UNIVERSITÉ Concordia UNIVERSITY

Challenges on Antennas for Millimeter-Wave Applications

Ahmed A Kishk

Professor and Canada Research Chair

President of Antennas and Propagation Society

November 27th, 2019. Lisbon, Portugal

IEEE

To Meet the Demand for Mobile Data Traffic , MM-Wave Offer Solution

The channel capacity, C, (bit/s/Hz),

$$C = NBlog_2(1 + SNR)$$

N : is the number of antenna elements,

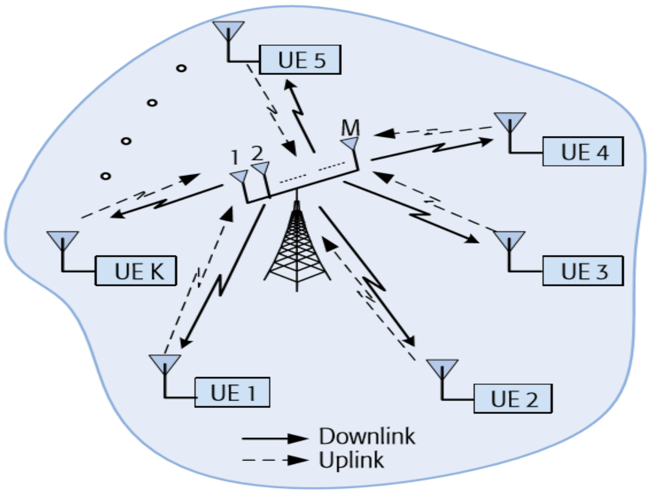
B : is the bandwidth in (Hz), and

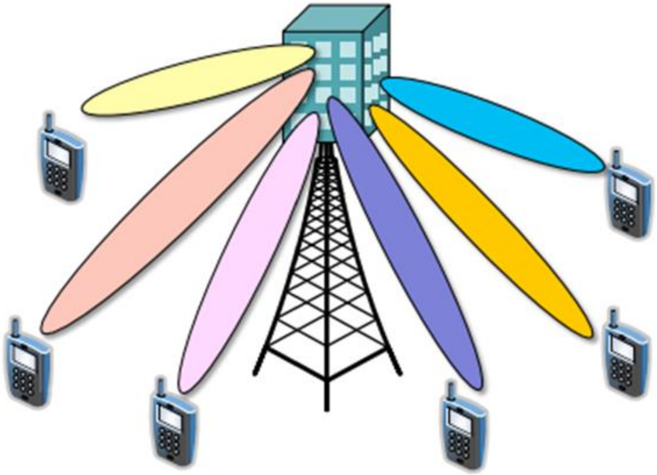
SNR : is the signal to noise ratio.

Based on that, to increase the channel capacity

- -Increase the power to get high SNR, (system constrains and regulations, interference levels increase).
- -Increase the bandwidth,(limited due to spectrum regulations) or
- -Increase the number of antenna elements (size and performance).

Increase Number of Antennas (Massive MIMO)

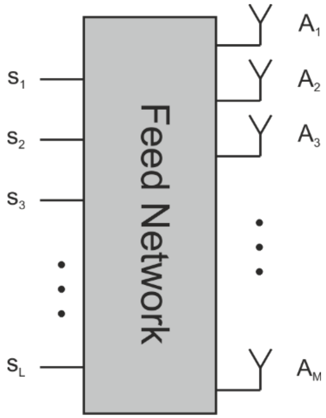




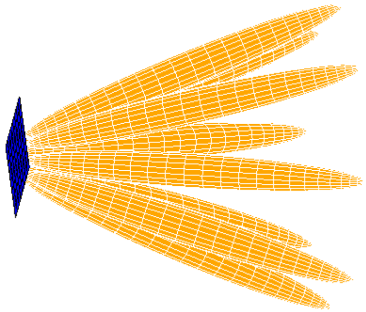
- ❑ In Massive multiple-input multiple-output (MIMO) BSs will be equipped with an excess of antennas to achieve multiple orders of spectral and energy efficiency gain.
- ❑ Massive MIMO (MM) is a multi-user MIMO (MU-MIMO) technology where K user equipment's (UEs) are serviced on the same time-frequency resource by a base station (BS) with M antennas, such that M >> K
- ❑ When the number of antennas at the BS is increased, the system throughput R can be improved because higher multiplexing gains are achievable
- ❑ Massive MIMO technology offers multiple orders of spectral and energy efficiency gains.

Multiple Signal Transmission

Creating *L* Narrow Beams using *M* Antennas



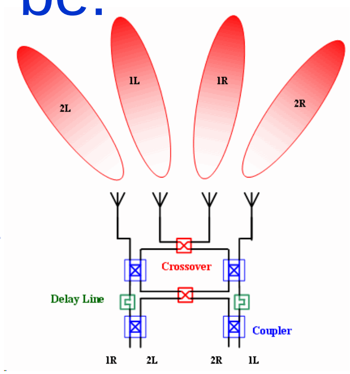
s_l *is directed to the* l^{th} *beam*



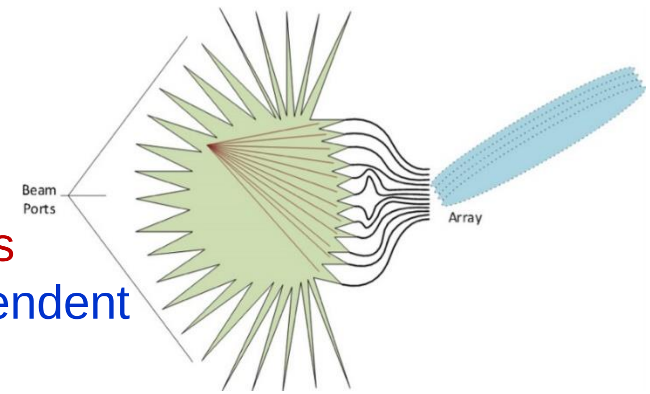
- ***L*** and ***M*** are principally independent, but M>L
- Narrow beams and weak crosstalk between signals necessitate large values of ***M***

Feed Network can be:

Butler Matrix
L & M dependent

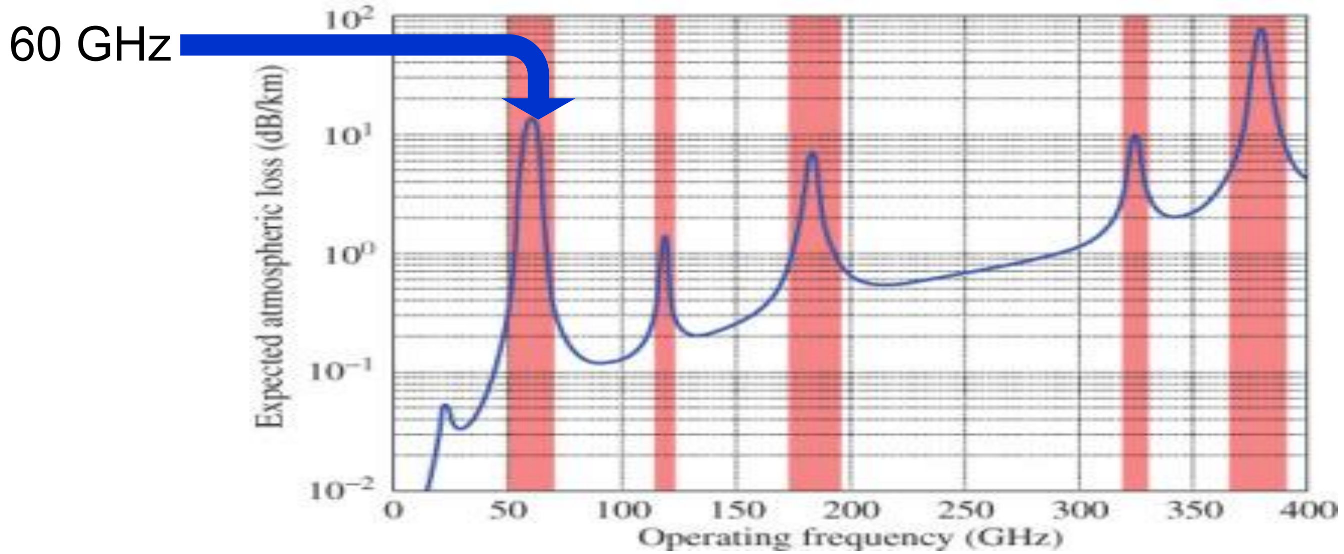


Rotman Lens
L & M independent



Wide Bandwidth Solution mm-Wave

- High bandwidths are available at mm-wave frequency.
- Due to high propagation loss, penetration loss and rain fading the mmWave is not recognized for cellular applications.



Atmospheric path loss vs. frequency under normal atmospheric conditions.

- Due to the oxygen molecule, which absorbs electromagnetic energy (at 60 GHz , the mm-Wave have been used for backhaul links , indoor, short range and line of sight communication systems).

Millimeter-Wave Communication System Requirements and Challenges

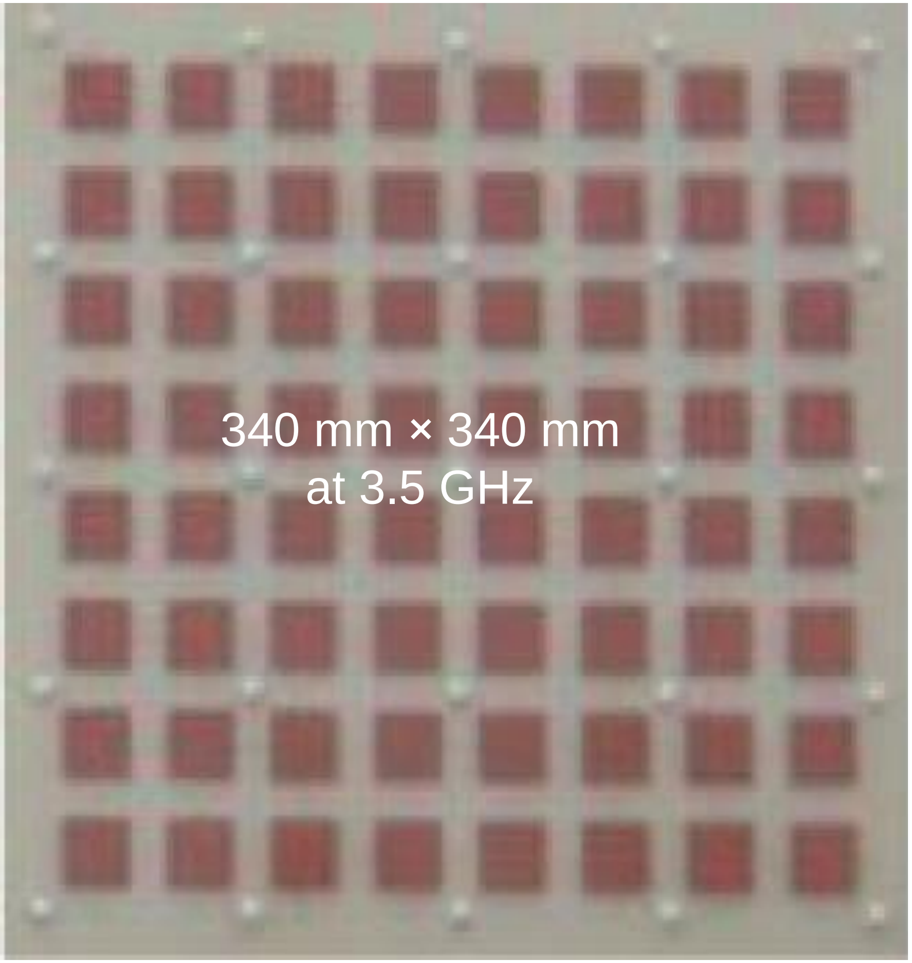
- Modern millimeter-wave (mmWave) communication systems require high-gain antennas with beam-steering ability to support user mobility or beam switching for reconfigurable backhauling.

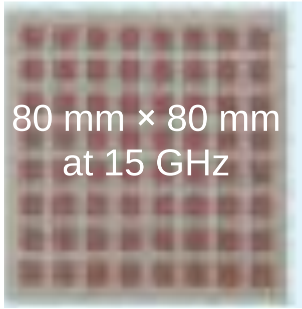
- The higher antenna gain requires a large antenna aperture that scales proportionally to the square of the wavelength.

- However, for mmWave frequencies, even large antenna arrays with a size of tens or hundreds of wavelengths will have a relatively small form factor in comparison with lower-band antennas. The compact size of the mmWave antennas may pose a problem in terms of heat dissipation and losses in thin feeding lines.

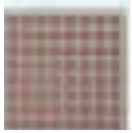
- At the same time, the high antenna gain leads to a very narrow beam, which requires perfect adjustment of the fixed antennas and special beam-steering and beam-tracking algorithms for mobile applications.

Antenna Challenges





42 mm × 42 mm
at 28 GHz



20 mm × 20 mm
at 60 GHz

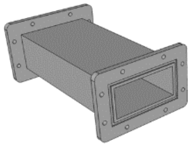
Small Size make it possible to design array for the mobile terminal and have MIMO system.

8 x 8 arrays for 3.5, 15, 28, and 60 GHz

Feeding network also bosses a challenge

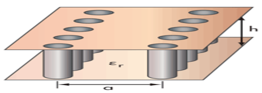
Guiding Structure at Millimeter Wave Frequencies
(>30 GHz Applications)

- **Hollow Waveguides:**



  - Low losses. ***13dB/100meter at 15 GHz.***
  - Manufacturing in several pieces requires conducting joints.
  - Too small hole diameter.
  - Hard to ensure good electrical contact.

- **Substrate Integrated Waveguide**
  - Low cost, no packaging, and easy to design circuit components (divider, coupler, filters, ...etc.)



  - High dielectric losses and high d***ispersion issue***

- **Microstrip Lines:**
  - Low cost, low dispersion and easy to design circuit components (divider, coupler, filters, ...etc.
  - High losses in the dielectric substrate. ***123dB/100meter at 15 GHz.***
  - Radiation losses, packaging problem.

Gap Waveguide Characteristics

- The new structure overcomes the disadvantages of the current guiding structures operating at high frequencies (> 30 GHz).

  It should be:

  Low losses, ***16dB/100meter at 15 GHz.***

  Low despersion for the quasi-TEM structures.

  Low manufacturing cost

  Low profile

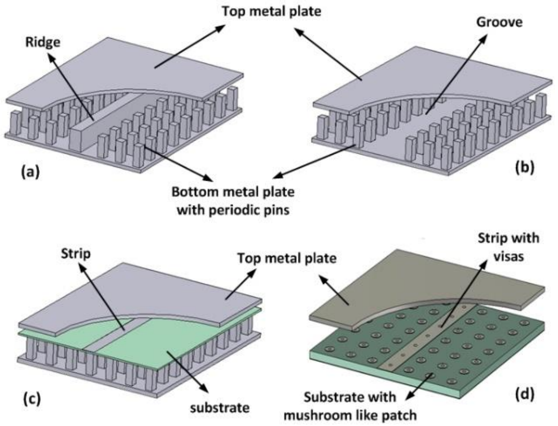
  High efficiency

  Can be integrated with MMIC and other technologies.

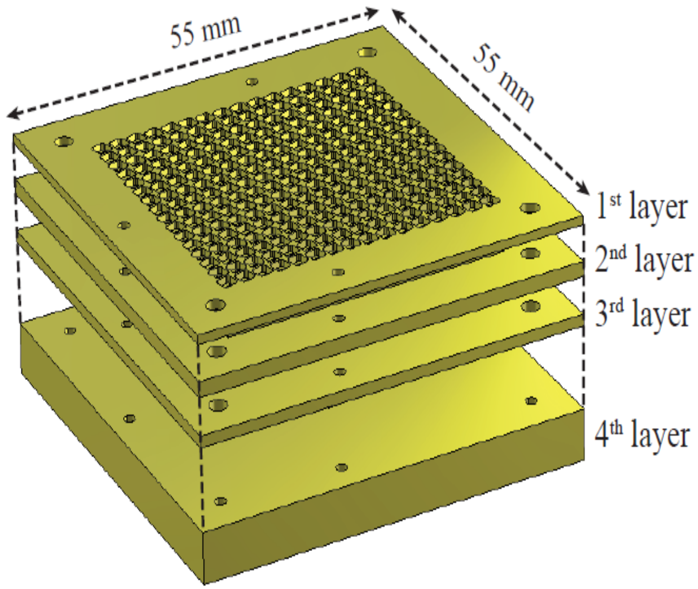
  Easy to design different kind of printed circuit elements such as dividers, filters, directional couplers, .. etc.

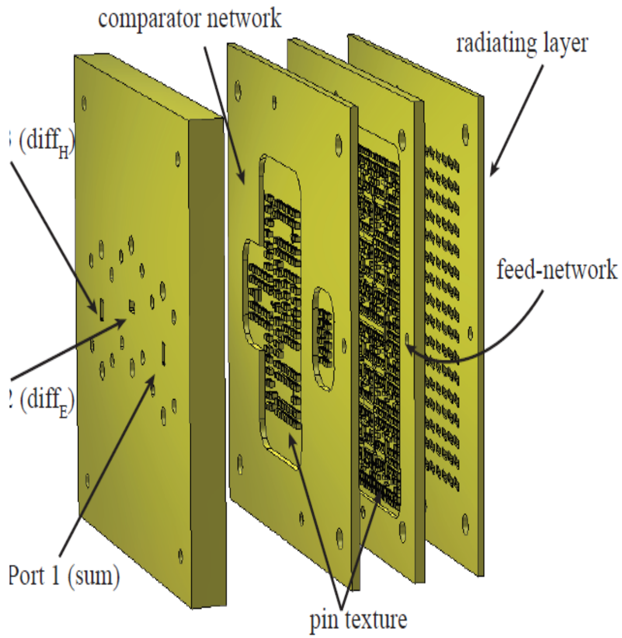
  Overcome the electrical contact problem.

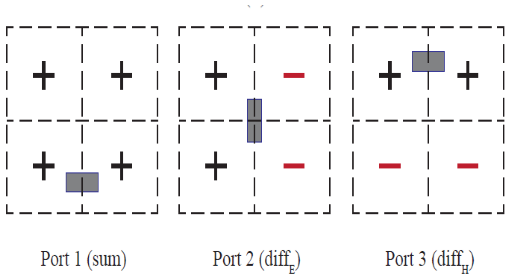
  No radiation losses.

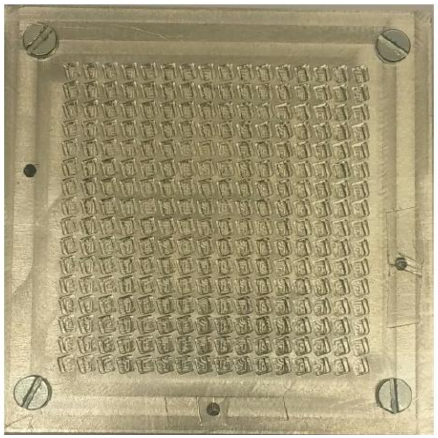


W-Band Low-Profile Monopulse Slot Array Antenna Using Gap Waveguide Corporate-Feed Network





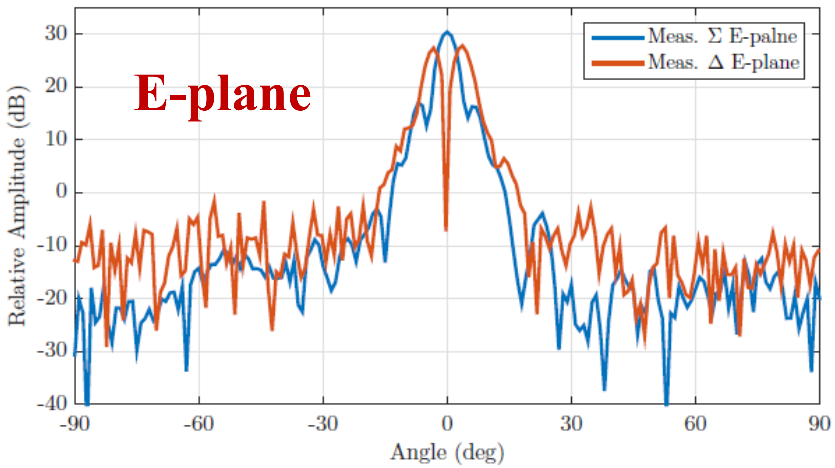


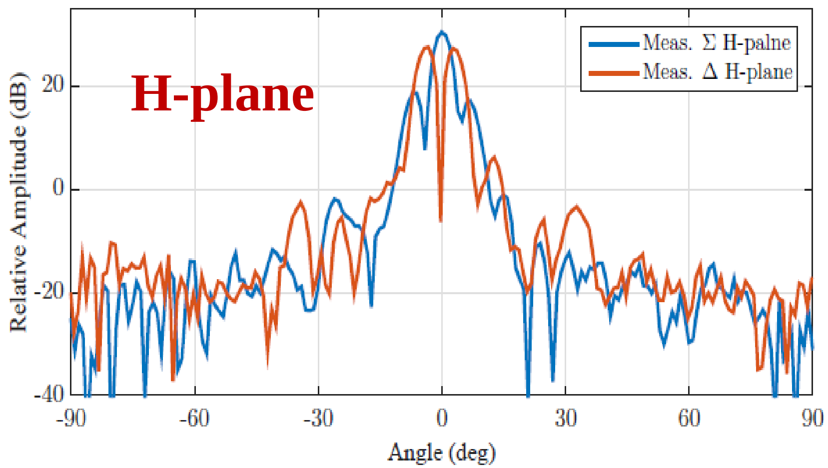


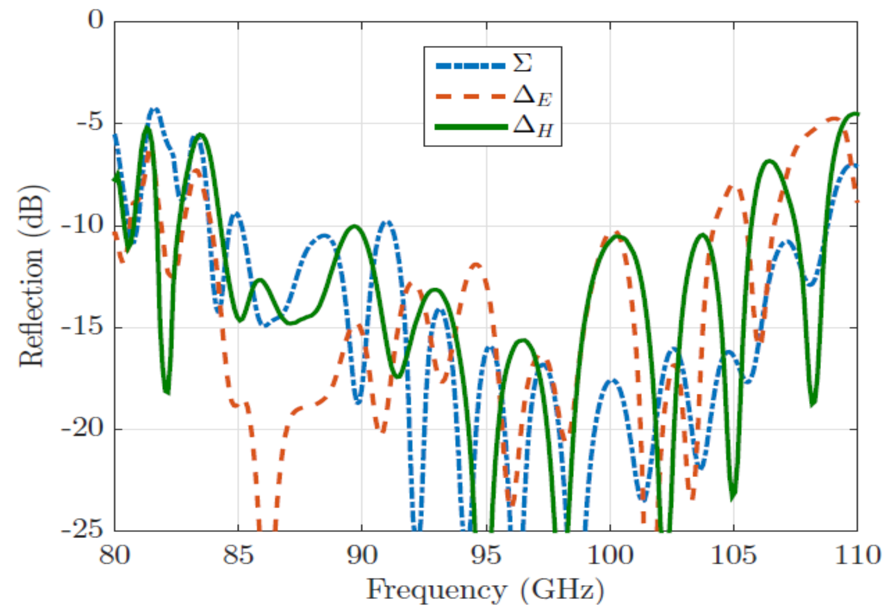
Abbas Vosoogh, Abolfazl Haddadi, Ashraf Uz Zaman, Jian Yang, Herbert Zirath, and Ahmed A.Kishk," W-Band Low-Profile Monopulse Slot Array Antenna Using Gap Waveguide Corporate-Feed Network," *IEEE Transactions on Antennas Propagation,* September 2018.

Measured Reflection Coefficients and Radiation of Sum and Difference

94 GHz







Measured reflection coefficient of the Σ port, Δ_E port, and Δ_H port.

New possible use is a MIMO not far field antenna for high channel capacity

Summary

- High demand for faster data and reliable service in mobile communication.
- Millimeter-wave for wireless network is aiming to provide such requirements.
- Such wireless network will help the development of other technologies such as Autonomous Vehicles, Smart Cities, Health Care, Virtual Reality (VR) and Internet of Things (IoT), and others.
- Millimeter waves (30-300 GHz), small cells, massive multi-input-multi-output (MIMO), full duplex, and beamforming are favored.
- Millimeter waves suffer from its inability to penetrate objects or building and the environment such as fog and snow, rain are severely affecting millimeter waves, which cause high attenuation.
- For low power use, the antenna must be of the high gain type, which means narrow directive beam. Such narrow beam nature reduces interference and allows the reuse of the frequencies on different nearby regions to serve the users.
- High gain antenna arrays are the proper concept.
- Gap waveguide technology offers solution for feeding networks.
- Massive MIMO system will support more than 100 ports, which allow the base station to send and receive from much more users simultaneously.
- Base station must use beamforming, which identifies the data level to a user and reduce the interference with the nearby users.


Thank You!

Suggested 5G Standards and Specifications

- Data Rate: 20 Gbps downlink and 10Gbps uplink per mobile base station.
- Density: 1M (10^6) devices per square kilometer.
- Mobility: Support everything from 0km/h all the way up to "500km/h high speed vehicular" access (i.e. trains).
- Latency: A maximum of just 4ms, down from about 20ms on LTE cells.
- Spectral Efficiency : DL/UL ≈ 30/15 bps/Hz using 8 x 8/4 x 4 MIMO
- Energy Efficient: Radio interfaces when under load, but also drop into a low energy mode quickly when not in use (10ms).
- Increased reliability (packets get to the base station within 1ms), and 0ms interruption time when moving between 5G cells (no drop-outs).

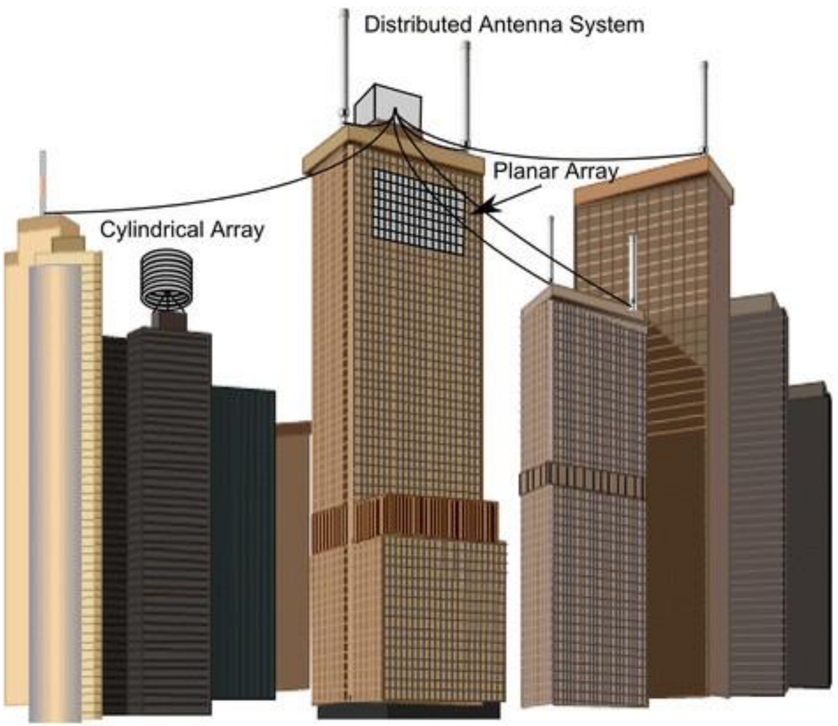
That Means access to information and sharing of data is provided anywhere and anytime for anyone and anything.

The realization of this vision requires low cost devices, low energy consumption. (reliability).

Different Array Configurations for Massive MIMO

Array Configurations

Array Mounting



Concordia University

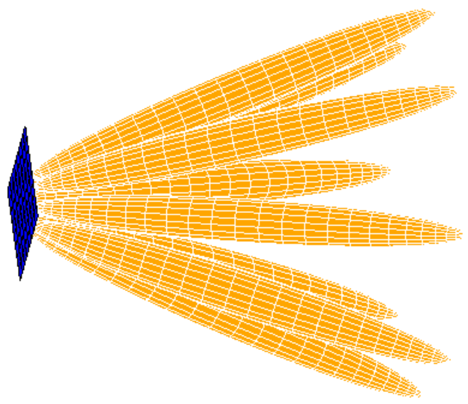
Phased Arrays and Beamforming

Radiation Pattern

$$E(r,\theta,\varphi) = -j\omega\mu_0 \frac{e^{-jk_0 r}}{4\pi r} \sum_n \sum_m I_{nm} \cdot e^{jk_0 \sin\theta \cdot (m \cdot d_x \cos\varphi + n \cdot d_y \sin\varphi)}$$

Beamforming and steering through $I_{nm} = A_{nm} \cdot e^{-j\alpha_{nm}}$

- Magnitudes A_{nm}: Beam Shape and Side-Lobe Reduction
- Phases α_{nm}: Steering and Nulling



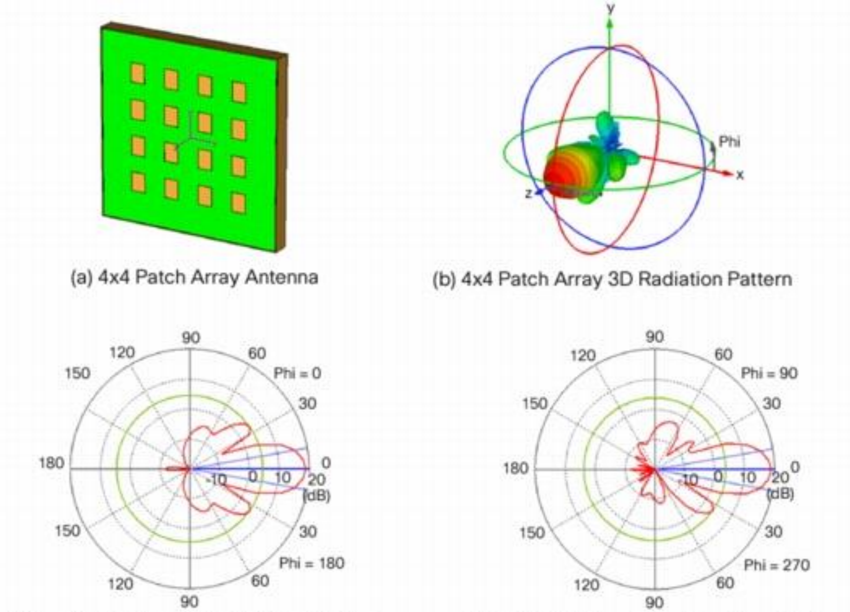
$$\alpha_{nm} = m \cdot a \cdot k_0 d_x + n \cdot b \cdot k_0 d_y \rightarrow$$

Main Lobe:

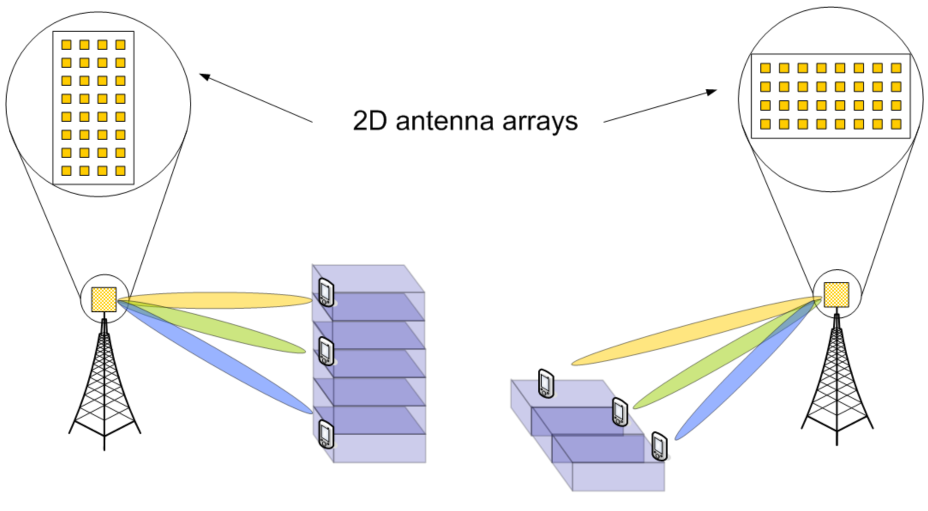
$$\theta_{ML} = \sin^{-1}\left(\sqrt{a^2 + b^2}\right) \quad , \quad \varphi_{ML} = \tan^{-1}\left(\frac{b}{a}\right)$$

Phased Arrays and Beamforming

Beamforming Scenarios



(a) 4x4 Patch Array Antenna (b) 4x4 Patch Array 3D Radiation Pattern (c) 4x4 Patch Array Azimuth Plane Pattern (d) 4x4 Patch Array Elevation Plane Pattern



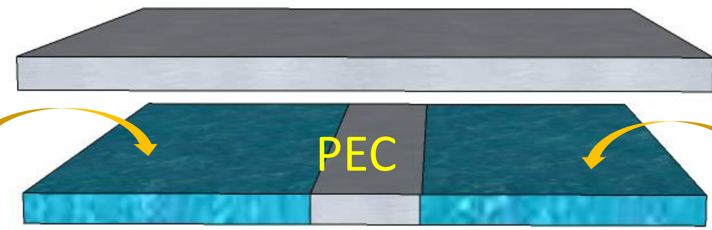
Beamforming in the elevation domain

Beamforming in the azimuth domain

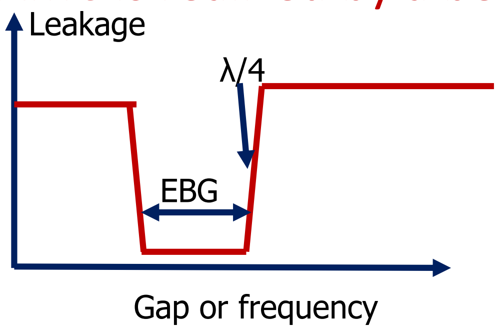
Both Provide Elevation and Azimuthal Scanning

Gap Waveguide Realization

- PMC is realized by an artificial magnetic conductor (AMC).



AMC is realized by a bed of conducting nails Acting as a bandstop filter



Lower limit: d=λ/4

Upper limits: h=λ/4, d=λ/2

2:1 Bandwidth

- The waves will only propagate along the trace of PEC/PEC and attenuate elsewhere.

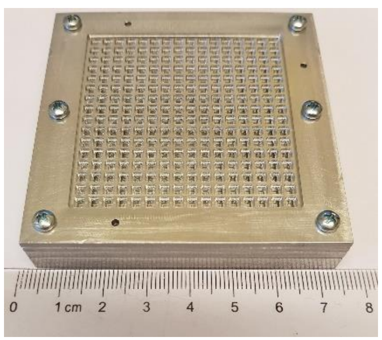
Requires Milling of the ridge and the nails.

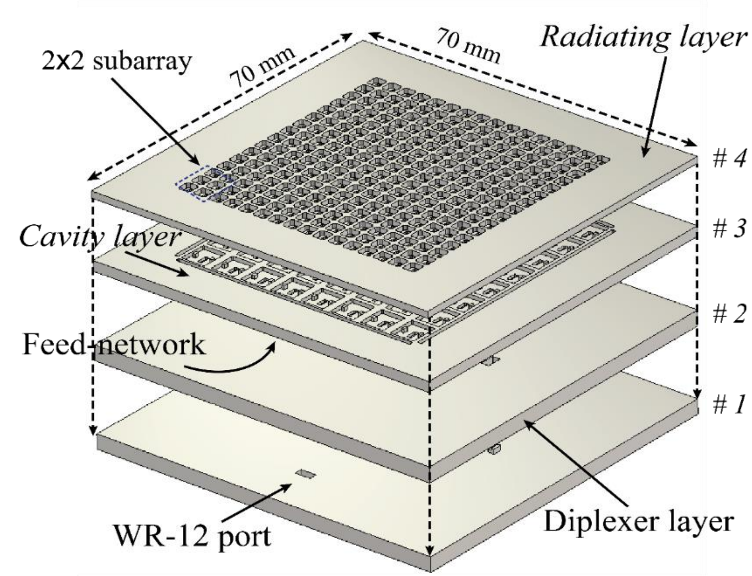
Concordia University

Losses in Gap Waveguide (comparison)

Prototype (frequency)	Simulated loss from CST (dB/cm)	Measured min. loss (dB/cm)	Measured max. loss (dB/cm)
Rect. Waveguide (50-75 GHz)	0.0136	0.0295	0.042
VER-pol Groove (50-75 GHz)	0.019	0.03	0.0442
HOR-pol Groove (56-75 GHz)	0.036	0.05	0.058
Ridge gap (50-75 GHz)	0.0373	0.058	0.0705
Micro-ridge gap (56-68 GHz)	0.0805	0.162	0.23
Invert-micro. gap (56-72 GHz)	0.0934	0.21	0.288
Microstrip line (50-75 GHz) 0.127mm subst.	0.372	0.62	0.77

E-band Antenna-diplexer Compact Integrated Solution Based on Gap Waveguide Technology





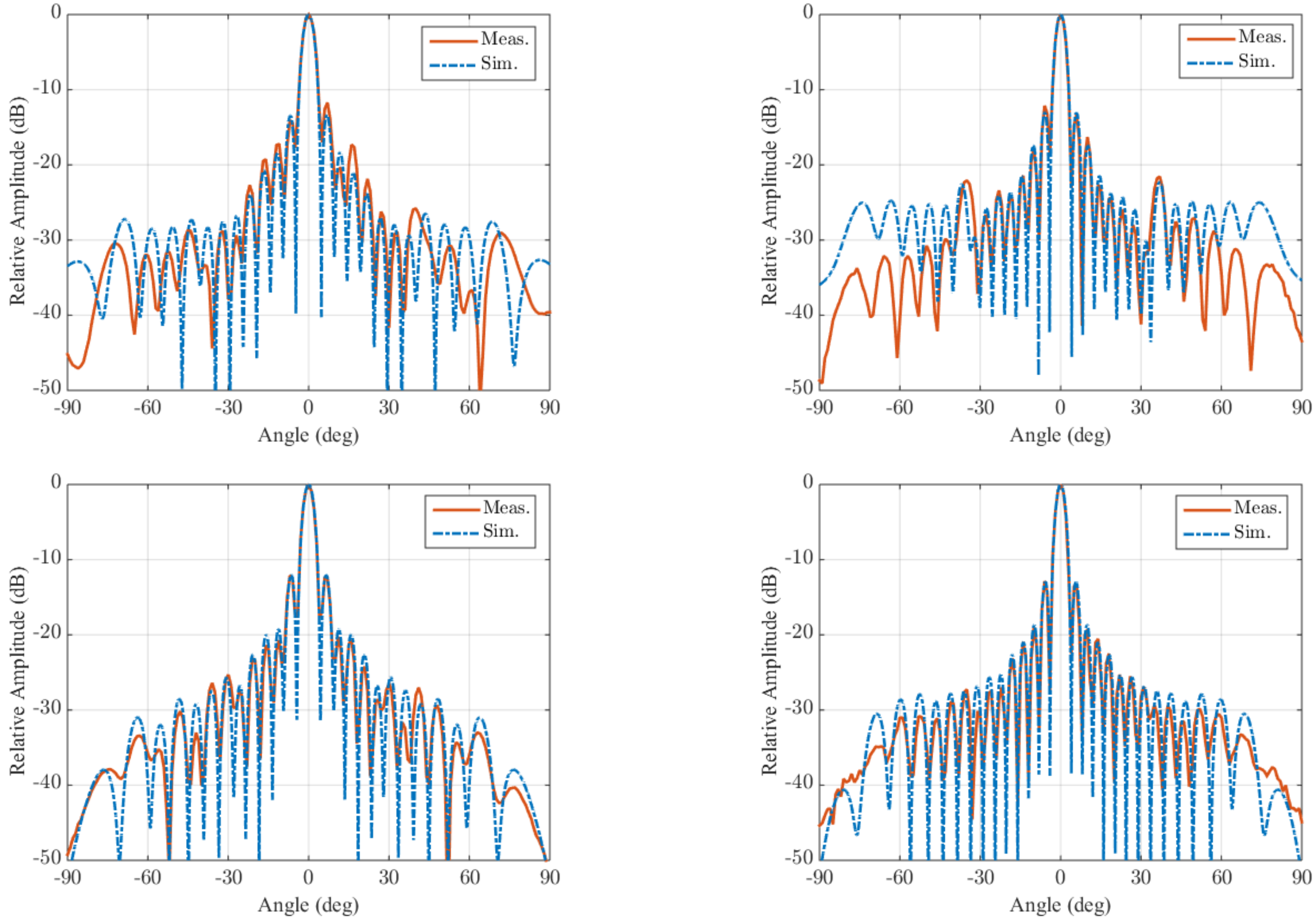
Distributed view of the proposed module

Abbas Vosoogh, Ashraf Uz Zaman, and Jian Yang, Milad Sharifi, and Ahmed Kishk," An E-band Antenna-diplexer Compact Integrated Solution Based on Gap Waveguide Technology, " *2017 **I**nternational **S**ymposium on **A**ntennas and **P**ropagation, ISAP 2017*, Thailan, *November 2017. 3rd Best Paper Award.*

Radiation Patterns of Integrated Antenna-diplexer

E-plane

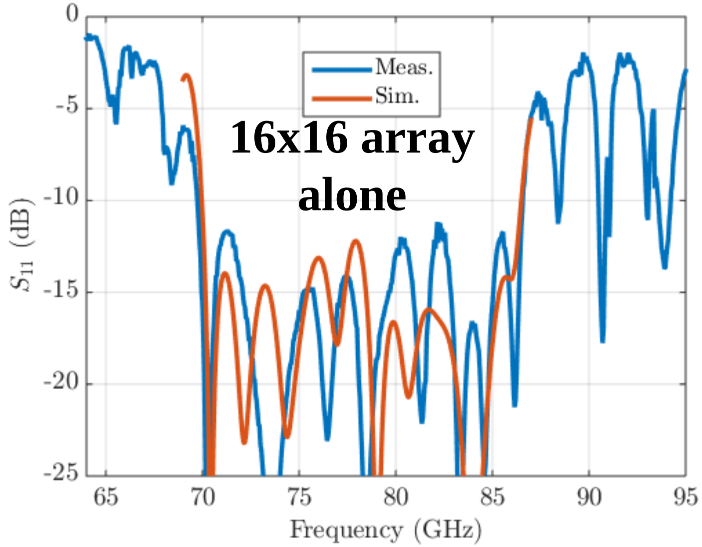
H-plane



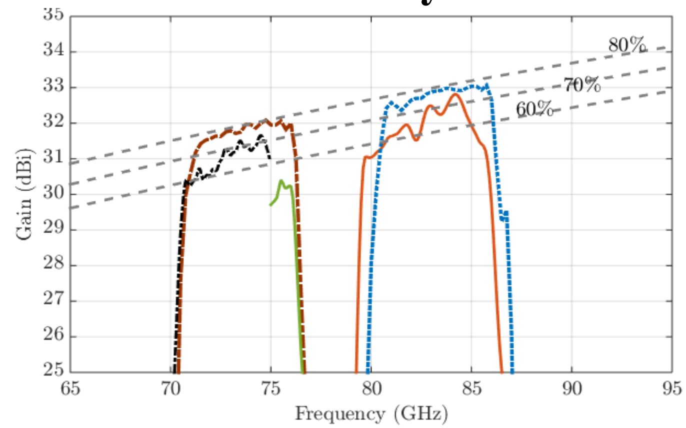
73.5 GHz (Ch. 1)

83.5 GHz (Ch. 2)

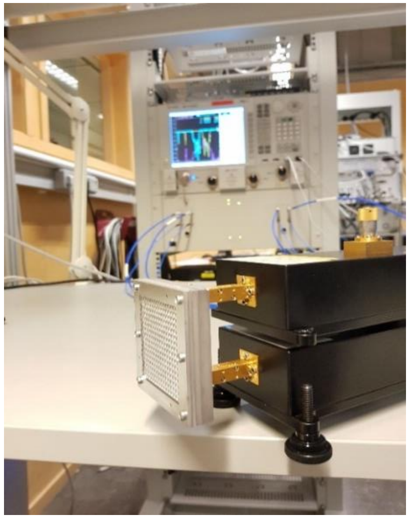
Integrated 16x16 Slot Array

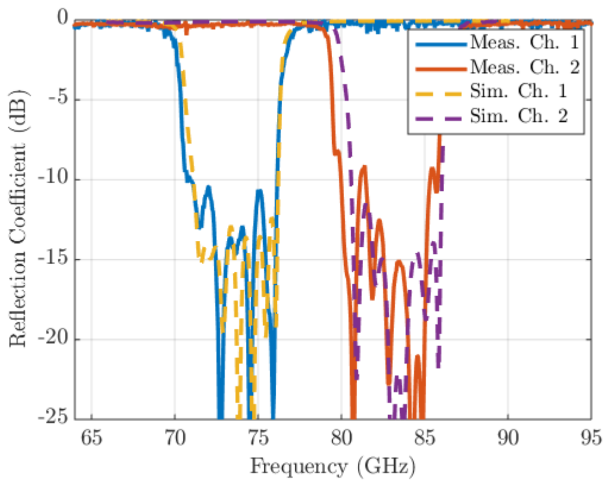


Antenna efficiency > 65 %

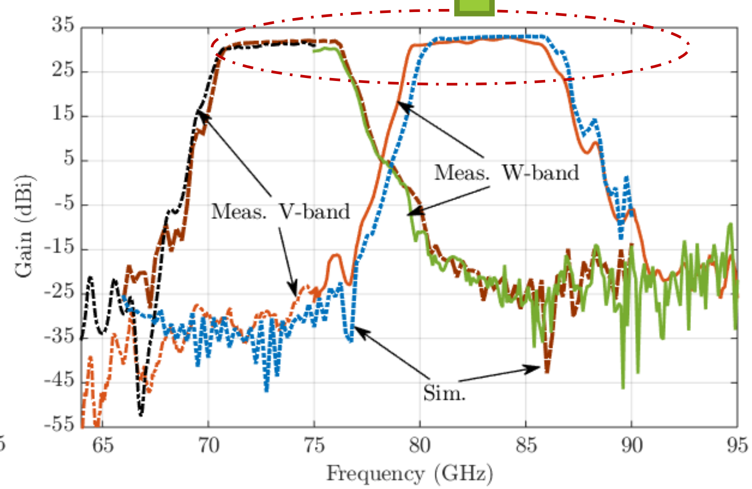


Measurement setup

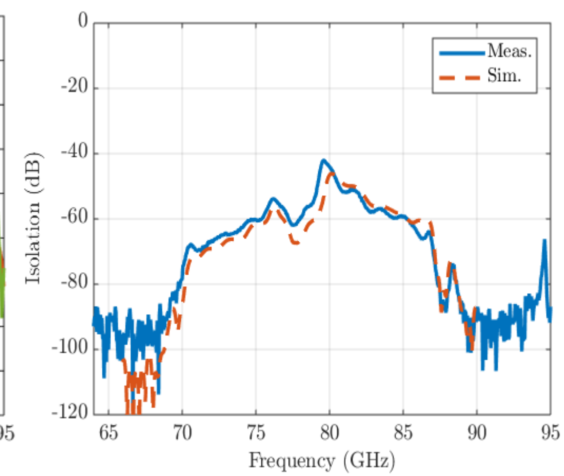




Reflection coefficient

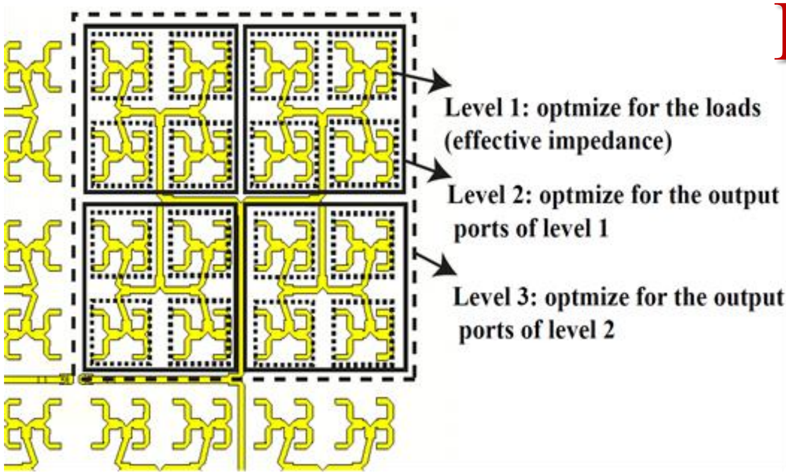


Antenna Gain



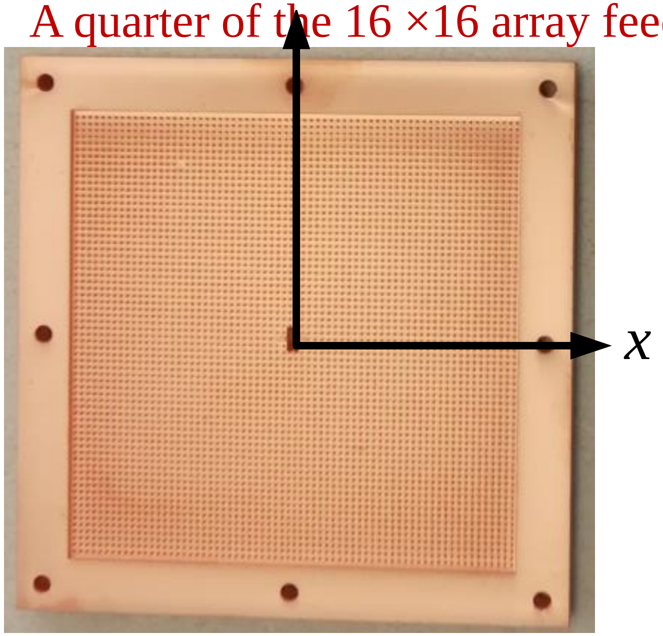
Input ports isolation

16×16 Array with Optimized Feeding Network

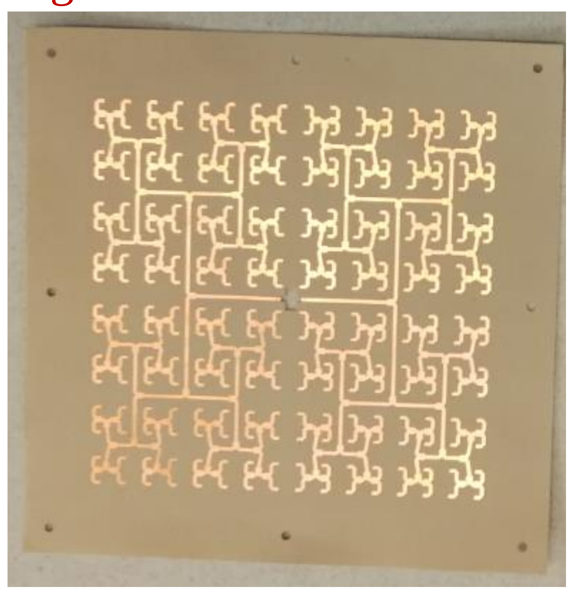


A quarter of the 16 ×16 array feeding network

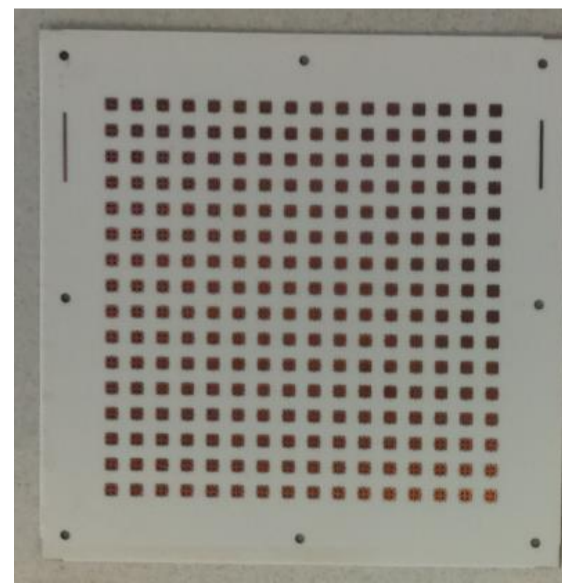
A WR-15 on the bottom plane of the structure is used to excite the ME dipole.



Textured Layer



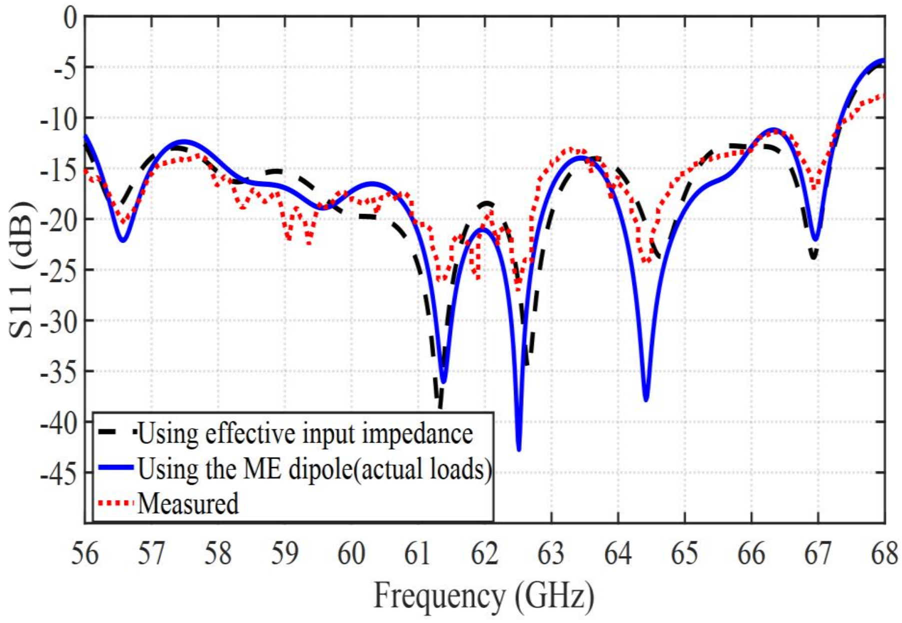
Feeding Layer

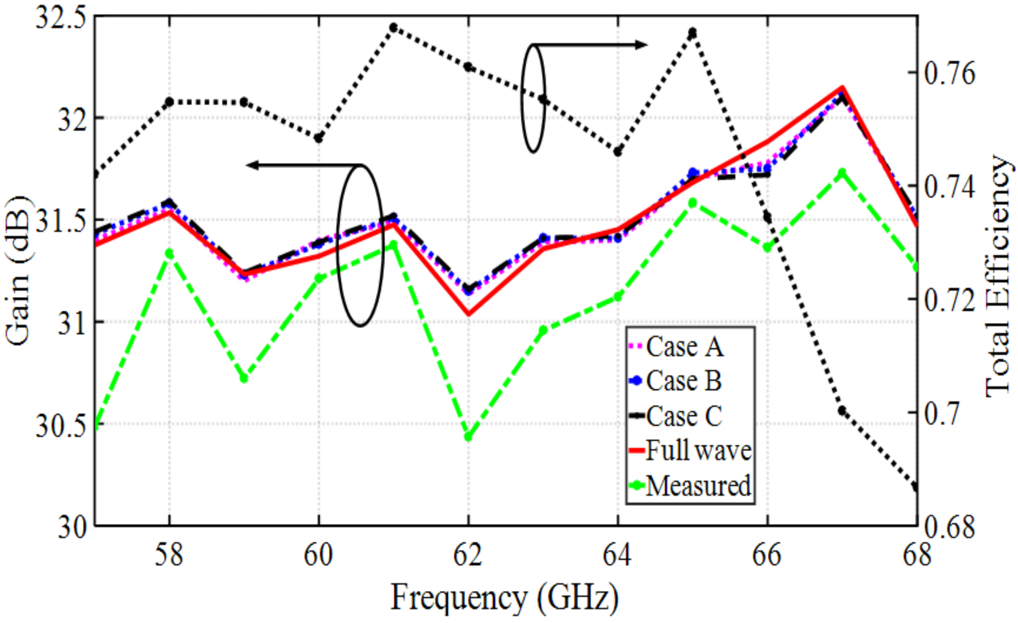


Radiating Layer

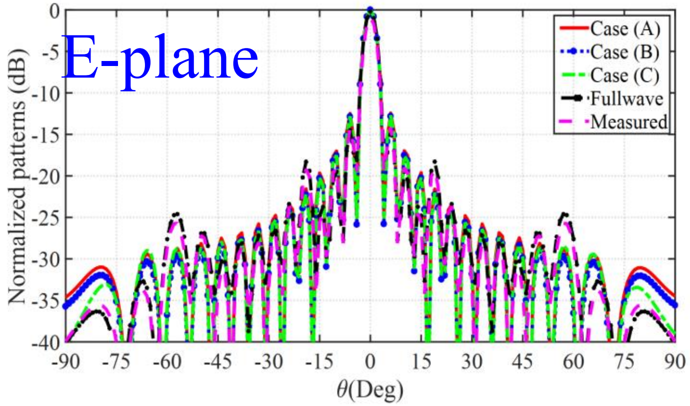
Reflection Coefficient and Gain

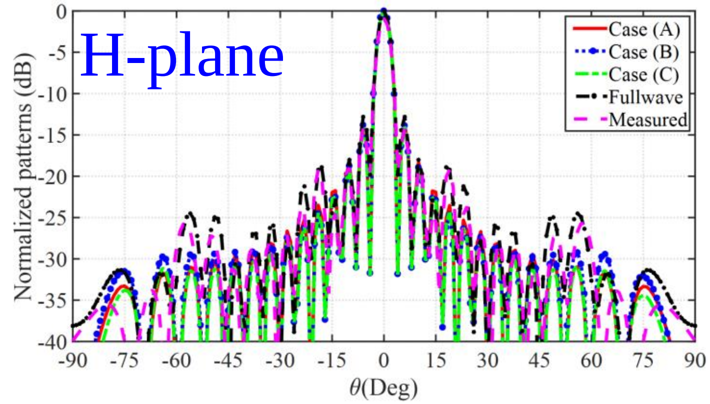
16 × 16 with ME-dipole antennas
(feed network optimized with effective impedances loads)



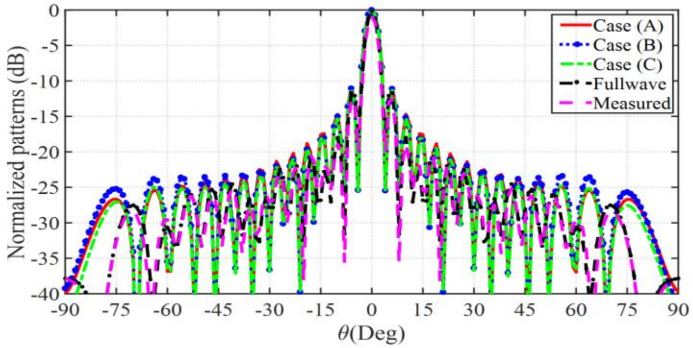


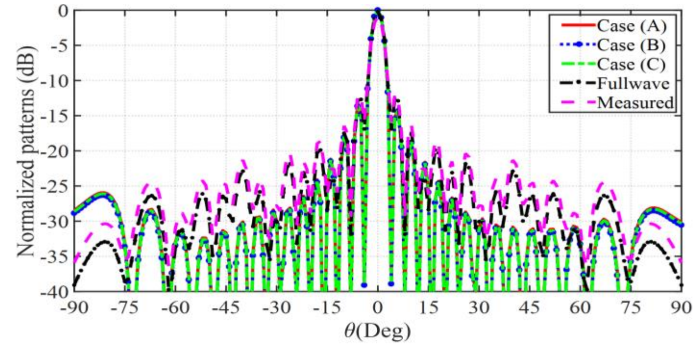
16×16 array Radiation Patterns



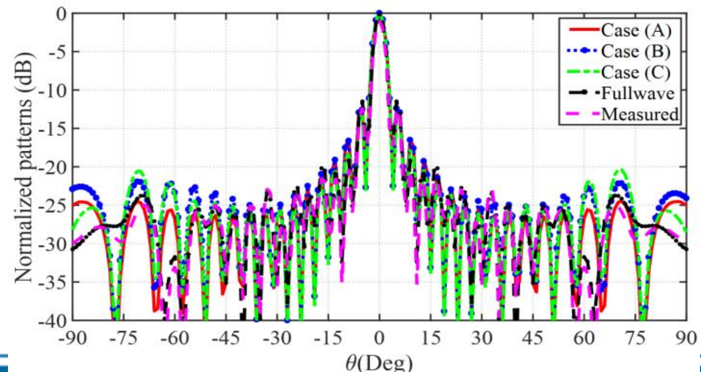


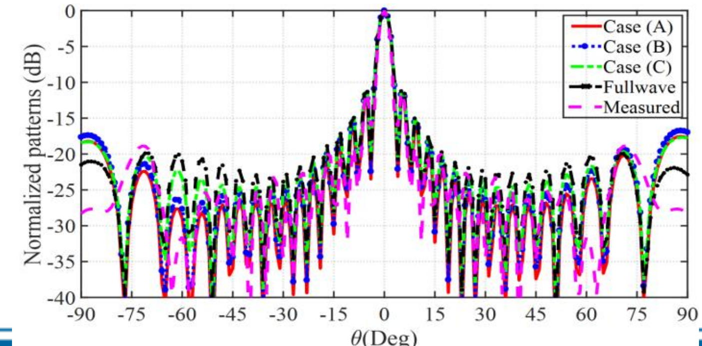
57 GHz





60 GHz





64 GHz