5G Antenna System Characteristics and Integration in Mobile Devices

Sub 6 GHz and Milli-meter Wave Design Issues

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About Ethertronics

- Leader in advanced antenna system technology and products from mobile phones to Wi-Fi and Internet of Things
- Driving antenna system performance and technology development

**Antenna System Leadership**
- 1.8 billion Units Sold
- 220 Patents

**Faster Time-to-Market**
- 1000+ Platforms Designed

**Expand Network Efficiency**
- 250+ Employees
- 80% Engineers

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**Core Competencies**
- Antenna Architecture
- Custom RFICs
- Proprietary Algorithms
World Class Antenna Testing Capabilities

6 Global Design Centers
26 Antenna Measurement Systems

A wide variety of measurement systems to provide system level performance metrics on passive and active antenna systems for mobile and fixed applications.
Antenna Concepts for 5G Systems

Sub 6 GHz implementations

- Antenna system techniques available for implementation in sub 6 GHz applications:
  - Higher orders of MIMO
  - Phased, Adaptive, and Hybrid arrays on the Node
  - Adaptive Array techniques on the mobile side

mmWave System implementations

- Based on the need for high gains to support a specific range for a communication system operating at mmWave frequencies and the Gain/Beamwidth relationship in antennas, three antenna configurations are preferred for mmWave systems:
  - Phased arrays
  - Adaptive arrays
  - Hybrid arrays (combination of phased and adaptive)
- These antenna configurations provide the capabilities for both fixed and mobile applications, with the array techniques requiring pointing methodology and algorithm
Antenna Technology Improvements Needed for 5G

• For mobile cellular applications antenna systems have evolved from a 1 antenna solution for 2G, to a 2 antenna solution for 3G (main and secondary) and 4G(main and secondary for MIMO).

• For Wi-Fi applications the industry has moved from a 1 antenna system (SISO) to 2x2, 3x4, 4x4, and now 8x8 MIMO systems on the access point side to improve Throughput while the client (mobile) side has gone from SISO to 2x2 MIMO; some fixed client devices are 4x4.

• Moving toward 5G and the higher data rates envisioned a few features can be implemented in the antenna system to improve performance:
  – Higher orders of MIMO
  – Array techniques needed to boost peak gains
  – mmWave frequencies

• Six antenna functions designed into the typical smartphone today
  • Main, Secondary, WiFi1, WiFi2, GPS, NFC
Current Smartphones Configured With Antennas Grouped at Top and Bottom

Galaxy S7

iPhone 7

Antenna assemblies

Antenna regions
Antennas in Current Smartphones

- Common approach used to group antennas in optimal location

  Two region antenna system approach
  - Main cellular
  - Secondary cellular
  - Wi-Fi
  - GPS

- 4 region approach lends itself to higher orders of MIMO with better de-coupling of antennas

  Four region antenna system approach
  - Main cellular
  - Secondary cellular
  - Wi-Fi
  - GPS
  - Cellular 3 high band
  - Wi-Fi 1
  - Cellular 4 high band
  - Wi-Fi 3*

  * Future 4x4 implementation
The Problem to Correct as We Move to 5G

- 3G and 4G cellular relies on broad beamwidth, near omni-directional antennas, i.e. 0 to 3 dBi peak gain on the mobile or client side.
- Wi-Fi relies on higher orders of MIMO and digital beamforming applied to passive antennas to boost antenna system gain; with passive antennas this process is not optimized.
- For 5G we need to get dynamic control of the antenna system and generate higher peak gains to better optimize the communication process.

\[
P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2}
\]

- \(P_T\) = transmit power
- \(G_T\) = transmit antenna gain
- \(G_R\) = receive antenna gain
- \(R\) = range
- \(\lambda\) = wavelength
- \(P_R\) = receive power

Friss Transmission Formula
Free space calculation; factors can be applied to address multipath

Instead of gain varying from -30 to +2 dBi, form an array of elements and beam-steer to boost gain.
Results are:
- Higher Throughput
- Less interference

Array Gain

Dipole antenna
Peak gain = 2.1 dBi
Average gain = 0 dBi*
Regions where gain is -10 to -30 dBi
* for 100% eff antenna
Limitations of MIMO in Terms of Antenna Spacing

• Transitioning from 4G to 5G systems, some size limitations will set limits to order of MIMO achievable in a mobile or consumer wireless device

• To achieve higher order of MIMO, more antennas need to be integrated into a device (smartphone, Tablet, access point, etc)

• To maintain optimal system performance (Throughput, for example), the antennas need to be de-correlated and have high isolation

• The following slides show simulations for linear and 2D placement of antennas to achieve 8xN and 32xN MIMO; 20 dB isolation used as a design metric

• A “Rule of Thumb”:
  – for antenna systems with 4 or more antennas, 1$$\lambda$$ per antenna required for linear placement
  – 4$$\lambda^2$$ required per antenna in 2D placement

You can fit more antenna in the area at the expense of isolation, correlation, and efficiency …
Antenna Configuration (8 Aligned Dipoles)

- Isolation calculation
- 5.4 GHz
- Inter-element separation of 1.1λ
- Inter-element isolation > -20 dB
- High efficiency (90% in simulation)
- Printed dipoles on FR4 substrate

- Scaling for 2.1 GHz (LTE Bands 1, 4), length required for 8-element MIMO configuration is 700 mm
Antenna Configuration, 32 Dipoles in 2D Configuration

- 5.4 GHz
- Inter-element separation of 1.1\(\lambda\) in the Y direction and 3\(\lambda\) in the X direction
- Inter-element isolation > -20 dB between the 32 elements
- High efficiency (90% in simulation)
- Printed dipoles on FR4 substrate
- Alternating polarization between adjacent elements does not improve the spacing requirement; 3\(\lambda\) limitation on “broadside” dipole alignment
- Dimensions grow to 630mm by 700mm (~0.5 m\(^2\)) at 2.1 GHz
Practical Limits to Antenna Count for MIMO Implementations

• A review of previous and current antenna systems integrated into smartphones provides insight into feasible MIMO antenna count:
  • 600 MHz to 1 GHz, 2 x 2 MIMO
  • 1 GHz to 4 GHz, 4 x 4 MIMO
  • 4 GHz to 6 GHz, 6 x 6 MIMO

• For a typical smartphone size isolation will improve with increasing frequency
  • 8 dB isolation at 600 MHz
  • 10 dB “ “ 700 MHz
  • 12 dB “ “ 800 MHz
  • 15 dB “ “ above 1 GHz
  • 20 dB “ “ above 3 GHz

• More antennas can be integrated into a device at the expense of isolation, efficiency, correlation …
The Problem to Address at mmWave

- The Friss Transmission Formula determines receive power on one end of a communication link when transmit power and antenna gains are known:

\[ P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2} \]

- The effective aperture for any antenna can be expressed as:

\[ A_e = \frac{\lambda^2}{4\pi} G \]

\[ P_R = \frac{P_T}{4\pi R^2} G_T A_e \]

- At 28 GHz, 30 dB of additional antenna gain is required to maintain the same receive power level when compared to 830 MHz propagation!!!
Antenna Sizing Issues

- Path loss is proportional to frequency².

- As you increase in frequency you need to increase antenna gains to maintain the same range performance for a communication system.

- As you increase gain the beamwidth will decrease and you will need to address scanning requirements.

- The graph on the right shows antenna gain as a function of “aperture area” of the antenna.

- A high gain antenna can be problematic:
  - Which direction to “point” the peak gain of the antenna?
  - Optimal pointing angle can vary with frequency due to reflections.
  - The reduced beamwidth of the antenna will act as a “filter” to reduce power scattered into the antenna.
  - As array gain increases more beams will be required to cover the field of view.

\[ G = \frac{4\pi}{A} \frac{1}{\lambda^2} \]
The Problem with Planar Arrays

- Planar arrays will exhibit reduced gain as a function of scan angle in both principal planes.
- This will limit practical array field of view to ± 60°.
mmWave Array Placement is Critical

- The high gain characteristics of mmWave antennas will require beam scanning
- Total scan angle of the array will define the field of view
- Multiple mmWave arrays will be required to provide full spherical coverage of a handset
- Sectorized approach will allow for arrays to be assigned per sector, with coordination between arrays/sectors
- Due to ID constraints, mmWave and sub-6 GHz antennas will need to share aperture
8x8 Array Patterns at 39 GHz

- A planar array will provide for narrow beamwidth in both principal planes, providing a narrow beamwidth, high gain pattern.
- Result is a square or low aspect ratio area that needs to be accommodated.
1x16 Array Patterns at 28 GHz

- A linear array will provide for wide beamwidth in one plane and a narrow beamwidth in the other plane, with high gain.
- This narrow, linear form factor lends itself to integration along the perimeter of a mobile device.
A Proposed Antenna System Configuration

- 4 sector approach proposed to house all antenna functions
- Co-located mmWave and sub-6 GHz antennas
- Supports 4x4 MIMO (higher above 3 GHz) and 4 mmWave arrays

- Composite material configuration required to support mmWave array and lower frequency antenna functions
- Adaptive array anticipated for mmWave array, so RFICs need to be integrated at antenna elements
- Multi-layer PCB configuration required for mmWave array; antenna layer, RF, Digital, Power
- Full screen design can be accommodated; back cover is non-metallic
- “All metal” ID is problematic
Some Issues with the design …

- Good mmWave coverage around perimeter of device
- Gain drops normal to screen and backside
- Complex array configuration: multi-layer substrate, flexible, thin, tight tolerances

Array scans in the plane of the handset

Less gain in direction of screen and backside

1.5mm element dimension, nominal

Antenna elements
RF layer
Digital layer
Power layer
RFICs

May need to be flexible assembly …
Beam Steering Methodology

- Beam steering required for phased array and adaptive array applications
- Control software (algorithm) can be implemented to sample beam states of the array to lock onto desired signal
- Algorithm is implemented in adaptive arrays to sample signals from each RF chain (antenna) and calculate coefficients to apply to beam steer in a specific direction
- Benefit of adaptive array is that interference mitigation can be applied when the right metrics are available from baseband (SINR for example)
- Important to note: **Array gain** will translate to **3dB beamwidth** which will translate to **number** of required beams which will translate to **latency**
Adaptive Arrays

- Distributed power amplifiers and receivers
- Weighting coefficients calculated and applied to each element to generate an array pattern in a specific direction
- Signal processing techniques used to increase desired signal and reduce interference
- Instead of a specific number of pre-defined beams, a custom beam is calculated as needed
- Lower feed losses can be realized compared to some corporate networks used in complex phased arrays
- *Digital Beamforming implemented in 802.11ac applications is an example of adaptive arrays*
Hybrid Arrays

- Adaptive array approach is modified to allow for multiple antenna elements to be driven by a radio chain.
- Higher ratio of antenna element / RFIC provides better economics, power consumption, and heat dissipation at the expense of beam pointing accuracy.
- Technique works well where scan angle is restricted in one plane or precise beamwidth or beam pointing is not critical.
- An “array of sub-arrays”
Beam States Associated with Single Linear Array

As the array scans off-axis the beamwidth broadens, but the amplitude drops due to scan loss resulting in reduced 3 dB beamwidth at larger scan angles.

Beam States, 3 dB Contours

Beam States, 10 dB Contours
Beam States Associated with Planar Array

Array Gain vs Scan Angle
4 x 4 array, \(\lambda/2\) element spacing, element pattern, amp taper

Beam contours prior to applying scan loss

Beam contours with scan loss

Beam States, 3 dB Contours

3dB Gain Contour Chart

Array Gain (dBi)
Scan Angle (deg)
Elevation Angles (deg)
Azimuth Angle (deg)

\(\phi\) [Deg]
\(\theta\) [Deg]
Variable Gain and Beamwidth Implemented

- System level metric (SINR for example) tracked during acquisition phase to determine optimal array and beam state configuration
- Reduced element count in adaptive array provides wide beams for signal acquisition, with higher element counts implemented to boost gain (SINR) during operation

![Graph showing variable element count in array](image)

- Higher gain/narrow beamwidth profiles improved SINR at system level
- Reduced beamwidth for better resolution
- Wide beamwidth for signal acquisition across multiple sectors or arrays
Test Considerations: Certification

• 43 dBm EIRP limit set for mmWave mobile applications

• For an adaptive array composite gain can be determined by

\[
\text{COMPOSITE GAIN} = 10 \times \log\left(\frac{(\text{antgain}_1 + \text{antgain}_2 + \text{antgain}_N)^2}{N}\right)
\]

where antgain\(_1\) = peak gain of antenna 1
where antgain\(_2\) = peak gain of antenna 2
where antgain\(_N\) = peak gain of antenna N
N = number of antennas

• A conducted power measurement is required along with measurement of peak gain of antenna elements populating the array

• SAR: mmWave power density measurements addressed in IEC TC106 AHG10 draft technical report for power density measurements of wireless devices operating between 6 – 100 GHz, publication of which is expected in 2018.
Test Considerations: Production Level

- Two areas to consider for production level test and verification:
  - Functional interface between RFIC and antenna element (did the etch and SMT process work?)
  - Beamforming characteristics: beamwidth, pointing angle, field of view (spatial coverage)
- A production test fixture can be used to sample radiated signal from adaptive array, an S21 based near-field measurement
- On a sampling basis, mmWave adaptive arrays can be tested to verify beamforming and field of view characteristics
Summary

• Improved gain performance will be required from the antenna system to help meet communication link Data Rate goals at 5G
• ID of a smartphone and other handheld devices not optimal for mmWave antenna system integration when wide field of view required
• A minimum of 4 apertures or regions need to be reserved for antenna placement to accommodate higher order of MIMO (sub 6 GHz) and mmWave arrays
• The transition from a single broad beamwidth antenna (3G/4G mobile devices for example) to an array for improved gain will result in the need to control array beam pointing
• Baseband designs need to have a low latency metric available for antenna system optimization
Available mmWave Spectrum for 5G Applications

- July 2016 FCC makes available three bands for 5G operation:
  - 27.5 to 28.35 GHz
  - 37 to 40 GHz
  - 64 to 71 GHz
- 28 GHz band has advantages for communication systems:
  - Propagation loss increases with the square of frequency
  - Peak gain for a fixed aperture size is lower at 28 GHz, allowing for best gain/beamwidth characteristic
Beamwidth Decreases with Increasing Gain

- Treating the antenna as a rectangular aperture that radiates energy, the beamwidth in each plane can be calculated.

- For a rectangular aperture that is $L_x$ wide and $L_y$ in height, the 3 dB beamwidth is

  $$3 \text{ dB BW} = \frac{0.886 \lambda}{L_x} \text{ in the xz plane}$$

  $$3 \text{ dB BW} = \frac{0.886 \lambda}{L_y} \text{ in the yz plane}$$

  note: beamwidth in radians

- These equations are accurate for uniform illumination and apertures greater than 1 wavelength in width and height; the important point to note is that the beamwidth decreases as the antenna size increases.
Atmospheric Attenuation at Higher Frequencies

The plot of signal attenuation at sea level and 20°C versus log frequency shows how oxygen and water at the other peaks in the atmosphere significantly increase signal attenuation.

5G bands

Signal attenuation as a function of rain rate. Medium rain can introduce 3 dB/km attenuation.
Antenna Concepts for mmWave Systems

- Based on the need for high gains to support a specific range for a communication system operating at mmWave frequencies and the Gain/Beamwidth relationship in antennas, three antenna configurations are preferred for mmWave systems:
  - Fixed arrays
  - Phased arrays
  - Adaptive arrays
- These antenna configurations provide the capabilities for both fixed and mobile applications, the primary difference being when does a narrow beam antenna pattern need to track a mobile device or vice versa
Adaptive Arrays

- Weighting coefficients calculated and applied to each element to generate an array pattern in a specific direction
- Signal processing techniques used to increase desired signal and reduce interference
- Distributed power amplifiers and receivers
- Instead of a specific number of pre-defined beams, a custom beam is calculated as needed
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Adaptive Arrays, an example

802.11ac Beamforming

- A 4 antenna system, each antenna connected to a front-end module (FEM) with PA and LNA
- Algorithm on host processor samples RF signals at each antenna port and calculates coefficients for the RF chains to adjust phase characteristics to implement beam steering
- When beamforming is implemented, the four antenna system is used to generate a single directive array pattern to provide increased antenna gain in a specific direction
Feed Network and Beam Steering Topologies

- Array feed network topology will be dependent on whether fixed or phased array is required, and whether the beam needs to be scanned in one or two dimensions.

- Feed design needs to support manufacturing technique; small dimensions required for mmWave design (via dimensions, etch tolerance).

- Transmission line losses increase with frequency, and feed losses will subtract from array gain;
  - Typical feed network losses can range from 2 to 6 dB.
  - Typical insertion loss of phase shifters at 28 GHz is 6 dB …
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• For Wi-Fi applications the industry has moved from a 1 antenna system (SISO) to 2x2, 3x4, 4x4, and now 8x8 MIMO systems on the access point side to improve Throughput while the client (mobile) side has gone from SISO to 2x2 MIMO; some fixed client devices are 4x4

• Moving toward 5G and the higher data rates envisioned a few features can be implemented in the antenna system to improve performance:
  – Higher orders of MIMO
  – Array techniques needed to boost peak gains
  – mmWave frequencies

• Dynamic radiation pattern control can provide the capability to keep antennas optimized as a system switches from MIMO to array operation
Array Concepts for 5G Systems

- **Phased Array**: 1D or 2D array with variable radiation pattern where the peak antenna gain can track the other end of the communication link.

- **Adaptive Array**: 1D or 2D array with modified feed network where signal processing techniques are used to form a beam in specific directions.

- **Hybrid Array**: a combination of phased and adaptive array techniques.
Antenna Concept for the Communication Link: Node to Mobile

Phased array
- 15+ dBi gain
- Sectorized placement

Propagation channel

Adaptive arrays (embedded)
- Distributed transceivers or FEMs to eliminate feed networks and pointing requirements of traditional array
- Sectorized approach for full 3D coverage

Node

Serving Cell

Mobile device
Ideals Antenna System for 5G

**Sub 6 GHz antenna system implementations**
- A multi-antenna system that can be dynamically optimized for MIMO, array, and receive diversity applications

**mmWave antenna system implementations**
- Phased and adaptive array configuration where a subset or all elements populating array can be dynamically optimized
- Pattern adjustment on a per element basis in the array will provide for polarization and pattern diversity at the array level