaging

**Mobile – 5G and beyond**

- Physical Layer Modelling
- Massive MIMO (multiple-input and multiple-output)

**Medical**

- Wearable & implantable systems
- Antennas & propagation in biomedical applications

**Connected & Autonomous Vehicles**

- Ultra Reliable Low Latency Communications (URLLC)
- Machine-learning based 5G-V2X air-interface technology
- Multi-way communications for connectivity among several users
- Wireless Power Transfer

# Antenna Beamformers – A Few Definitions

- An **antenna** is the interface between radio waves propagating through space and electric currents moving in metal conductors (Modern Dictionary of Electronics).
- Beamforming is generally achieved by using **multiple antennas** in a form of an array.
- **Antenna beamforming** – the ability of an **antenna array** to steer the maximum radiation towards a prescribed direction, or conversely, the ability of the antenna array to estimate the direction of arrival of an impinging signal.

$$P_r = P_t + G_t + G_r + 20\log\left(\frac{c}{4\pi f \times r}\right)$$

$P_r$ – received power (dBm)
$P_t$ – transmitted power (dBm)
$G_t$ and $G_r$ – transmitter and receiver antenna gains
$r$ – distance between the point of received power $P_r$ and the radiator

H. T. Friis, “A note on a simple transmission formula,” *Proc. IRE*, vol. 34, no. 5, pp. 254–256, 1946.

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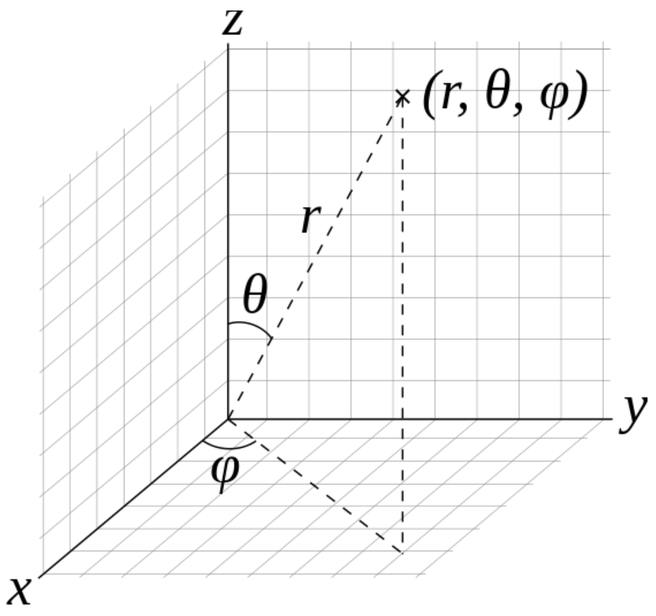
# Antenna Beamformers – A Few Definitions

Antenna structures with non-zero length exhibit preferential energy radiation in a given direction ($\theta$, $\phi$). This property can be defined as **antenna directivity,** *D*, as follows

$$G = \eta D$$

$$D = \frac{\text{radiation intensity in a given direction}}{\text{radiation intensity averaged over all directions}}$$




For a sphere the **average radiation intensity**, $\Phi$ ($\theta$, $\phi$), is 1/4π times the total power, $P_T$, radiated by the antenna, thus

$$D = \frac{4\pi\Phi(\theta,\phi)}{P_T} = \frac{4\pi\Phi(\theta,\phi)}{\int_0^{2\pi}\int_0^{\pi}\Phi(\theta,\phi)\sin\theta d\theta d\phi}$$

Fusco, Vincent F. *Foundations of antenna theory and techniques*. Pearson Education, 2005.

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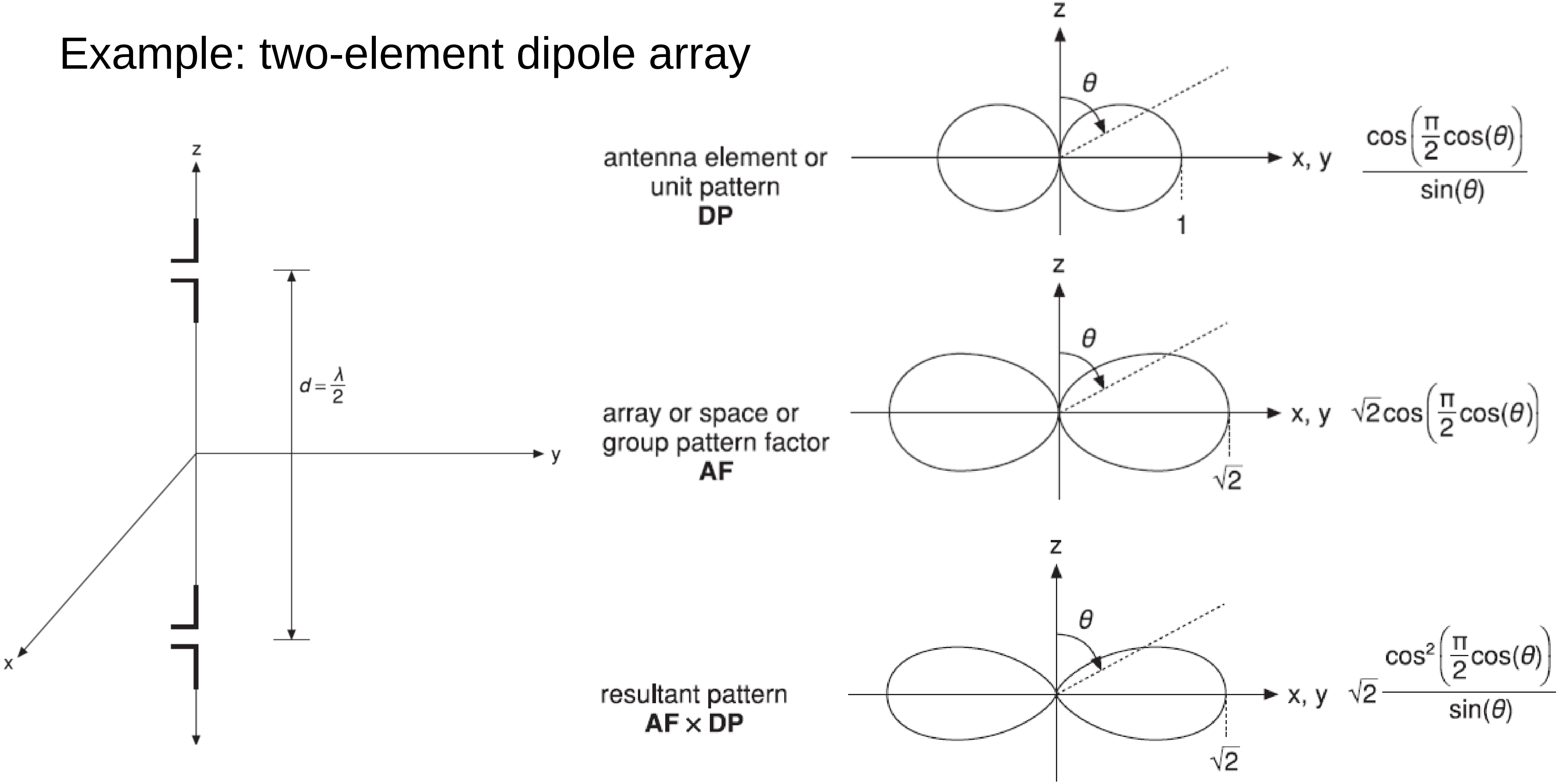
# Antenna Beamformers – A Few Definitions

In general, **beamformer gain/directivity pattern** along $(\theta, \phi)$ is given as

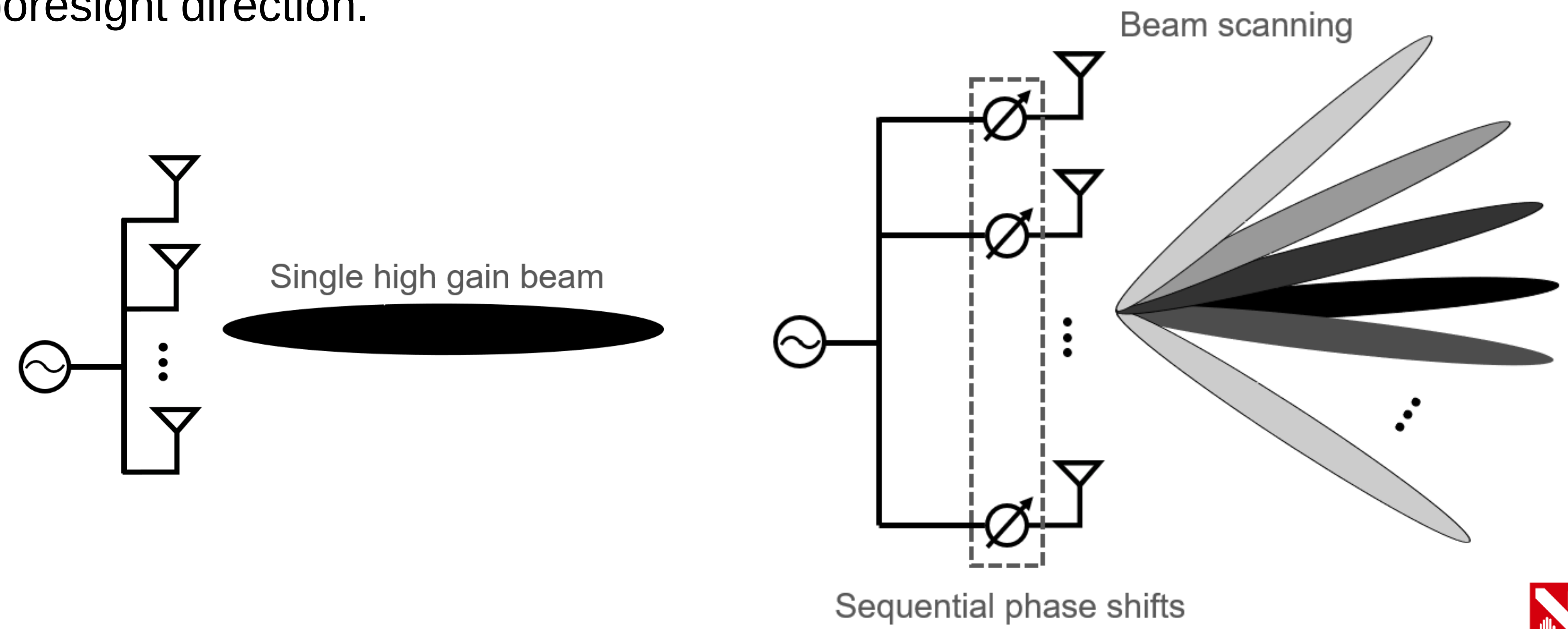
$$resultant\ \ pattern = antenna\ element\ \ pattern \times antenna\ array\ \ factor$$

Example: two-element dipole array



# Why Do We Need Beamforming?

- Multiple antennas connected to a single radio frequency source - beamforming only along boresight direction.
- Same antenna array with bank of phase shifters – beam scanning at an angle $\theta$ from the boresight direction.




Abbasi MA, Fusco VF. Beamformer development challenges for 5G and beyond. *Antennas and Propagation for 5g and Beyond:* IET. 2020 Sep 14:265.

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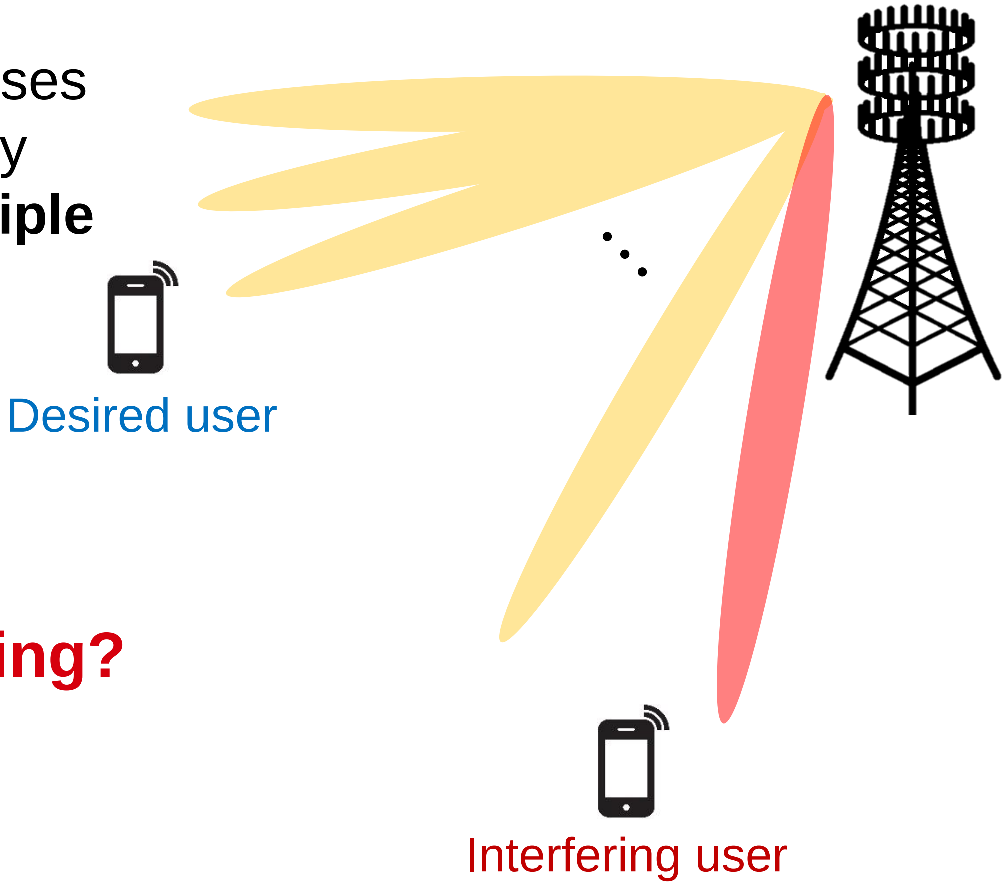
# Why Do We Need Beamforming?

- In communication systems, beamforming focuses the signal energy at certain places, less energy arrives to other places – **space-division multiple access** (SDMA)
- Spatially separated users are served **simultaneously**.




## What should be the optimal beamforming?

SDMA: E. Björnson, M. Bengtsson and B. Ottersten, "Optimal Multiuser Transmit Beamforming: A Difficult Problem with a Simple Solution Structure [Lecture Notes]," in *IEEE Signal Processing Magazine*, vol. 31, no. 4, pp. 142-148, July 2014

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# Beamformer Classifications

- Classification based on **architecture**
  - Analogue beamformer
  - Digital beamformer
  - Hybrid or analogue/digital beamformers
  - Lens based hybrid beamformers

- Classification based on **frequency** (w.r.t 5G and beyond)
  - Beamformers at sub-6 GHz
  - Beamformers at mmWave

- Classification based on the **use case**
  - Fixed beamformers
  - Variable beamwidth Fixed Beamformer
  - Mobile beamformers

Beamformer Classification Based on

**Architecture**

Frequency

Use Case

# Based on Architecture

### Analogue Beamformer

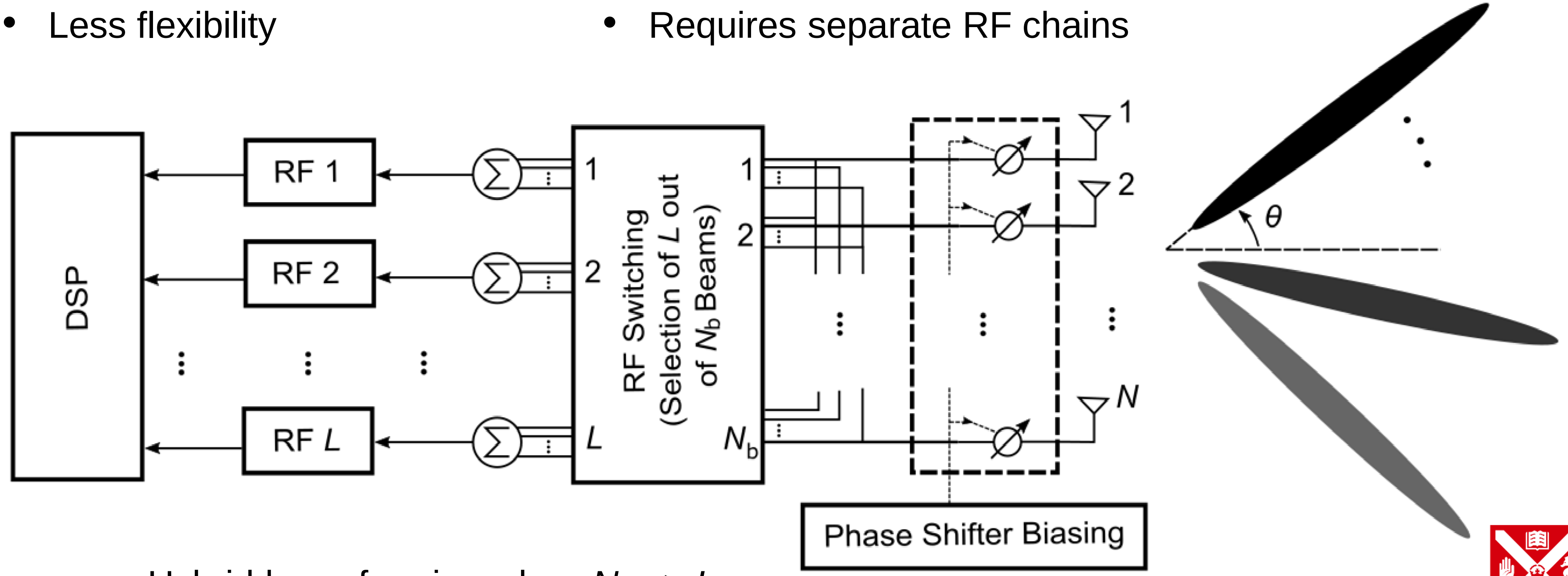
- ✓ Low power consumption
- ✓ Less baseband processing
- Less flexibility

### Digital Beamformer

- ✓ Extremely Flexible
- Highest power consumption
- Requires separate RF chains

### Hybrid Beamformers

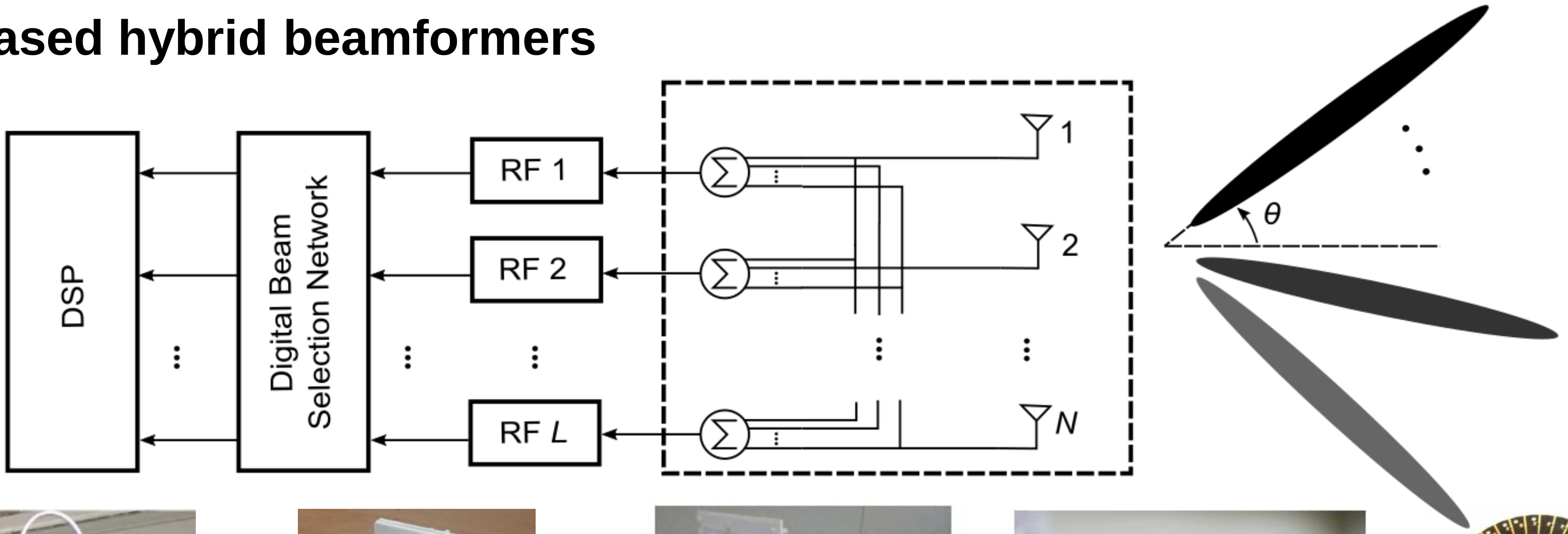
- ✓ The best of both

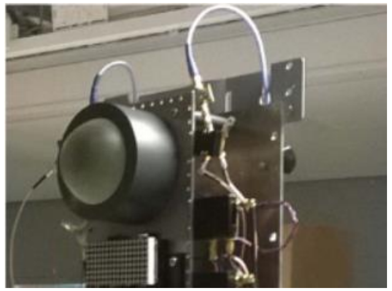



Hybrid beamforming when $N_{ant} > L$

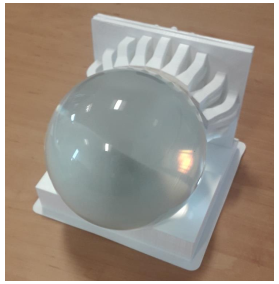
# Based on Architecture

- **Lens based hybrid beamformers**

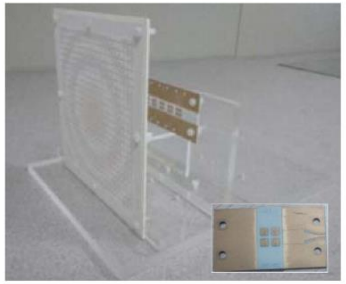


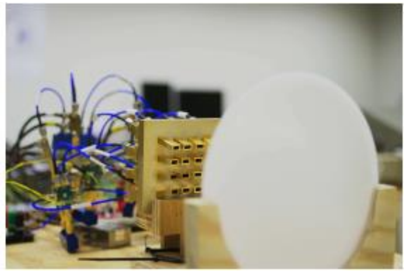
Luneburg lens



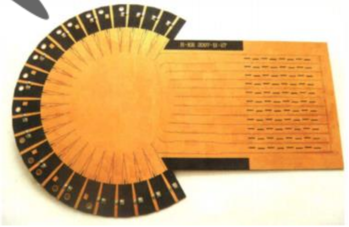
Sph. Const. Lens



Flat lens



Dielectric Lens



SIW Rotman lens

J. Brady, J. Hogan and A. Sayeed, "Multi-Beam MIMO Prototype for Real-Time Multiuser Communication at 28 GHz," *2016 IEEE Globecom Workshops (GC Wkshps)*, Washington, DC, 2016, pp. 1-6.
Hong, Wei, et al. "Multibeam antenna technologies for 5G wireless communications." *IEEE Transactions on Antennas and Propagation* 65.12 (2017): 6231-6249.
Ala-Laurinaho, Juha, et al. "2-D beam-steerable integrated lens antenna system for 5G E-band access and backhaul." *IEEE Transactions on Microwave Theory and Techniques* 64.7 (2016):



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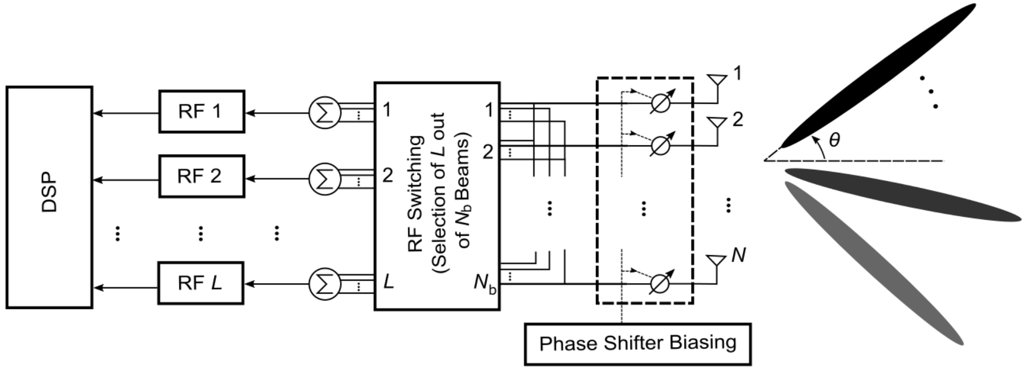
# Latest Beamformer Trends – Based on Architecture

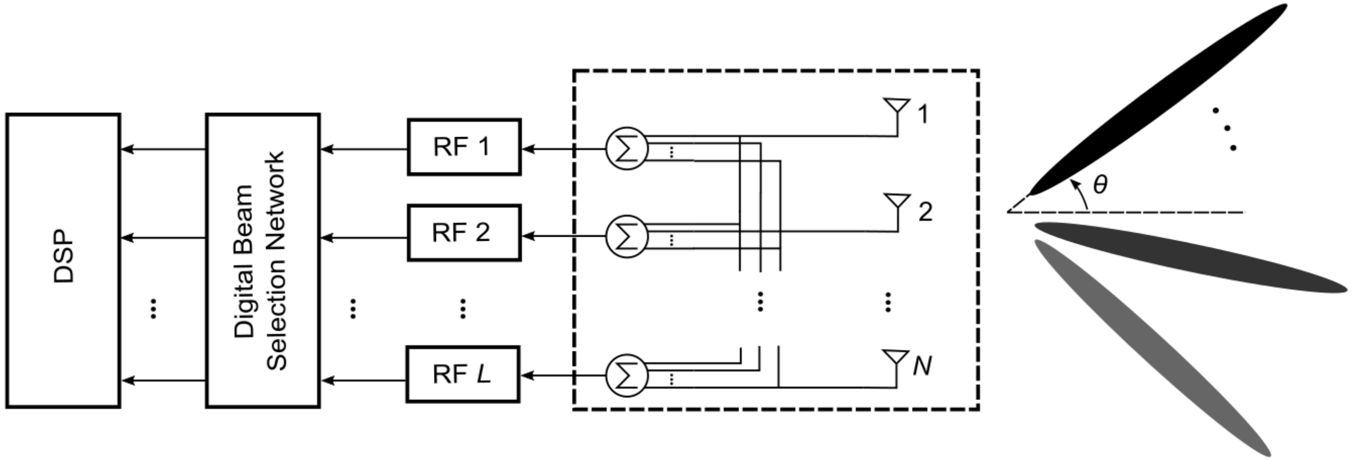
## Future insight

Hybrid beamforming architecture

Phase-shifter based

Lens-based




RF front end requirements

Implementation complexity

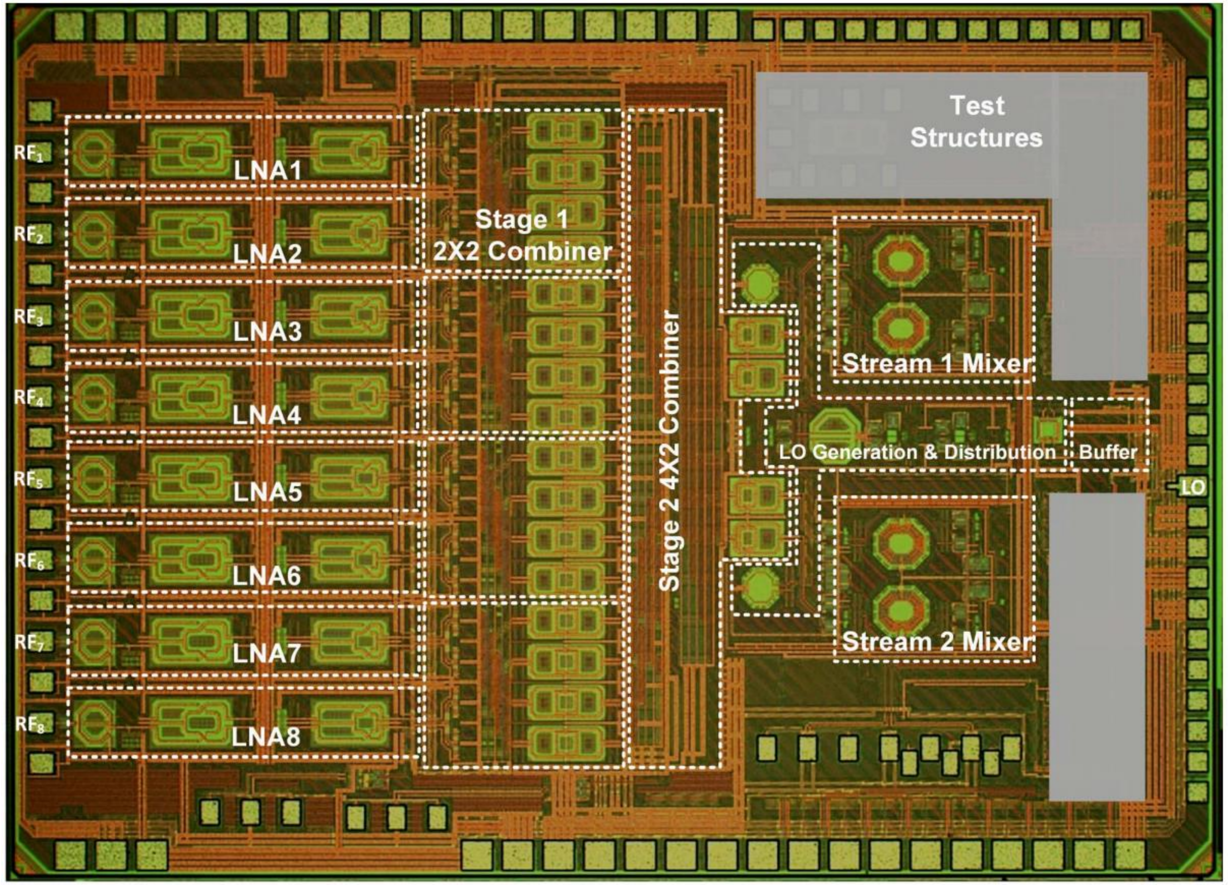
Flexibility and scalability

System implications

# Latest Beamformer Trends – Based on Architecture

- **Hybrid or Analogue/Digital Beamformers**
- mmWaves – analogue beamforming is required

- Die photograph of 25–30 GHz Fully-Connected **Hybrid Beamforming Receiver**
- implemented on 64-nm CMOS




S. Mondal, R. Singh, A. I. Hussein, and J. Paramesh, “A 25–30 GHz fully-connected hybrid beamforming receiver for MIMO communication,” *IEEE J. Solid-State Circuits*, vol. 53, no. 5, pp. 1275–1287, 2018.

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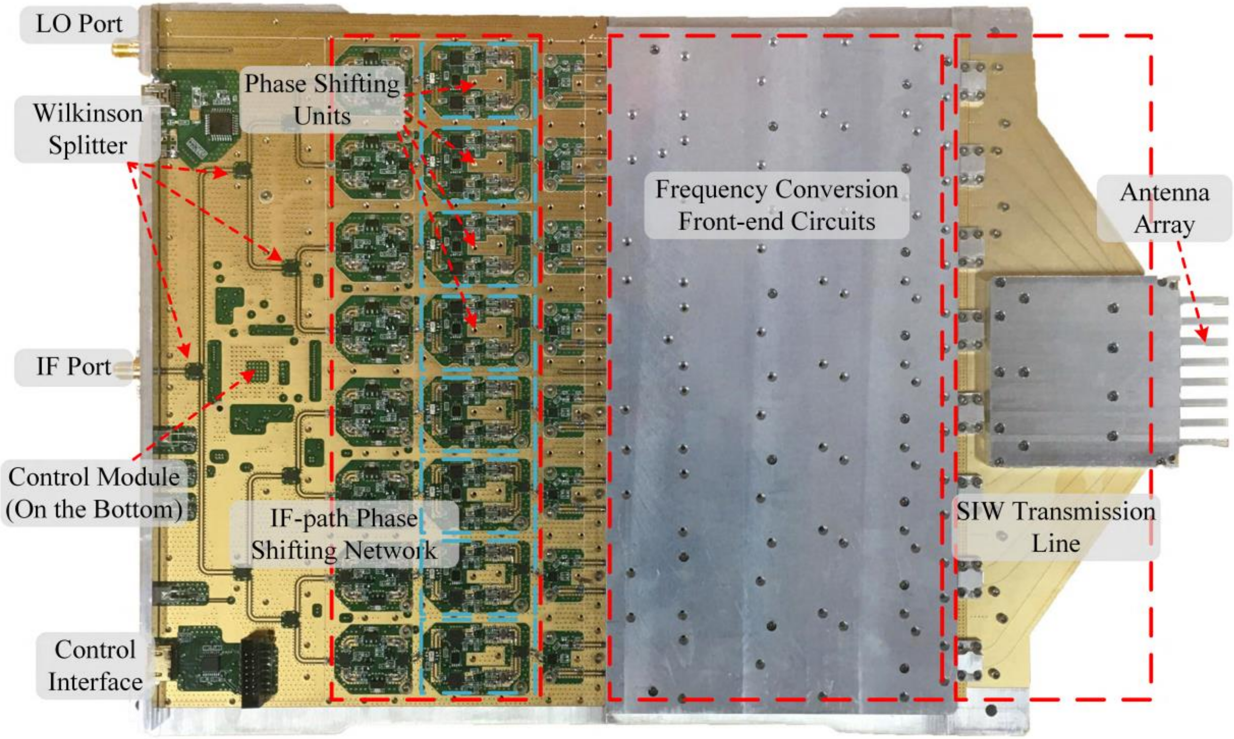
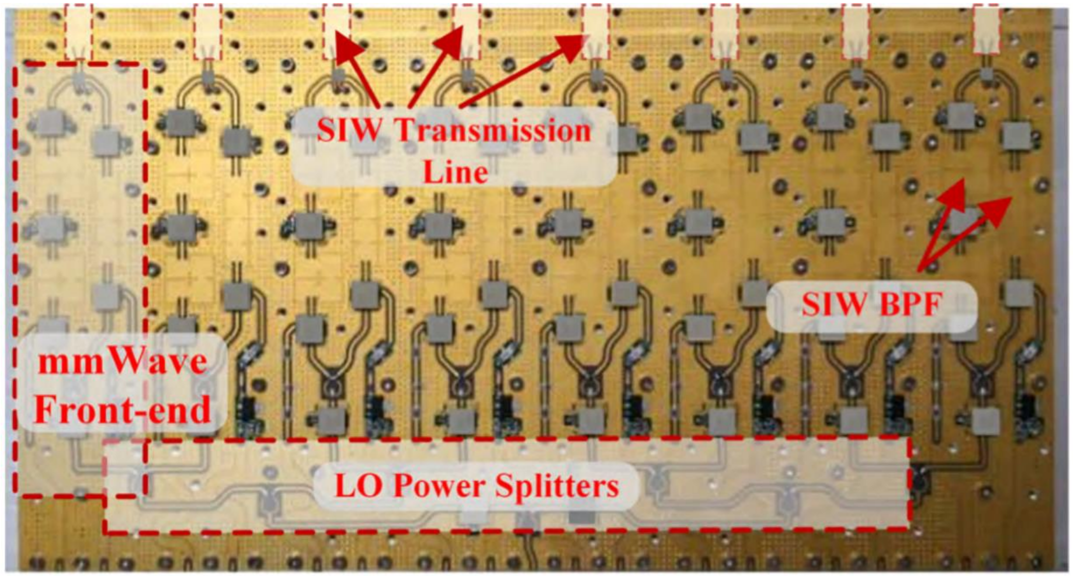
# Latest Beamformer Trends – Based on Architecture

- **Hybrid or Analogue/Digital Beamformers**




Sub-array phase shifting network




One phased sub-array system

R. Zhang, J. Zhou, J. Lan, B. Yang, and Z. Yu, "A High-Precision Hybrid Analog and Digital Beamforming Transceiver System for 5G Millimeter-Wave Communication," *IEEE Access*, vol. 7, pp. 83012–83023, 2019.

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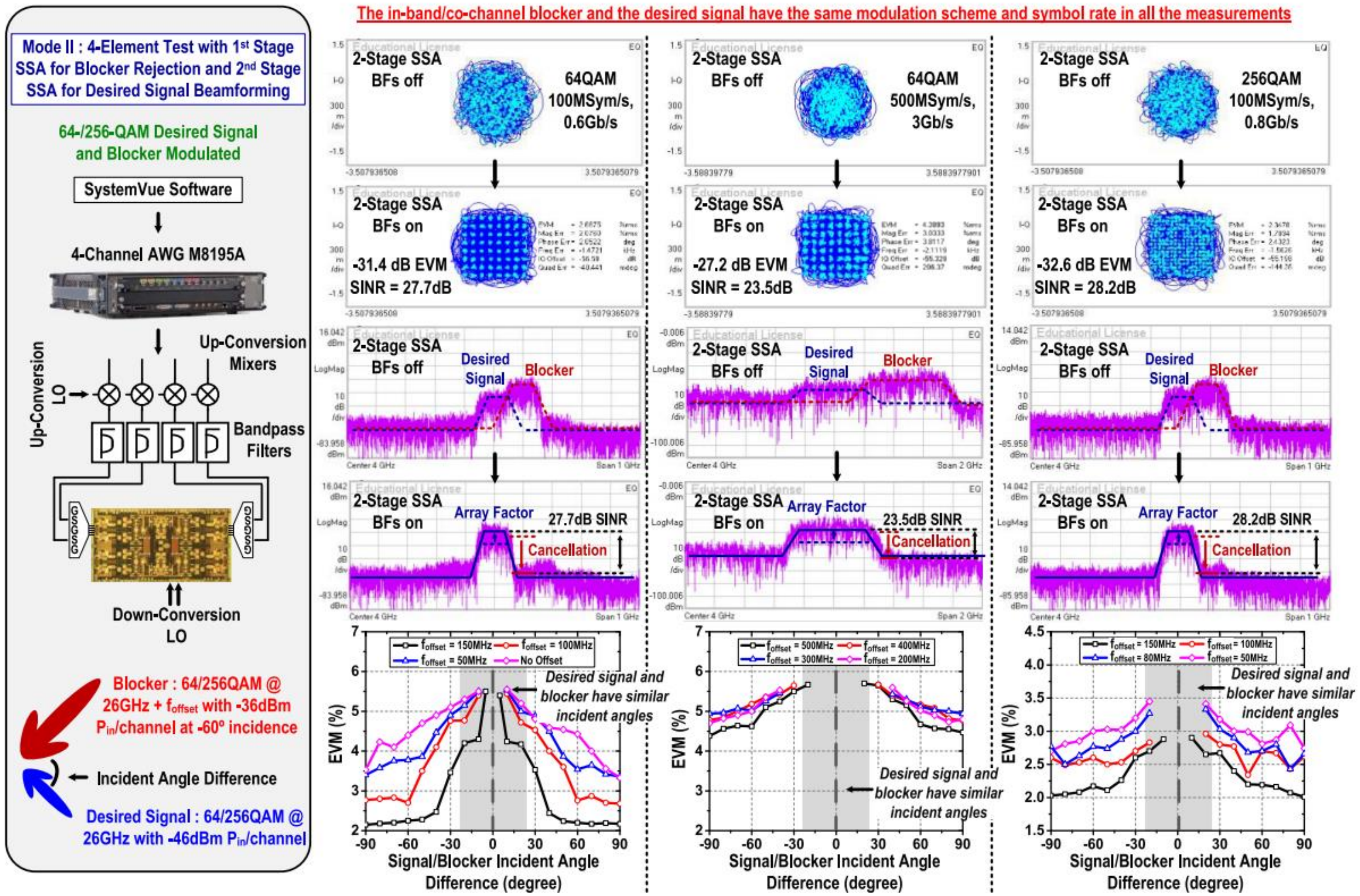
# Latest Beamformer Trends – Based on Architecture




- **Hybrid Beamformers**
- 64/256 QAM, 26 GHz, -36 dBm $P_{in}$/channel

- Left – hybrid beamformer array chip and its scalability for **phased array**.
- Right – the blocker rejection and desired signal beamforming

M.-Y. Huang, T. Chi, F. Wang, T.-W. Li, and H. Wang, “A Full-FoV Autonomous Hybrid Beamformer Array With Unknown Blockers Rejection and Signals Tracking for Low-Latency 5G mm-Wave Links,” *IEEE Trans. Microw. Theory Tech.*, 2019.

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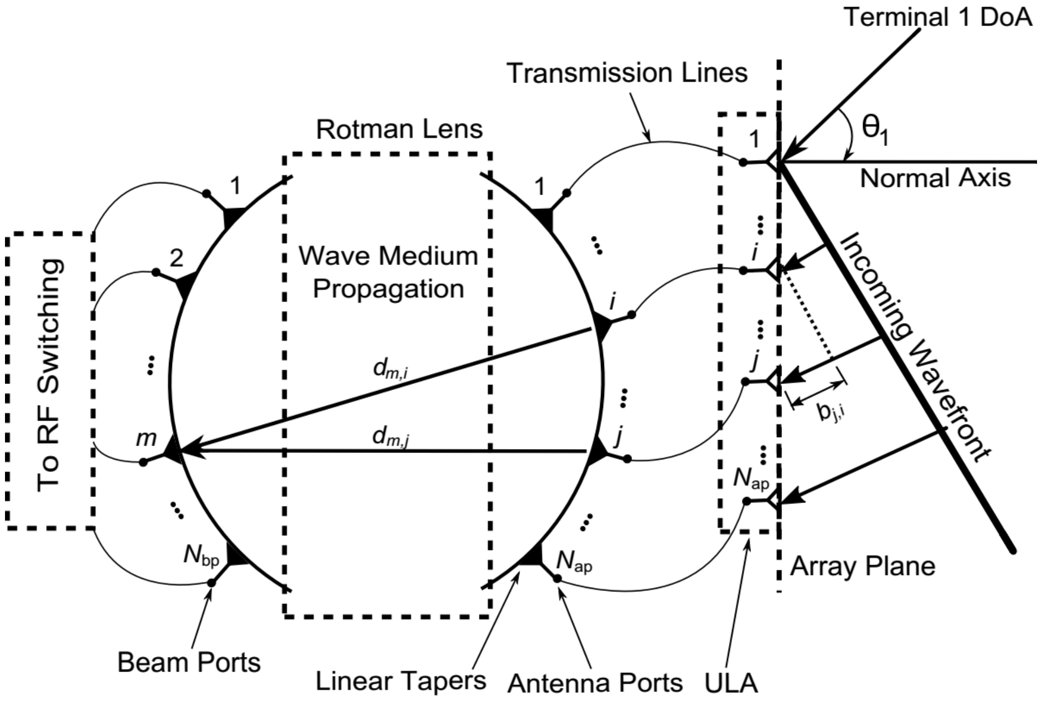
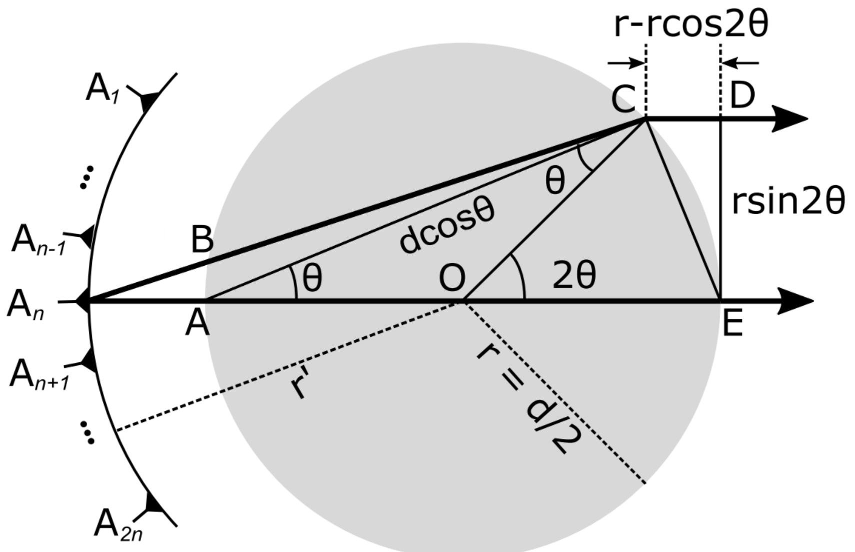
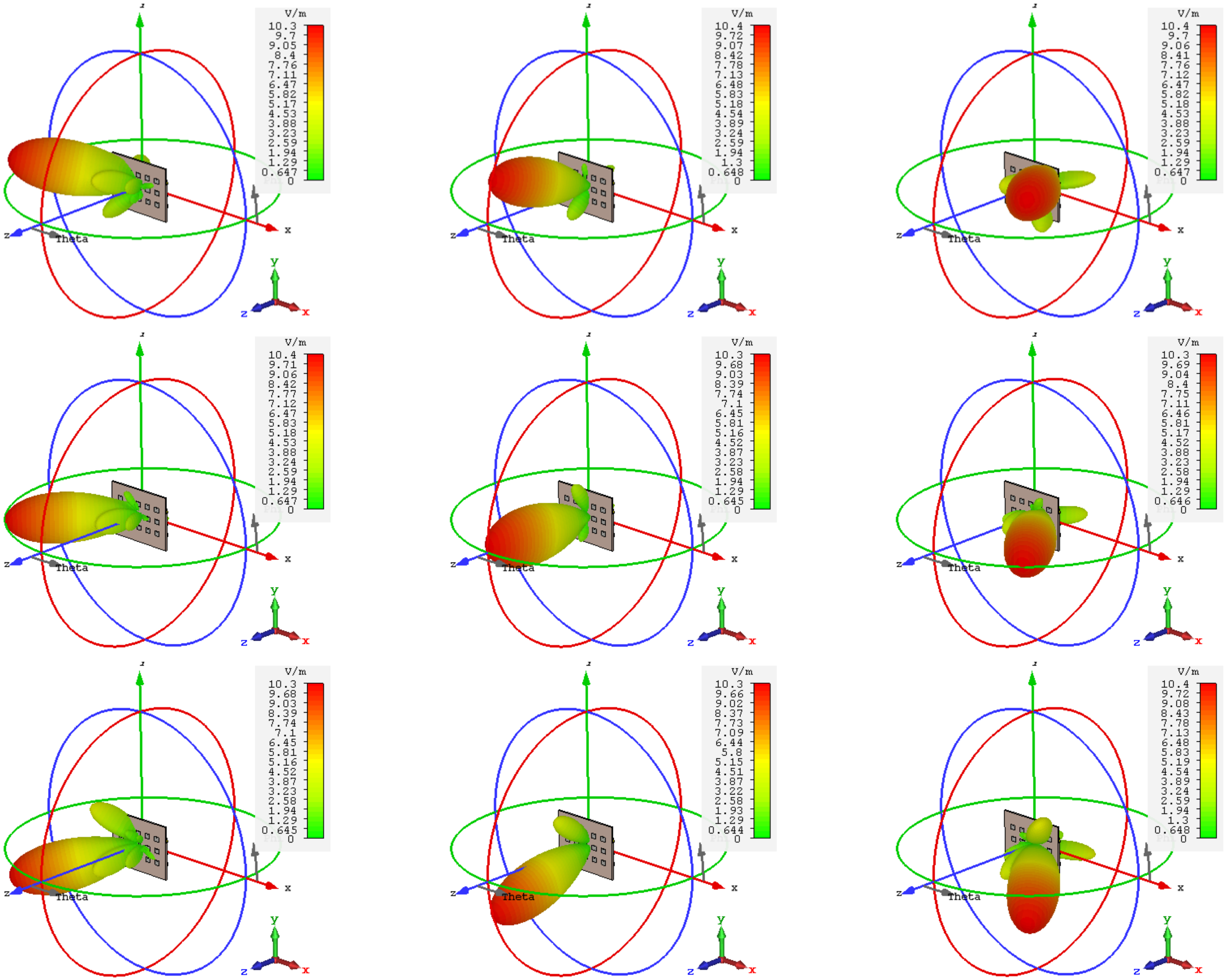
# Latest Beamformer Trends – Based on Architecture

- **Lens based hybrid beamformers**
  - Lens **before** radiators
  - Lens **after** radiators




Abbasi, Muhammad Ali Babar, and Vincent F. Fusco. "Beamformer development challenges for 5G and beyond." *Antennas and Propagation for 5g and Beyond: IET* (2020): 265.




MWC19 Barcelona

| Main beam direction(s) | HPBW |
|---|---|
| Azimuth | |
| 39° | 28.1° |
| 0° | 24.6° |
| -39° | 28.1° |
| Elevation | |
| 18° | 29.0° |
| 2° | 35.4° |
| -16° | 31.2° |

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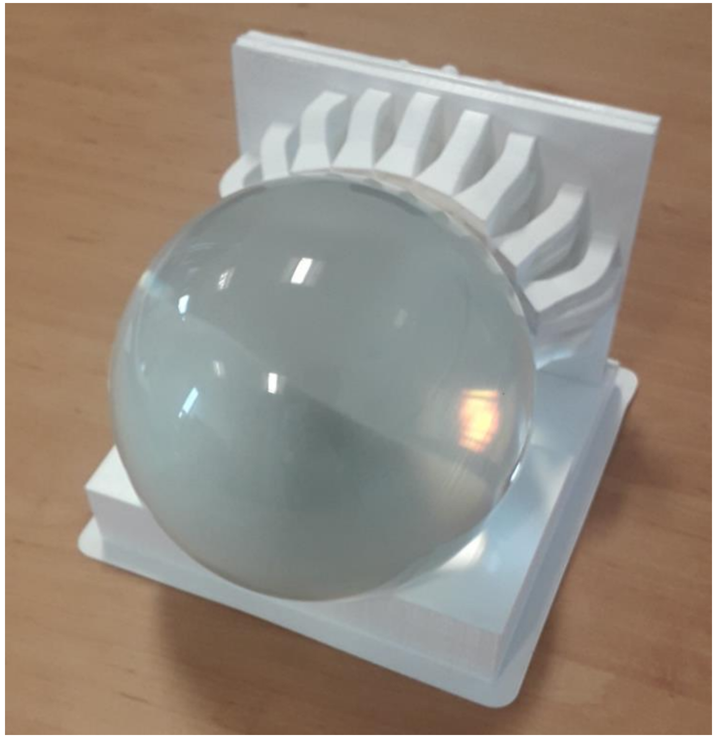
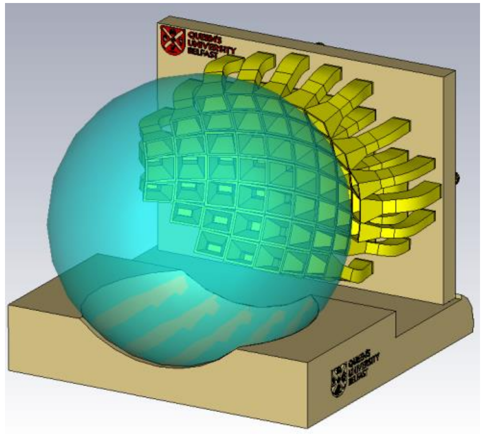
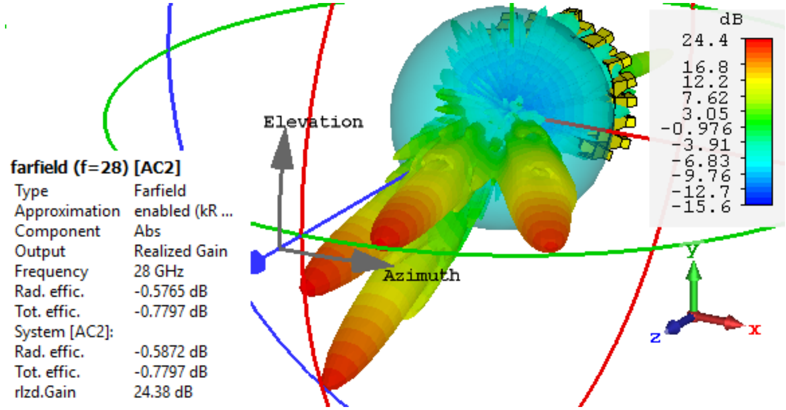
# Latest Beamformer Trends – Based on Architecture

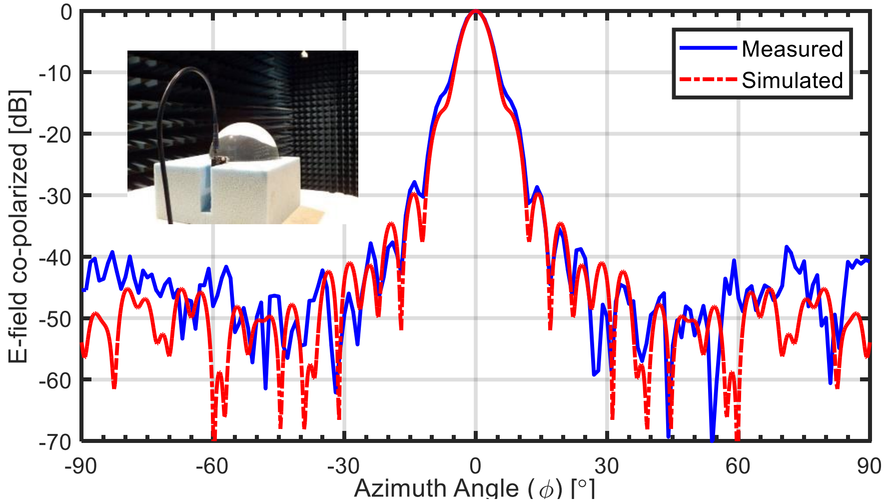
- **Lens based hybrid beamformers**



51 beam mmWave beamformer



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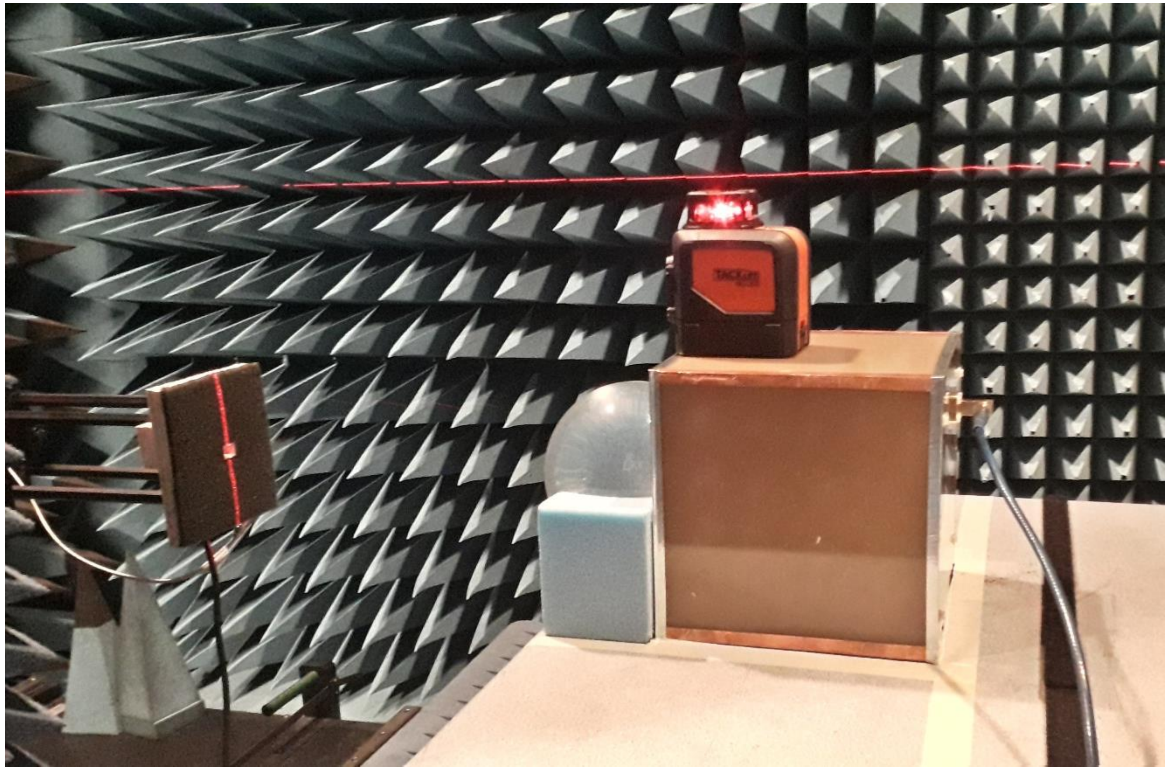
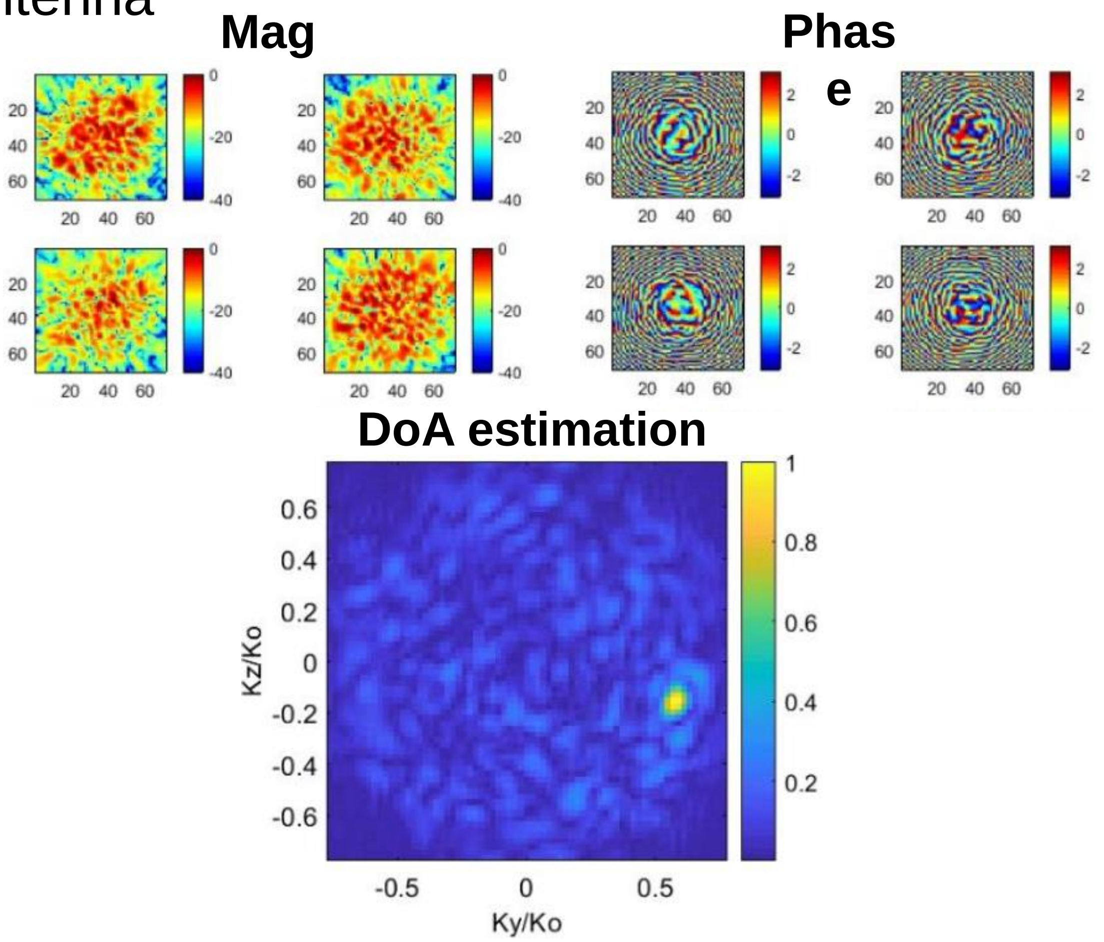
Abbasi, Muhammad Ali Babar, et al. "Constant-${\epsilon} _ {r} $ Lens Beamformer for Low-Complexity Millimeter-Wave Hybrid MIMO." *IEEE Transactions on Microwave Theory and Techniques* 67.7 (2019): 2894-2903.

# Latest Beamformer Trends – Based on Architecture

- **Lens based beamformers,** frequency diverse antenna






Abbasi, M. A. B., et al. "Frequency-diverse multimode millimetre-wave constant-ϵ r lens-loaded cavity." *Scientific Reports* 10.1 (2020): 1-12.

# Beamformer Classification Based on

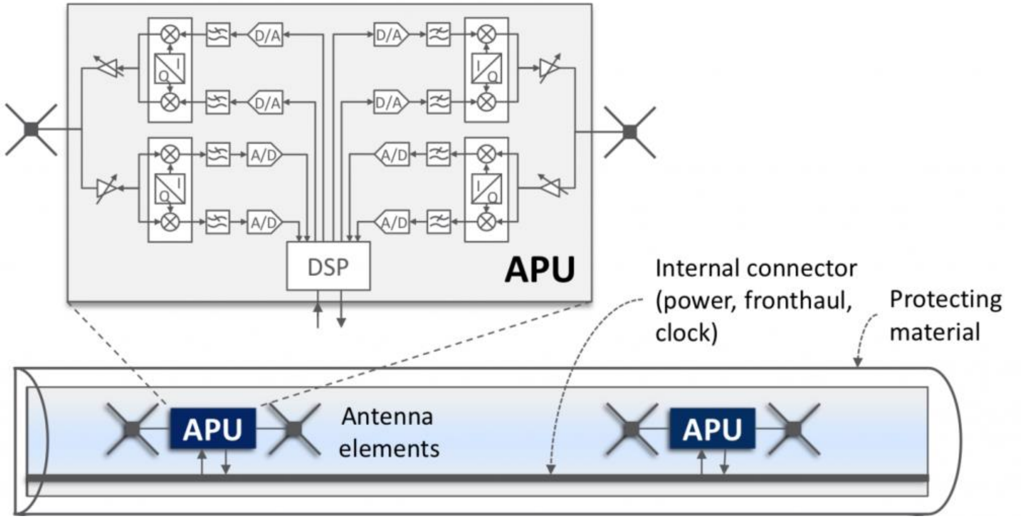
Architecture

**Frequency**

Use Case

# Based on Frequency

- **Beamformers at sub-6 GHz**
- MIMO and Massive MIMO - hundreds of antennas act phase-coherently and serve tens of terminals in the same time-frequency resource (**Thomas Marzetta**)
- Base station antenna array can acquire instantaneous channel state information (CSI)
- Cell-free massive MIMO - The **Ericsson Radio Stripes** (3.5 GHz)


Massive MIMO and 5G: E. Ali, M. Ismail, R. Nordin, and N. F. Abdulah, "Beamforming techniques for massive MIMO systems in 5G: overview, classification, and trends for future research," Front. Inf. Technol. Electron. Eng., vol. 18, no. 6, pp. 753–772, 2017.
The Ericsson Radio Stripes: https://www.ericsson.com/en/blog/2019/2/radio-stripes

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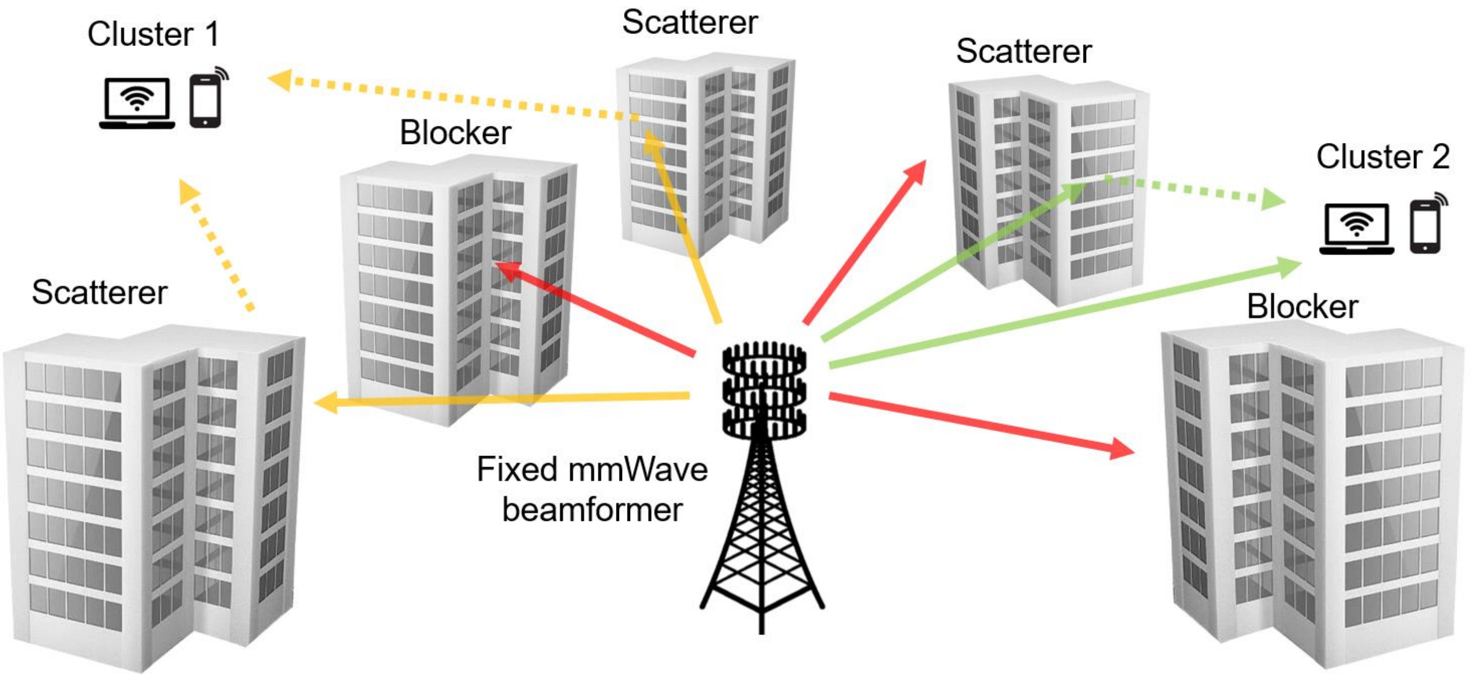
# Latest Beamformer Trends – Based on Frequency

- **Beamformers at mmWave –major considerations:**

- Large bandwidth
- High Path loss – **is that so?**
- The number of multipath required to serve users in mmWave cells are **few**




mmWave pathloss: W. Roh *et al.*, "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 106–113, 2014.

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# Latest Beamformer Trends – Based on Frequency

| | |
|---|---|
| **Limited coverage and too costly**<br>Significant path loss means coverage limited to just a few hundred feet, thus requiring too many small cells | **Significant coverage with co-siting**<br>Analog beamforming w/ narrow beam width to overcome path loss. Comprehensive system simulations reusing existing sites. |
| **Works only line-of-sight (LOS)[1]**<br>Blockage from hand, body, walls, foliage, rain etc. severely limits signal propagation | **Operating in LOS and NLOS[1]**<br>Pioneered advanced beamforming, beam tracking leveraging path diversity and reflections. |
| **Only viable for fixed use**<br>As proven commercial mmWave deployments are for wireless backhauls and satellites | **Supporting robust mobility**<br>Robustness and handoff with adaptive beam steering and switching to overcome blockage from hand, head, body, foliage. |
| **Requiring large formfactor**<br>mmWave is intrinsically more power hungry due to wider bandwidth with thermal challenges in small formfactor | **Commercializing smartphone**<br>Announced modem, RF, and antenna products to meet formfactor and thermal constraints, plus device innovations. |

https://www.qualcomm.com/media/documents/files/deploying-mmwave-to-unleash-5g-s-full-potential.pdf

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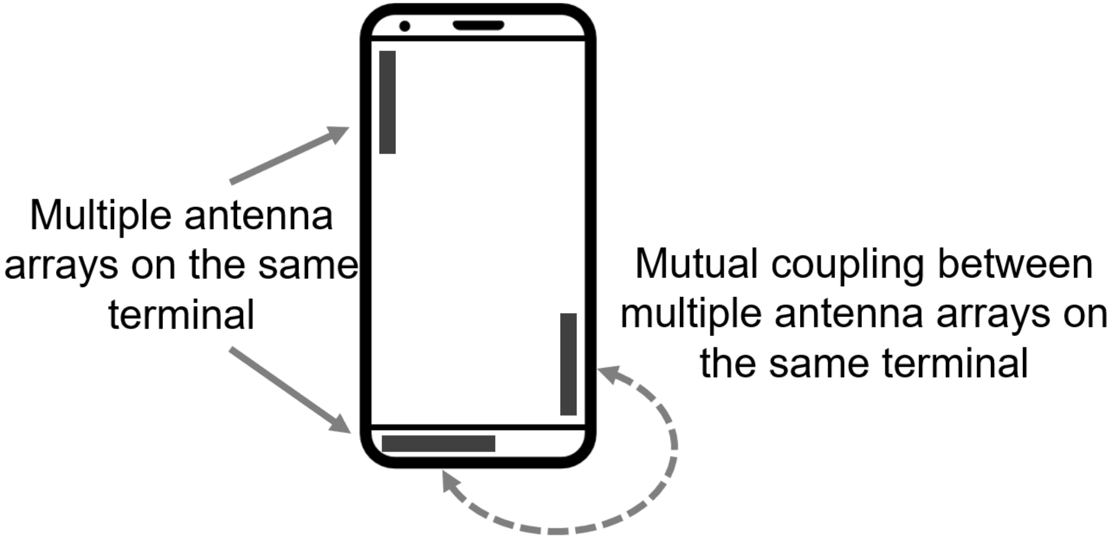
# Latest Beamformer Trends – Based on Frequency

- **Beamformers at mmWave – additional considerations**
- Spatial consistency
- Human body blockages

- **NYUSIM:** The open source 5G and 6G channel model simulator software
- **QuaDRiGa:** The next generation radio channel model




NYUSIM: S. Ju, O. Kanhere, Y. Xing and T. S. Rappaport, “A Millimeter-Wave Channel Simulator NYUSIM with Spatial Consistency and Human Blockage,” 2019 IEEE Global Communications Conference (GLOBECOM), Hawaii, USA, Dec. 2019, pp. 1-6.
https://quadriga-channel-model.de/

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# Latest Beamformer Trends – Based on Frequency

- **Beamformers at mmWave**
- World’s first – to aggregate **mmWave** and **sub-6** for ultimate 5G performance and support for all-day battery life.
- 5G mmWave 800 MHz bandwidth, 8 carriers, 2x2 MIMO



- Peak Download Speed - 7.5 Gbps
- Peak Upload Speed - 3 Gps

https://www.qualcomm.com/media/documents/files/qualcomm-snapdragon-x60-5g-modem-rf-system-product-brief.pdf

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# Beamformer Classification Based on

Architecture

Frequency

**Use Case**

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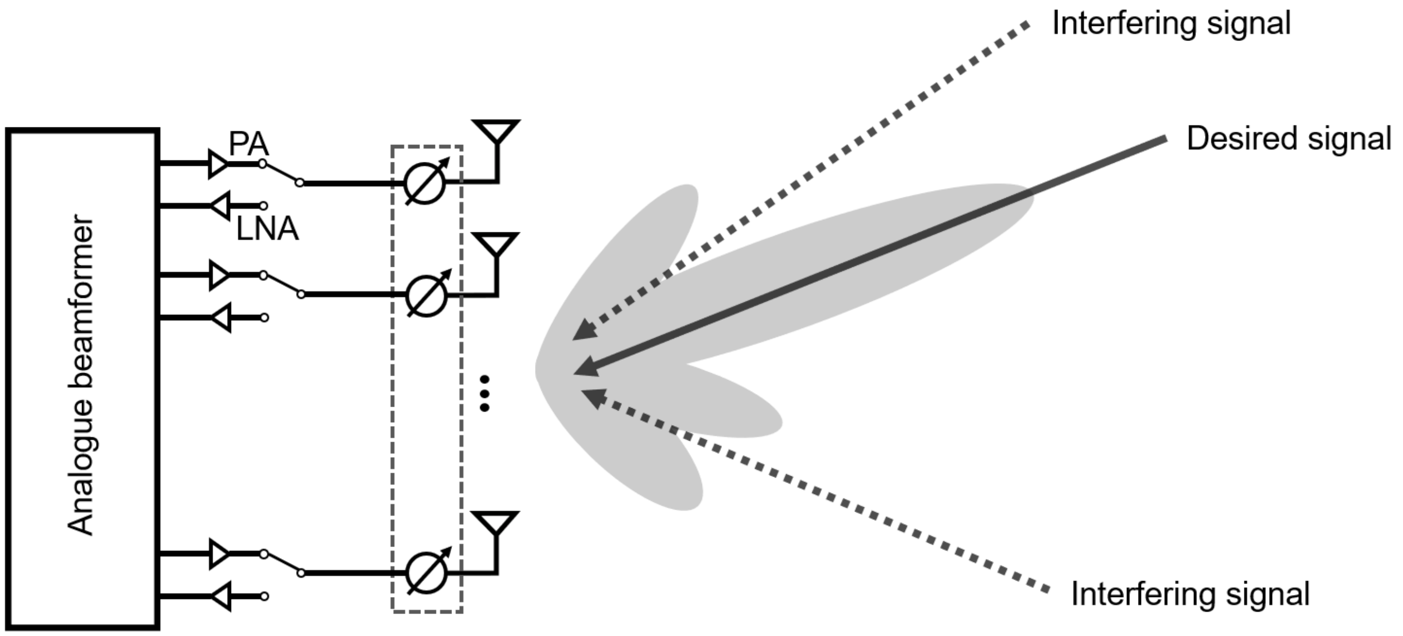
# Based on Use Case

- **Fixed beamformers**
- Not subject to mobility in a communication system

$$pathloss = \left(\frac{4\pi r \times f}{c}\right)^2$$

*r* – path length
*f* – frequency
*c* – speed of light
(all in SI units)



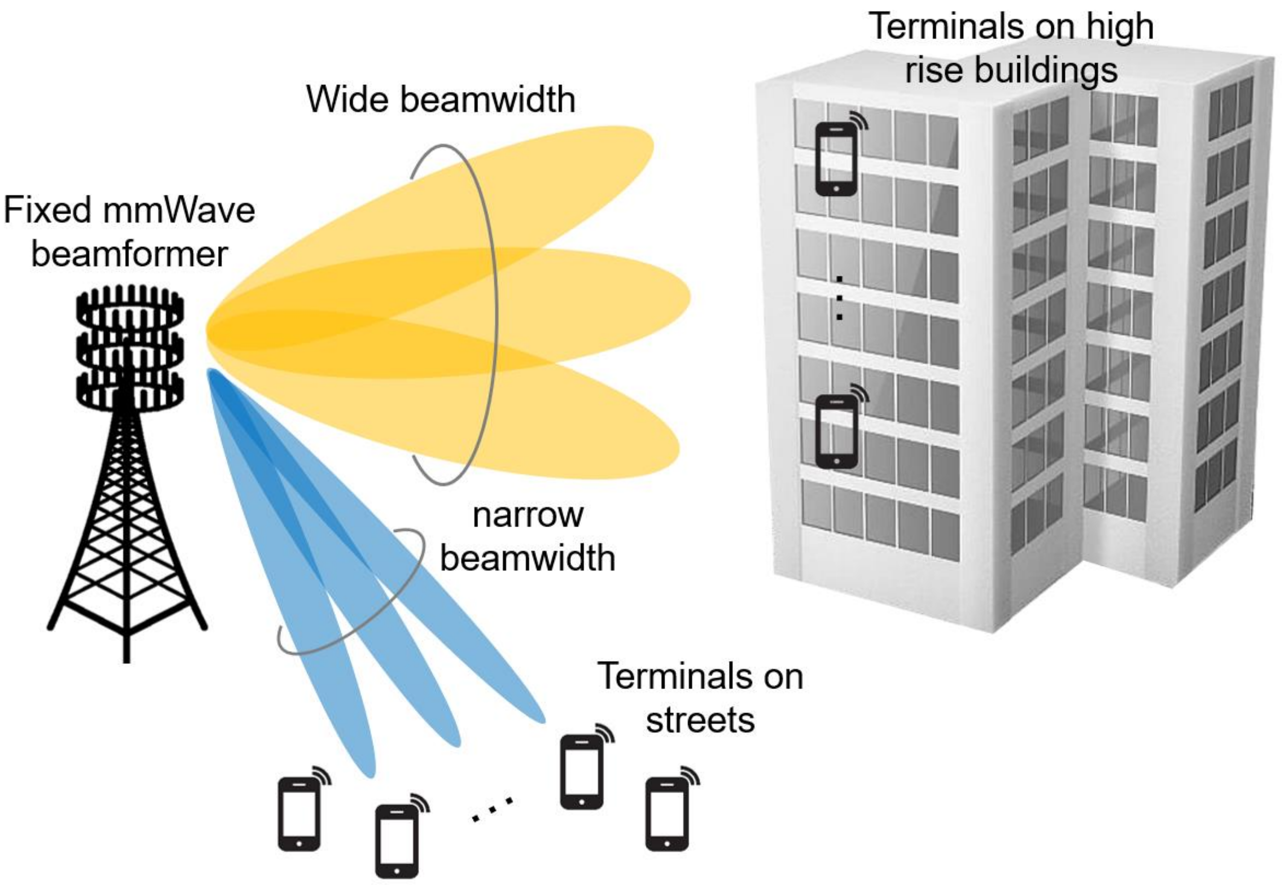

H. T. Friis, "A note on a simple transmission formula," *Proc. IRE*, vol. 34, no. 5, pp. 254–256, 1946.

# Latest Beamformer Trends – Based on Use Case

- **Variable Beamwidth Fixed Beamformer – consideration points**

Trade-off between the beamwidth and network overheads depends upon:

- number of service beams
- Coverage area (cell size)
- Number of users,
- Network mobility (coherence time)
- Terminal mobility




Variable beamwidth beamfoming: W. Liu and Z. Wang, “Non-Uniform Full-Dimension MIMO: New Topologies and Opportunities,” *IEEE Wirel. Commun.*, vol. 26, no. 2, pp. 124–132, 2019.

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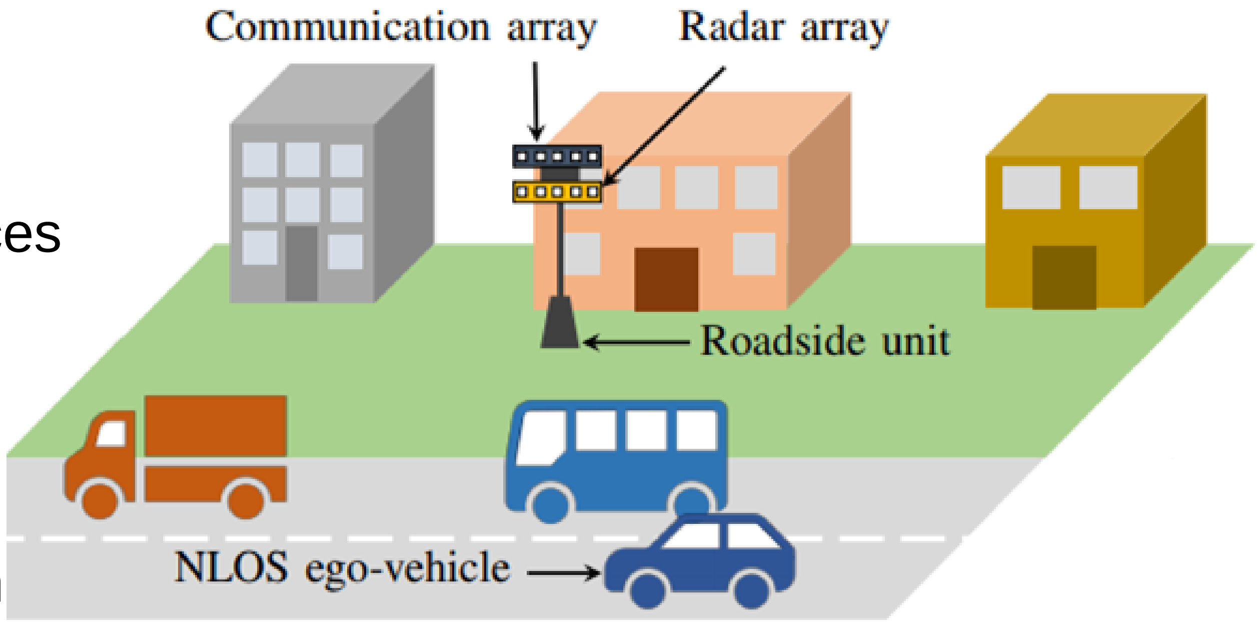
# Latest Beamformer Trends – Based on Use Case

- **Fixed beamformers**
- Passive Radar at the Roadside Unit for **Vehicle-to-Infrastructure Links**

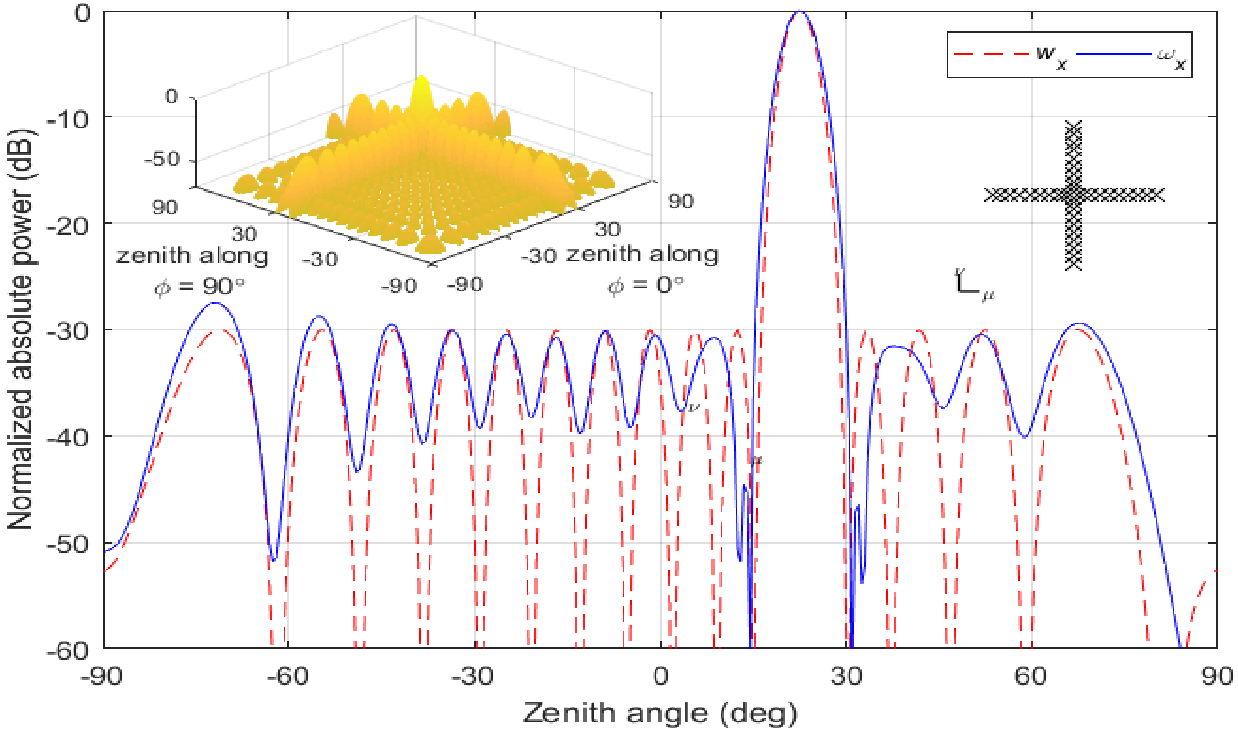
- Passive radar at the roadside unit reduces the **training overhead** via the **spatial covariance**
- To leverage the radar information for beamforming, the radar azimuth power spectrum (APS) and the communication APS should be similar.



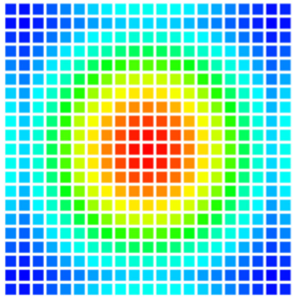

Roadside passive radar: Anum, Ali, Nuria GonzalezPrelcic, and Amitava Ghosh. "Passive radar at the roadside unit to configure millimeter wave vehicle-to-infrastructure links." *IEEE Transactions on Vehicular Technology* (2020).

# Latest Beamformer Trends – Based on Use Case

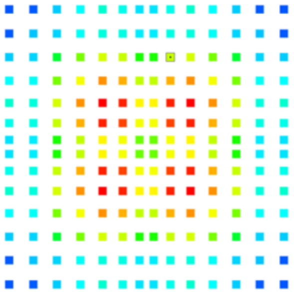
- **Fixed beamformers**
- **Compressive Sensing** for antenna array thinning and hardware reduction

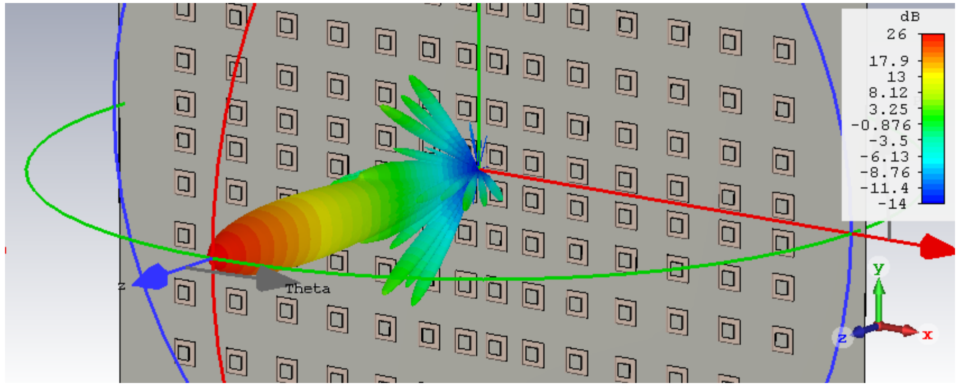



Microstrip patch antenna array



Thinned patch antenna array






31 x 31 antenna elements are shown to be reduced to 20 x 20 elements

Abbasi, Muhammad Ali Babar, Vincent Fusco, and Dmitry E. Zelenchuk. "Compressive sensing multiplicative antenna array." *IEEE Transactions on Antennas and Propagation* 66.11 (2018): 5918-5925.

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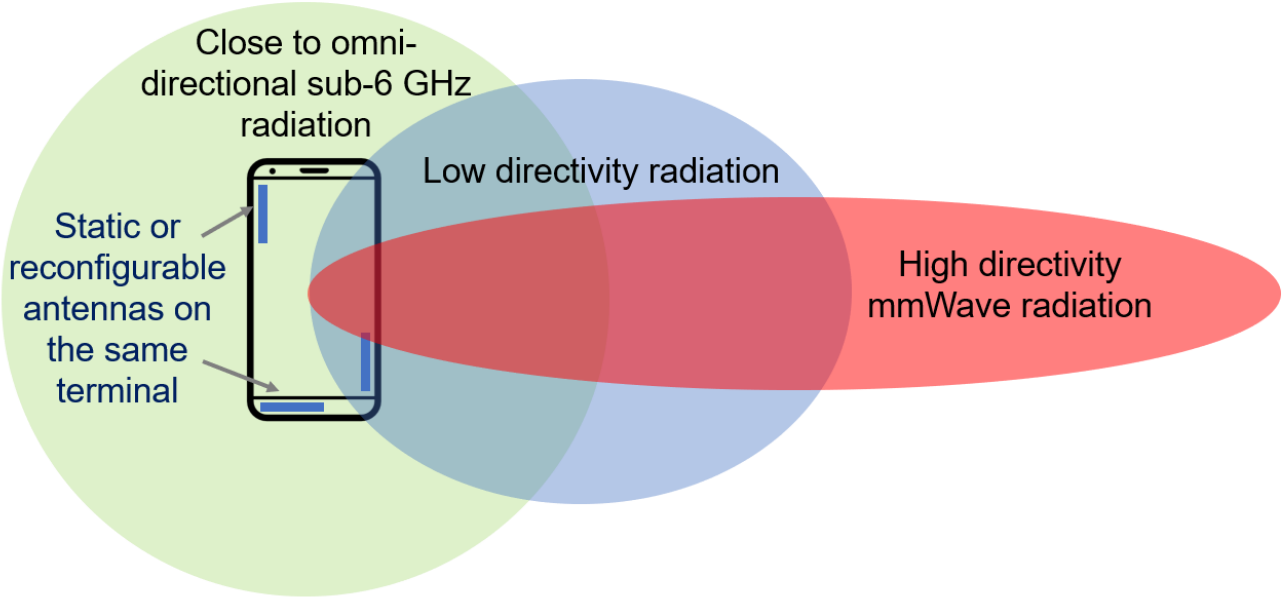
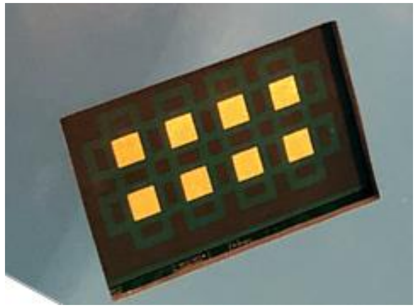
# Latest Beamformer Trends – Based on Use Case

- **Mobile beamformers**
- Beamformer performance is critical
- Multiple units to avoid blockage




> We've seen relatively few mmWave smartphones to date, and none have cost less than $800 at launch.



Raghavan, Vasanthan, et al. "Handling dynamic blockage in millimeter wave communication systems." U.S. Patent No. 10,819,409. 27 Oct. 2020.
mmWave 5G uncertainty: https://www.androidpolice.com/2020/06/16/mmwave-5g-is-at-a-crossroads/
mmWave in mobile phone: https://www.mediatek.com/blog/mediatek-shows-its-5g-mmwave-antenna-design-for-smartphones-at-computex-2018

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# CONCLUSIONS AND PROSPECTIVES

CENTRE FOR WIRELESS INNOVATION

- Beamformer Classifications
- Architecture – hybrid and lens-based hybrid
- Frequency – sub-6GHz and mmWave
- Use case – fixed, variable beamwidth fixed, mobile

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