mmWave Passive Reflectors

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Outline

• Motivation
• Network Capacity and 5G
• Relevance of mmWave Frequency Bands
• mmWave System Design Challenges
• Modular Antenna Array Architecture (MAA)
• HW Architecture from POC to Product
• Passive Gain Enhancement Techniques
Past and Future Capacity Improvement

Densification is the key to network capacity increase

- Interference Mitigation, Full Duplex
- New Waveform, MU-MIMO
- Beamforming, etc

- Licensed, Unlicensed, Shared, mmWave

- Densification
- Relay
- Edge Cloud
- Mesh Backhaul
- Fronthaul

3G→4G

Air Interface
- Available Spectrum
- Small Cell

4G→5G→xG
**mmWave Advantage**

**Capacity Increase Technique**

- Densification (D)
- Bandwidth & Throughput (B)
- Spectrum Efficiency (S)

**mmWave Advantage**

- Inherent Shorter Range and Beamsteering Mitigate Interference
- mmWave Bands Support Multi-Gbps Rates
- Beamsteering and MU-MIMO Techniques Support PtP and PtMP in Same Frequency Band

**Capacity Increase**

\[ \text{Capacity Increase} = D \times B \times S > 1000 \]
Search for Alternate Spectrum

Current IMT bands

- 24 GHz Band Licensed
- LMDS Band Licensed
- 40 GHz Band Licensed
- 50 GHz Band Licensed
- 60 GHz Band Unlicensed
- 70-80 GHz Bands Minimal Licensed

Increasing Bandwidth
Decreasing Range

- 1 GHz
- <4 GHz
- <4 GHz
- <3 GHz
- 7 GHz
- 5+5 GHz
mmWave Path-Loss Comparisons

Pathloss comparison for different frequency bands

- 2.3 GHz
- 28 GHz
- 38 GHz
- 60 GHz
- 73 GHz
- 60 GHz & O2

Oxygen Absorbance
Centralized Backhaul Network Concept
Distributed Backhaul Network Concept

- Fiber Node
- Distribution Node
- Access Node
Beam Forming
Challenges in RF & Antenna

- Feed line loss: (8-by-8) elements

![60 GHz Antenna spacing: \(\frac{\lambda}{2} = \frac{c}{f} = \frac{5\text{mm}}{2} = 2.5\text{mm}\)]

![28 or 39 GHz Antenna spacing: \(\frac{\lambda}{2} = \frac{c}{f} = \frac{7.69\text{mm}}{2}\)]

@ 28 GHz is 5.36mm and @ 39 GHz is 3.85mm

From 60 GHz to 28 GHz (or 38 GHz),
- The required area getting bigger then feed line getting longer (roughly double).
- Feed loss is also a function of frequency (higher loss at 60 GHz)
Modular RFEM Configurations

Antenna Side

60GHz Operation
16 Elements
25.2 mm x 9.8 mm

Shield Side

4x4
16 elements

4x8
32 elements

8x8
64 elements

8x16
128 elements

4x32
128 elements
EIRP Vs Modular Array Count

EIRP versus Module Count

- Measured Calibrated EIRP
- Perfect Calibrated EIRP

- FCC Tx Limit
- 0.6dB Tx Combining Loss at 4 modules
- 1.2dB Tx Combining Loss at 6 modules
- 1.7dB Tx Combining Loss at 8 modules

RFIC Count (16 elements per RFIC)
Intel’s MAA POC Evolution

- 2013: Discrete
  - MAA 128 (2x4)
  - WiGig M & R
  - EIRP ~ 43 dBm
  - 300 x 220 x 150

- 2014: Partial PCB
  - MAA 128 (1x8)
  - WiGig M & R
  - EIRP ~ 43 dBm
  - 160 x 140 x 110

- 2015: Stack up PCB
  - MAA 128 (1x8)
  - WiGig M & R
  - EIRP ~ 43 dBm
  - Reduce Side lobes

- 2016: G3M Indoor
  - Stack up PCB
  - MAA 128 (2x4)
  - Maple-M
  - EIRP ~ 48 dBm
  - 160 x 140 x 110

- G3 Indoor
  - 190 x 170 x 140

- G3S Indoor
  - 160 x 140 x 110

- G4 Outdoor
  - MAA RFEM
  - EIRP ~ 48 dBm
  - 160 x 140 x 110
MAA Steering Range

AZ cut

EL cut

Normalized antenna gain, dB

Angle in degrees

8x16
128 elements
G5 Evaluation Kit

- Hardware Overview
  - Indoor Design
    - Easy access to ports
    - Easy signal breakout for chamber tests
    - Easy tabletop, tripod, post, ceiling installation
  - Antenna Array
    - 128 elements - 8x16 array - balanced feeds
    - 8x RFEMs based on Intel WiGig product
    - 1x Intel WiGig Baseband Modem Module
Link Budget Calculation

Calculate SNR values and find supportable MCS in AWGN channels

ITU Region N (1 Gbps threshold)

Assumptions
- Noise figure + implementation loss: (10.5 + 3) dB
- PER < 1%
- AWGN channel (phase impairment considered)
Passive Gain Enhancement for Active RFEM

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Whayu Industrial Co., Ltd.
RFEM Options

2-by-8

FoV_H = ± 49 deg
FoV_V = ± 20 deg

4-by-4

FoV_H = ± 41 deg
FoV_V = ± 26 deg
RFEM Beam State

- Beam_Origin
- Beam_Down
- Beam_Up
- Beam_Right
- Beam_Right_Down
- Beam_Right_Up
Passive Gain Enhancement Options

**Reflection Type**
- **Reflectarray**
  - Platform: 4-by-4
  - FoV_H = ± 24 deg
  - FoV_V = ± 12 deg
- **Reflector**
  - Platform: 4-by-4
  - FoV_H = ± 24 deg
  - FoV_V = ± 12 deg
- **Lens**
  - Platform: 2-by-8
  - FoV_H = ± 47 deg
  - FoV_V = ± 2.5 deg

**Transmission Type**
- **Planar Lens**
  - Platform: 2-by-8
  - FoV_H = ± 33 deg
  - FoV_V = ± 2.5 deg
Reflector

Supporting full WiGig band
Beam_0

Feeding pattern

Total pattern
Beam_D

Feeding pattern

Total pattern
Beam_U

Feeding pattern

Total pattern
Beam_R

Feeding pattern

Total pattern
Beam_RD

Feeding pattern

Total pattern
Beam_RU

Feeding pattern

Total pattern
# Comparison

## RFEM

<table>
<thead>
<tr>
<th></th>
<th>Beam_O</th>
<th>Beam_D</th>
<th>Beam_U</th>
<th>Beam_R</th>
<th>Beam_RD</th>
<th>Beam_RU</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gain (dBi)</strong></td>
<td>18.33</td>
<td>17.11</td>
<td>17.06</td>
<td>16.95</td>
<td>16.04</td>
<td>16.07</td>
</tr>
<tr>
<td><strong>SLL (dB)</strong></td>
<td>-14.1</td>
<td>-8.8</td>
<td>-8.6</td>
<td>-8.5</td>
<td>-8.64</td>
<td>-8.77</td>
</tr>
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</table>

## RFEM + Reflector

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<tr>
<td><strong>Gain (dBi)</strong></td>
<td>23.83</td>
<td>22.69</td>
<td>24.42</td>
<td>24.58</td>
<td>25.70</td>
<td>23.30</td>
</tr>
</tbody>
</table>
Gain Enhancement

After the “mapping”, the vertical FoV reduces to 46% while the horizontal FoV reduces to 59%.
Different Techniques for Gain Enhancement

**Reflection Type**
- Reflectarray
- Reflector

**Transmission Type**
- Lens
- Planar lens

Platform: 4-by-4
FoV_H = ± 24 deg
FoV_V = ± 12 deg
Reflectarray Prototype

Without Polarization Rotation
V-pol. In => V-pol. Out

With Polarization Rotation
V-pol. In => H-pol. Out

Polarization rotation is achieved by the 180 phase delay of different arm length attached to each patch element.

Dimension: 100*100*0.127 mm
## Comparison

### Gain (dBi)

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<td>18.33</td>
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<td>16.95</td>
<td>16.04</td>
<td>16.07</td>
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### Gain Enhancement (dB)

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<th>Beam_RU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflect</td>
<td>5.262</td>
<td>5.209</td>
<td>6.323</td>
<td>6.43</td>
<td>8.607</td>
<td>5.494</td>
</tr>
<tr>
<td>Reflectarray (Strip type)</td>
<td>2.651</td>
<td>2.651</td>
<td>0.53</td>
<td>0.189</td>
<td>1.727</td>
<td>-0.009</td>
</tr>
<tr>
<td>Reflectarray (Patch type)</td>
<td>3.6</td>
<td>2.85</td>
<td>0.631</td>
<td>0.221</td>
<td>-0.759</td>
<td>-0.012</td>
</tr>
</tbody>
</table>

*Value in red text indicates serious pattern distortion.*

Bad cases due to large e-scan angle

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**Strip type**

- [Image of different types of antennas]
Problem Encountered

When the incidence angle between feed and reflectarray is large, 45deg in this case, specular reflection becomes prevailing.
Problem Encountered

This can be partially solved if the incidence angle is below 20deg by slanting the reflectarray.

However, the specular reflection will still occur when RFEM has a large e-scan angle, e.g., ± 41deg @ Beam_R. It’s the natural defect of reflectarray because of flatness.
## Comparison Table

<table>
<thead>
<tr>
<th></th>
<th>Reflectarray</th>
<th>Reflector</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weight</strong></td>
<td>Light</td>
<td>Heavy</td>
</tr>
<tr>
<td><strong>Gain Enhancement</strong></td>
<td>Inferior to reflector due to dielectric loss</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>Narrow BW for single layer, lower cost</td>
<td>Wide</td>
</tr>
<tr>
<td></td>
<td>Wide BW for multi layer, higher cost</td>
<td></td>
</tr>
<tr>
<td><strong>Degree of Difficulty for Production</strong></td>
<td>Yield concern</td>
<td>Normal</td>
</tr>
<tr>
<td><strong>Limitation</strong></td>
<td>Cannot support large steering angle</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Different Techniques for Gain Enhancement

Reflection Type
- Reflectarray
- Reflector

Platform: 2-by-8
FoV_H = ± 47 deg
FoV_V = ± 2.5 deg

Transmission Type
- Lens
- Planar lens

Platform: 2-by-8
FoV_H = ± 33 deg
FoV_V = ± 2.5 deg
Reflector & Lens

- Dielectric $K = 2$ (PTFE*)
- Assume lossless in simulation

*PTFE / Teflon = Poly Tetra Fluoro Ethylene
Beam_0

Feeding pattern

Total pattern
Beam_D

Feeding pattern

Total pattern
Beam_U

Feeding pattern

Total pattern
Beam_R

Large side lobe probably incurred by surface wave

Feeding pattern

Total pattern
Frequency Shift by Lens

Resonance freq. shifts to 57 GHz.

S11 = -16.4 dB

S11 = -2.3 dB
### RFEM + Lens

<table>
<thead>
<tr>
<th></th>
<th>Beam_O</th>
<th>Beam_D</th>
<th>Beam_U</th>
<th>Beam_R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directivity (dBi)</td>
<td>27.9</td>
<td>26.0</td>
<td>26.0</td>
<td>25.7</td>
</tr>
<tr>
<td>SLL (dB)</td>
<td>-12.6</td>
<td>-9.8</td>
<td>-9.8</td>
<td>-10.4 (-5.6)</td>
</tr>
</tbody>
</table>

FoV_V = ± 2.5 deg  
FoV_H = ± 33 deg

-10.4 for first sidelobe while -5.6 for the max.

### RFEM + Reflector

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<th>Beam_R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directivity (dBi)</td>
<td>29.7</td>
<td>26.3</td>
<td>27.3</td>
<td>27.0</td>
</tr>
<tr>
<td>SLL (dB)</td>
<td>-13.2</td>
<td>-12.8</td>
<td>-13.7</td>
<td>-9.2</td>
</tr>
</tbody>
</table>

FoV_V = ± 2.5 deg  
FoV_H = ± 47 deg
Comparison

Directivity Enhancement (dB)

- **Beam_O**: Lens 9.3, Reflector 10.5
- **Beam_D**: Lens 8.2, Reflector 8.5
- **Beam_U**: Lens 8.2, Reflector 9.5
- **Beam_R**: Lens 8.9, Reflector 10.2
Comparison table

<table>
<thead>
<tr>
<th></th>
<th>Lens</th>
<th>Reflector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>14<em>7</em>5.8 cm =568.4 cm³</td>
<td>18<em>5.5</em>10.5 cm =1039.5 cm³</td>
</tr>
<tr>
<td>Directivity Enhancement (dB)</td>
<td>8.2-9.3</td>
<td>8.5-10.5</td>
</tr>
<tr>
<td>SLL (dB)</td>
<td>Bad @ Beam_R</td>
<td>Good</td>
</tr>
<tr>
<td>FoV_V (initially ± 20 deg)</td>
<td>± 2.5 deg</td>
<td>± 2.5 deg</td>
</tr>
<tr>
<td>FoV_H (initially ± 49 deg)</td>
<td>± 33 deg</td>
<td>± 47 deg</td>
</tr>
<tr>
<td>Reflected Power @ 60GHz</td>
<td>58.9%</td>
<td>2.3%</td>
</tr>
</tbody>
</table>
Conclusion

• Substantial effort has been focused in the industry on the 5G access technology to improve capacity, latency, throughput, scalability and quality of service;

• mmWave technology is a great candidate for both access and backhauling to increase network capacity while creating less interference;

• Flexible steerable mmWave array provides better coverage for Mesh distribution network

• Passive reflectors are great candidate to increase system gain without complexity of the large array.
# Glossary

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLL</td>
<td>Side Lobe Level</td>
</tr>
<tr>
<td>FoV</td>
<td>Field of View</td>
</tr>
<tr>
<td>DK</td>
<td>Dielectric Constant</td>
</tr>
<tr>
<td>PTFE</td>
<td>Poly-tetra-fluoro-ethylene (Teflon)</td>
</tr>
<tr>
<td>LAA</td>
<td>Lens Array Antenna</td>
</tr>
<tr>
<td>RFEM</td>
<td>Radio Front End Module</td>
</tr>
</tbody>
</table>