5G mmWave Radio design for Mobile

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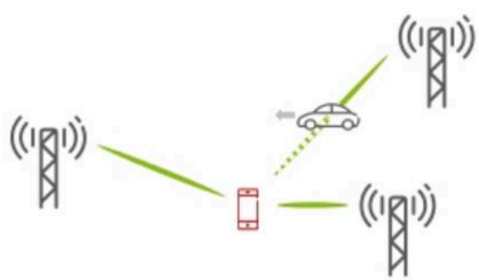
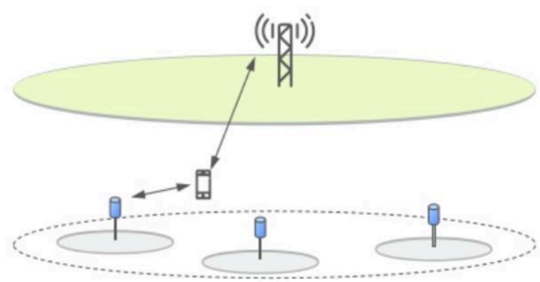
Agenda

- 5G RF standard
  - 5G mm Wave bands
- WAN Transceiver complexity over the last 5 years.
- Process technology requirements for mm wave
- Smart phone system architecture (RF centric).
- Antenna Arrays
- Phase shifter architectures
- Transceiver architectures.
- Large bandwidth challenges
- Measured results
- Conclusion

5G NR standard

- Release 15 accelerated to finish 5G standard by Q4 17
  - Non stand alone and Stand alone 5G
  - Non stand alone uses a 4G anchor cell to help extend coverage for 5G enabled mobile devices.
  - Stand Alone 5G enabled later in 2018





- 5G separated into sub 6 GHz and mmWave bands for initial deployment based on geographical region spectrum availability

24 – 40 GHz

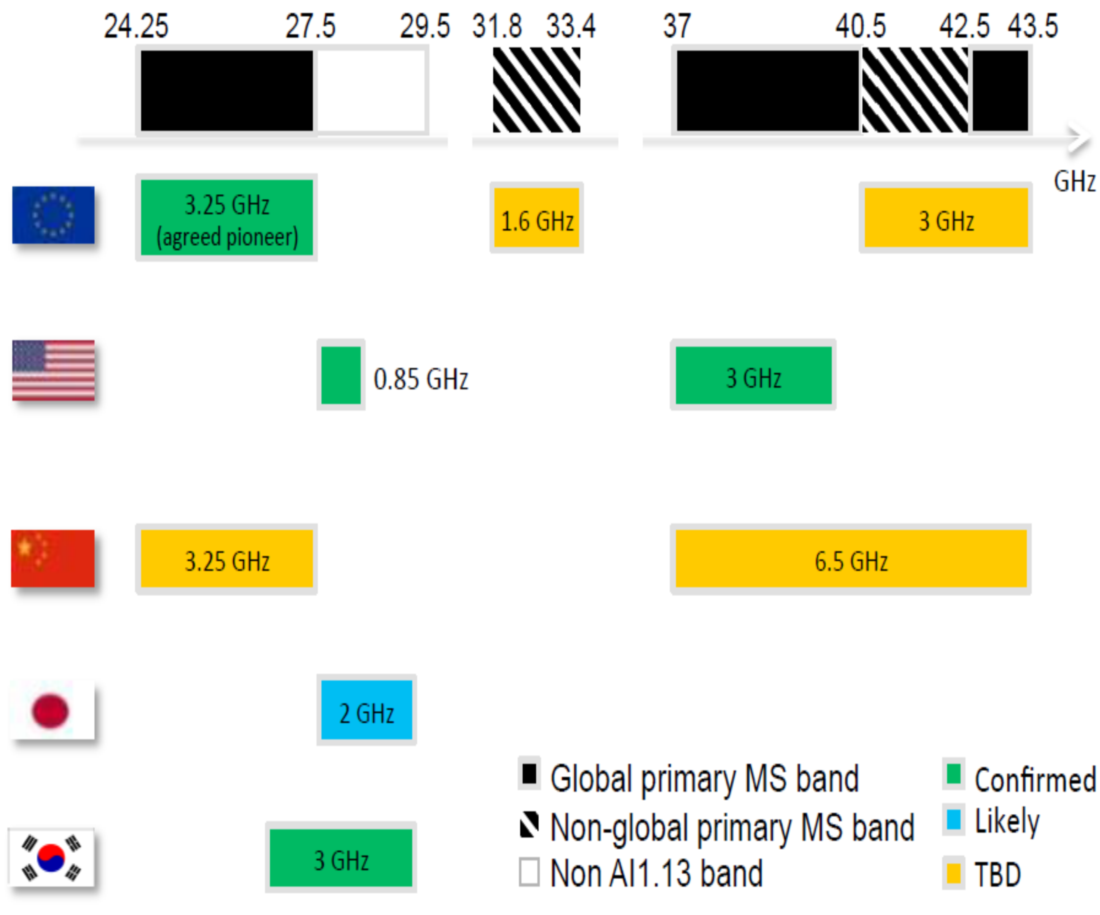
Europe's 5G pioneer band and other bands considered for 5G

U.S. has the bands 27.5-28.35, 37-38.6, 38.6-40 GHz for licensed use, the band 64-71GHz for unlicensed use

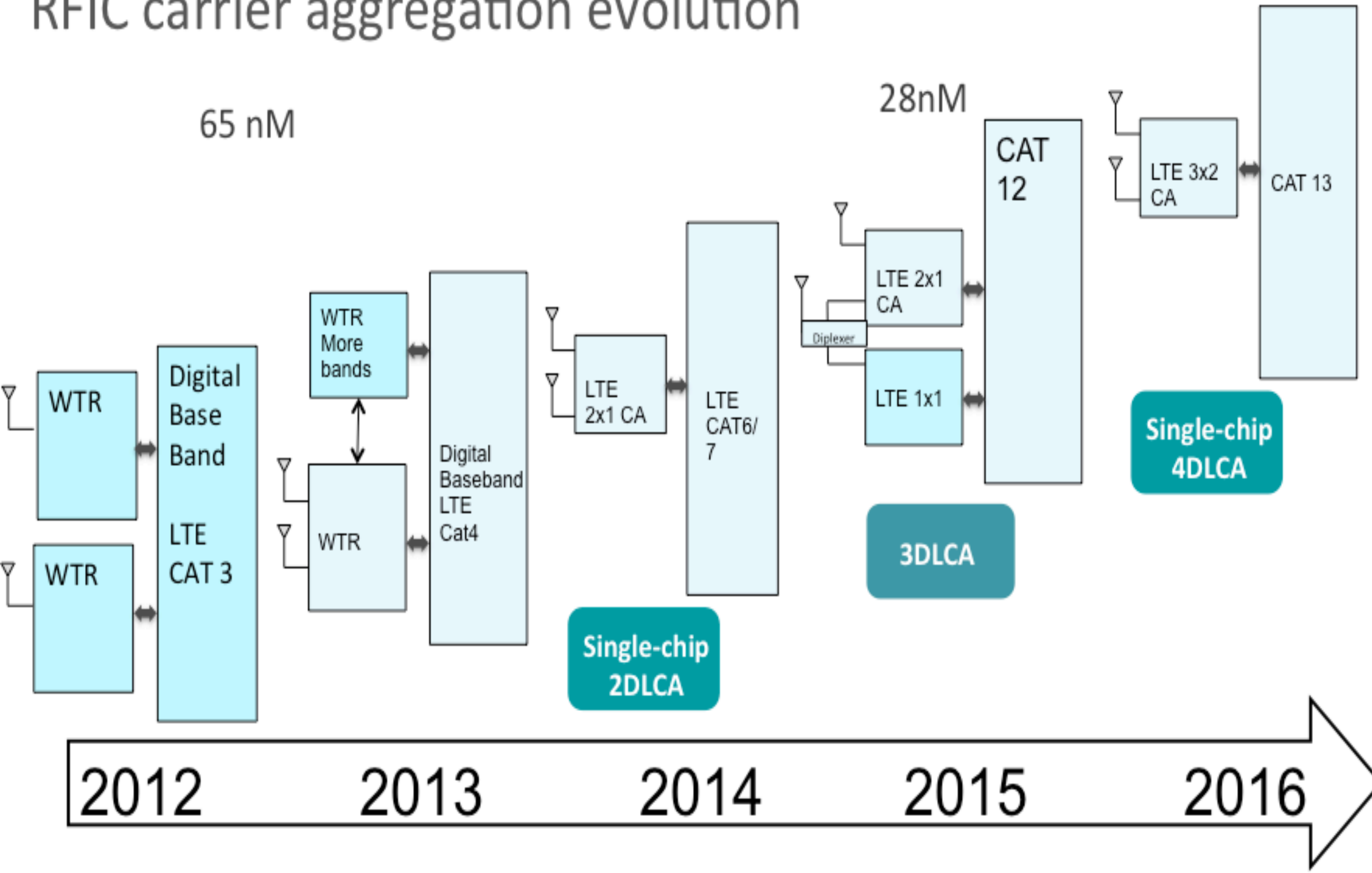
China is conducting compatibility studies for the 26 and 40 GHz bands

Japan is investigating the promising bands for 5G including 28GHz

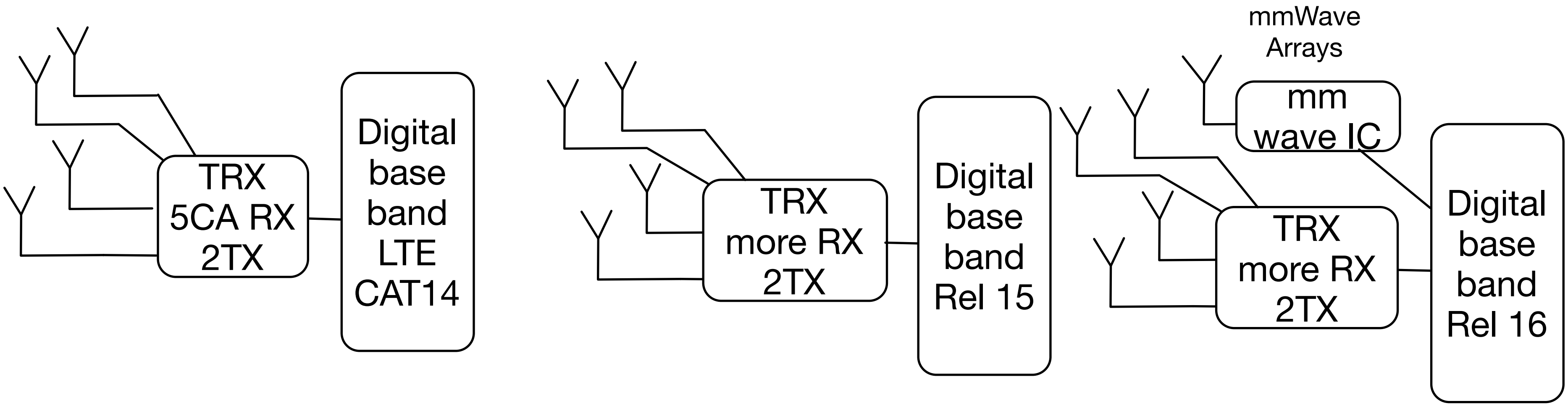
Korea: has decided 26.5-29.5 GHz for 5G trial



RFIC carrier aggregation evolution



RFIC 4G to 5G evolution



2017
4x4 MIMO on 2 CA+
2x2 MIMO on 1 CA
- 1GBps data rates

2018
4x4 MIMO on more CA+
- 1.5GBps data rates
- 256 QAM
- 60MHz UL BW

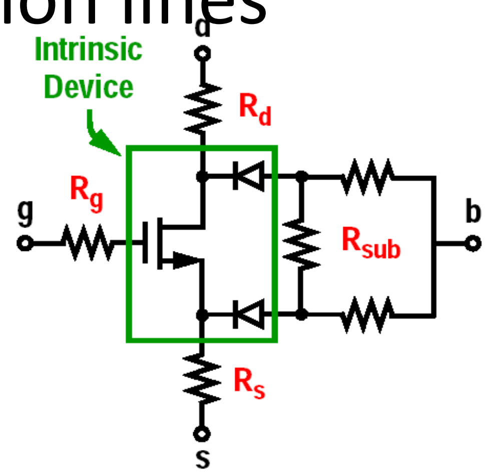
2019
4x4 MIMO on more CA+
Sub 6 5G
mm Wave 5G
100MHz component carrier
200MHz RF bw for sub 6
800MHz RF bw for mm Wave

Future 5G Transceiver implications

- Multi mode 5G/4G
  - 2017 LTE 5 RX Carriers aggregated
    - > 44 bands
    - > more than 1000 DL (Down Link) CA combinations
    - > UL (Uplink) CA concurrent with DL CA
  - 2G/3G also supported
- 5G adds further complexity
  - More bands both sub-6 and mm Wave.
  - Wider bandwidths
    - 100MHz component carrier, up to 8 component carriers
  - Higher carrier frequencies 24 to 71 GHz
  - Higher order modulation- 1024 QAM for sub 6GHz
  - Concurrent with 4G to enable > 5 GBps data rates
  - Low latency control paths
    - AGC switching times
    - PLL settling
  - More antennas and additional PCB components adding PCB area.

Process /Device requirements

- Fmax*Bvds > 500 GHz*V
  - High gain per stage
  - high breakdown voltage for PA’s.
  - Nfmin
- Digital Logic density for codebook updates and dynamic beam switching.
- Low cost
- Low resistivity metal for coils and Vdd/gnd routing
- Low loss transmission lines

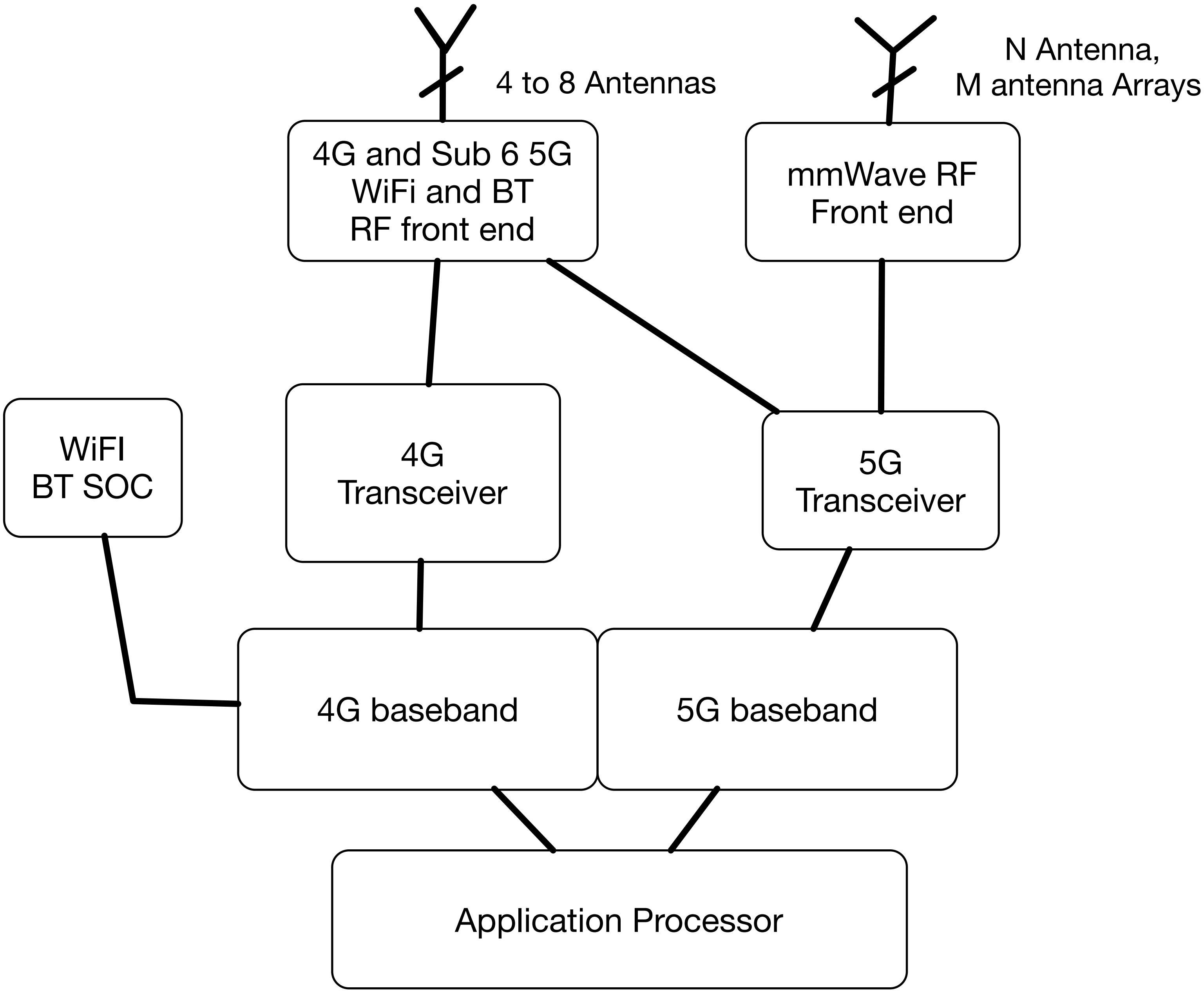


$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})}$$

$$f_{max} = \frac{f_T}{2\sqrt{g_{ds}(R_g + R_s) + 2\pi f_T R_g C_{gd}}}$$

$$NF_{min} = 1 + K \cdot \frac{f}{f_T} \cdot \sqrt{1 + g_m(R_g + R_s)}$$

System Architecture



Number of Antennas for mmWave

- For a given EIRP, doubling the Antennas results in :
  - + Reduces Element TX power by 4
  - + Reduces DC power dissipation by 2
  - – Increases PCB area by 2
  - +Allows for narrower beams, improved spatial filtering.
  - - More complexity and transceiver cost

Antenna Arrays compensate for additional propagation losses at mmWave frequencies

Parameter	5GHz	28GHz
Antenna gain (dB)	-4.5	5
Antenna efficiency	35%	80%
Beam forming gain (dB) (8elements)	0 dB	9 dB
TRP(dBm)	23	20 (12.5 mW per element)
Free space Path loss difference between 5 and 28GHz	0	21
EIRP	18.5 dBm	34 dBm
Mmwave link penalty relative to 5GHz		=EIRP_28GHz-EIRP_5GHz-path loss= -5.5 dB

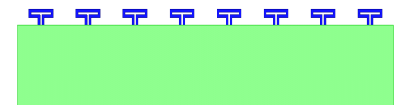
EIRP (dBm) = P_out (dBm/element) + $10*\log_{10}$(N_elem)+Individual_element_gain (dB) + $10*\log_{10}$(N_elem)

Beamforming Gain

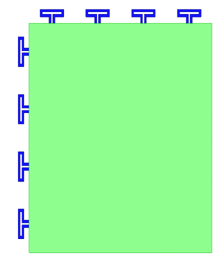
Antenna Gain

Antenna Configurations

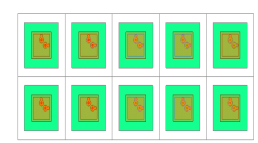
- 1x8 dipole
  - High feedline loss
  - Single polarization
  - Aperture area (without ground): ~1.6x43.2mm



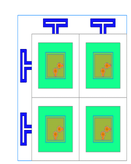
- Two 1x4 dipoles at corner, top and side edge
  - Single polarization in majority of directions
  - Aperture area (without ground): ~1.6x43.2mm



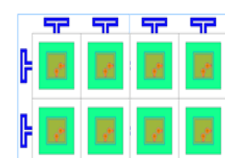
- 2x5 dual-pol patch
  - Allows for dual-pol MIMO
  - Poor Coverage
  - Aperture area: ~10.8x27mm



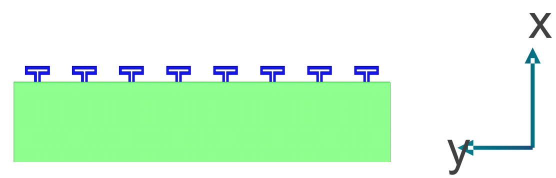
- 2x2 dual-pol patch and two 1x2 dipoles
  - Aperture area: ~12.4x12.4

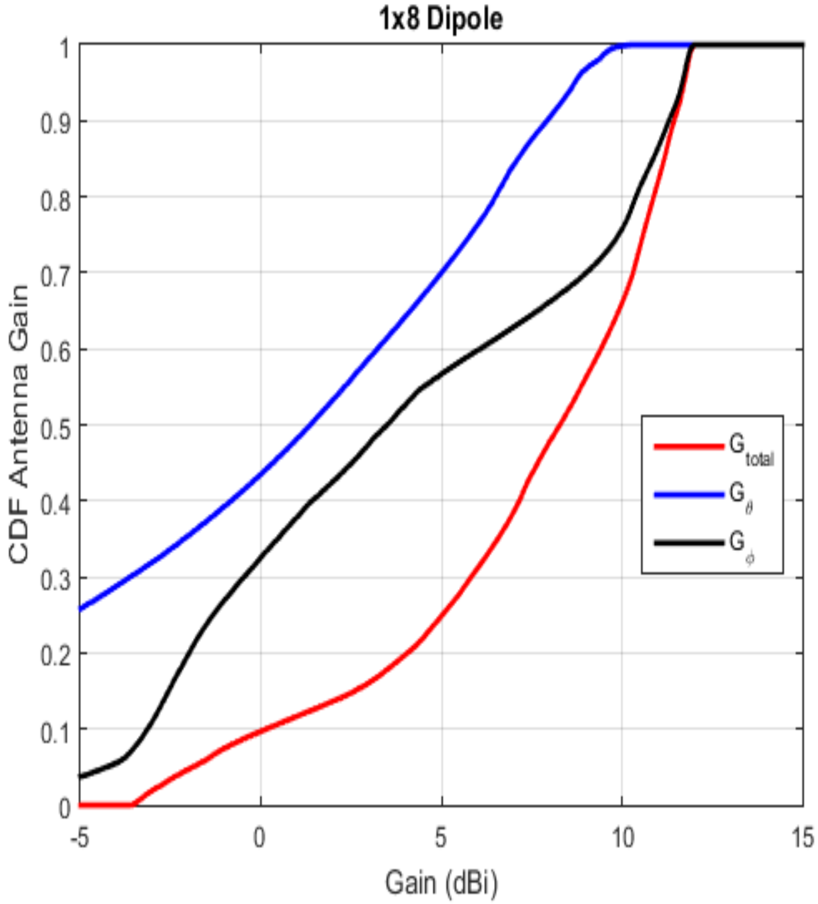


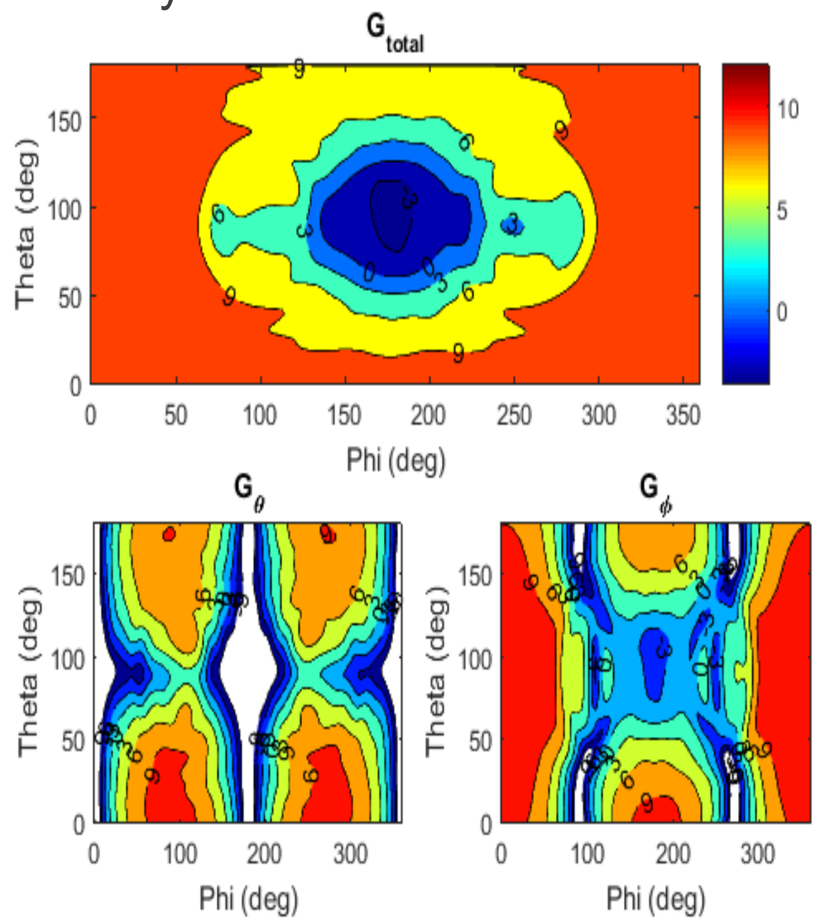
- 2x4 dual-pol patch and 1x2 & 1x4 dipoles
  - Aperture area: ~12.4x23.2



1x8 Dipole at One Edge

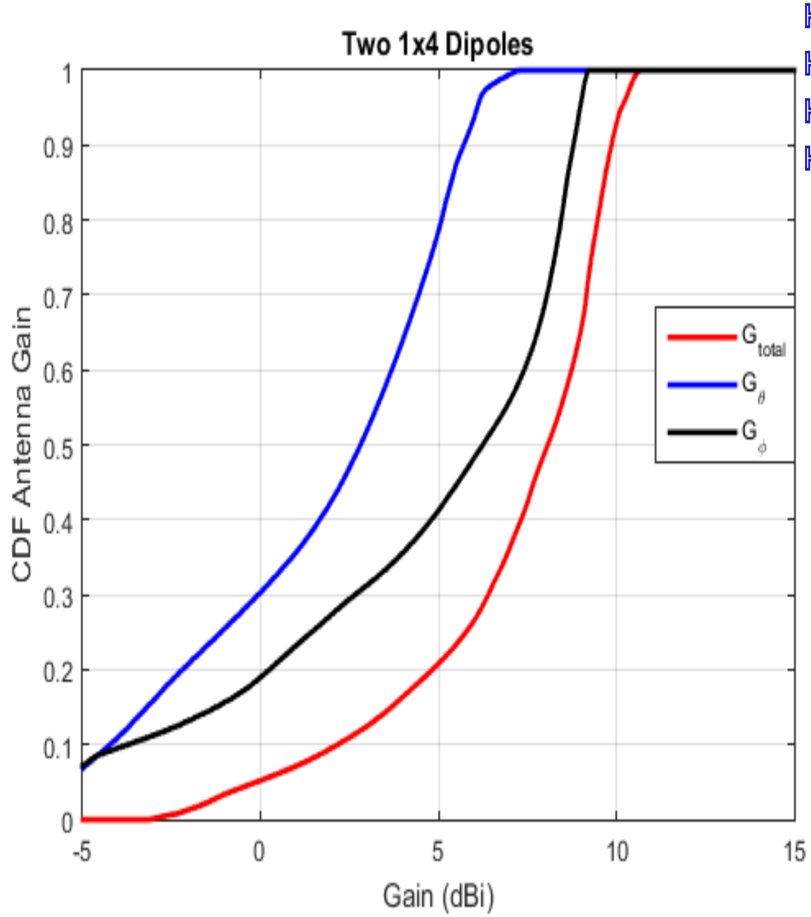


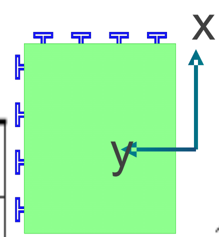


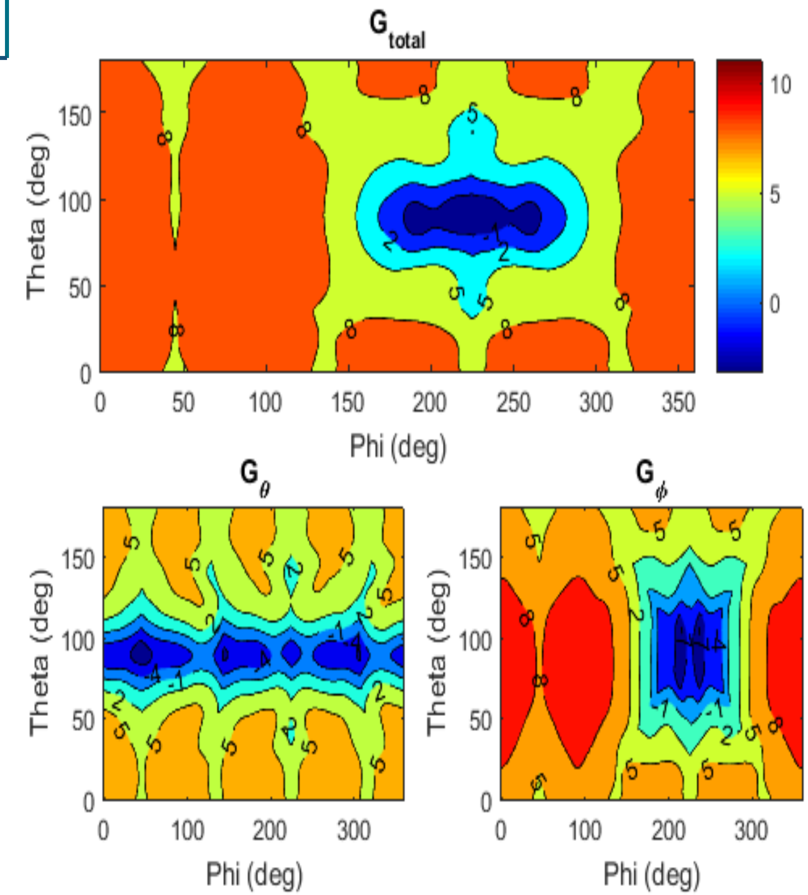


Distribution of gain over all angles
Envelop of all phase scanned beams

Two 1x4 Dipoles at Corner (2 Subarrays)



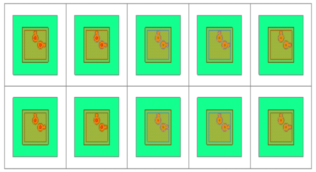


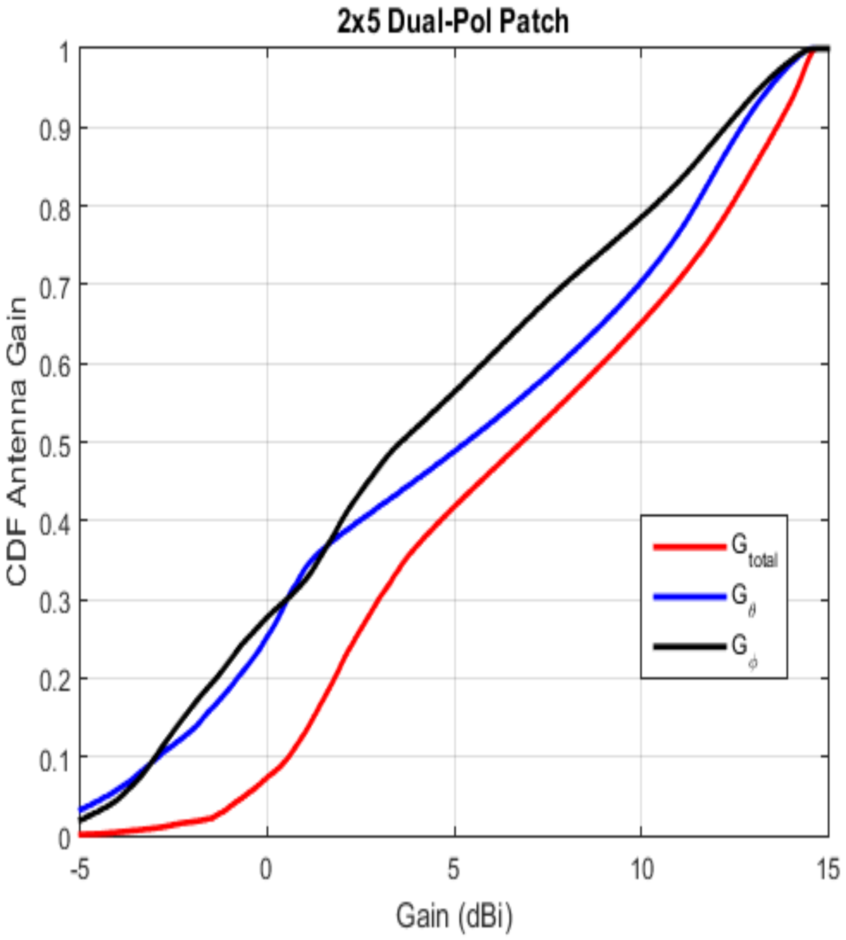


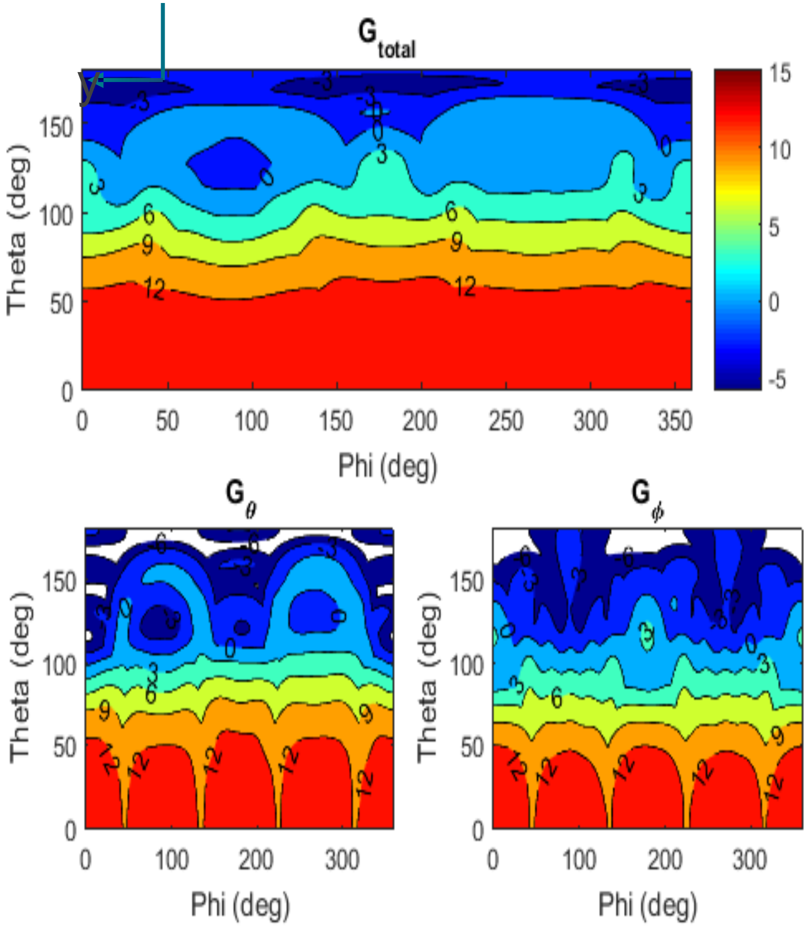
Distribution of gain over all angles

Best of all phase scanned beams between two subarrays

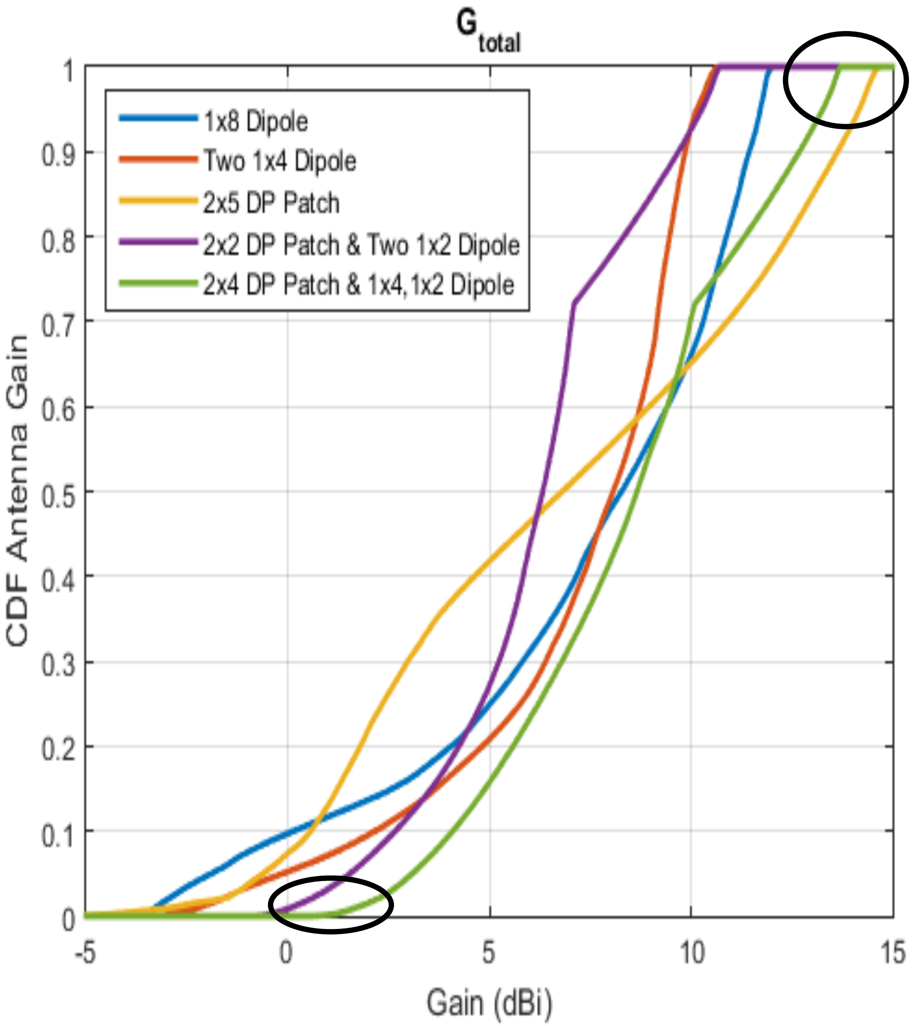
2x5 Dual-Pol Patch Array (Best of 2 Subarrays)





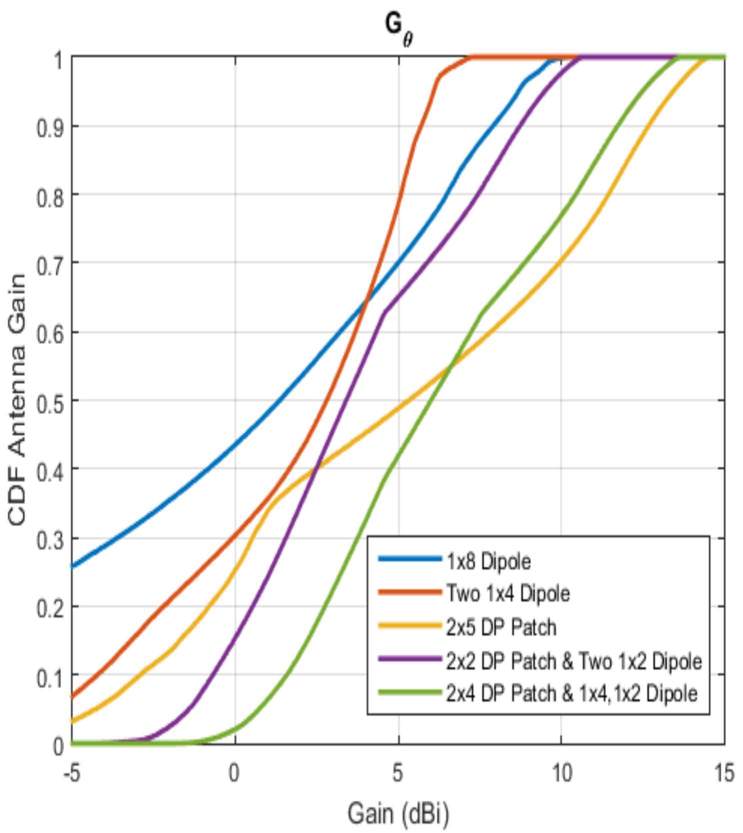


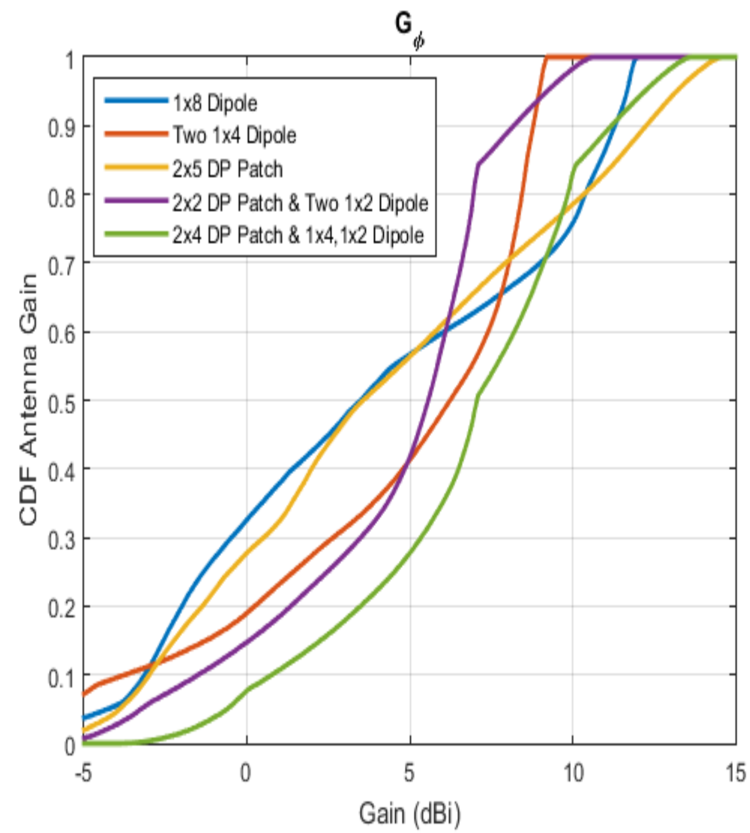
Comparison of Total Power Patterns



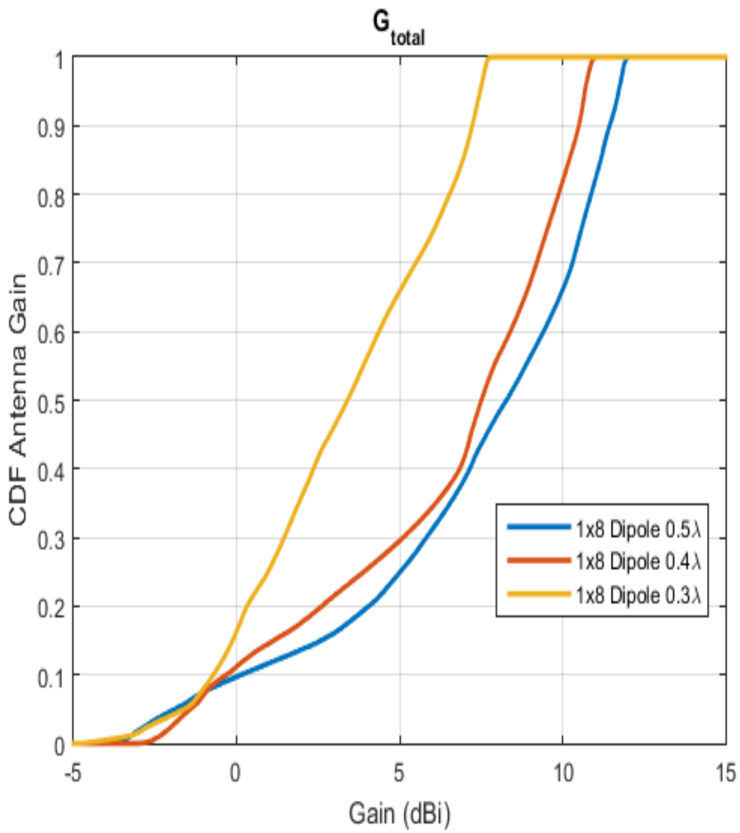
- Patch designs yield higher peak gain (and allow for dual-pol MIMO)
- Configurations with multiple arrays have better angular coverage
- Two 1x4 dipoles performs well for 50%ile angular coverage:
  - Not considering feedline losses!
  - No dual-pol MIMO
- Single array configurations have relatively poor angular coverage (1x8 dipole and 2x5 patch, ~1dBi at 10%)

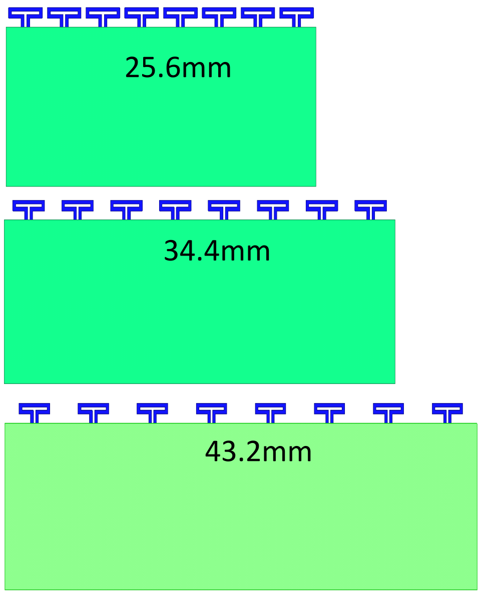
Comparison for Each Polarization





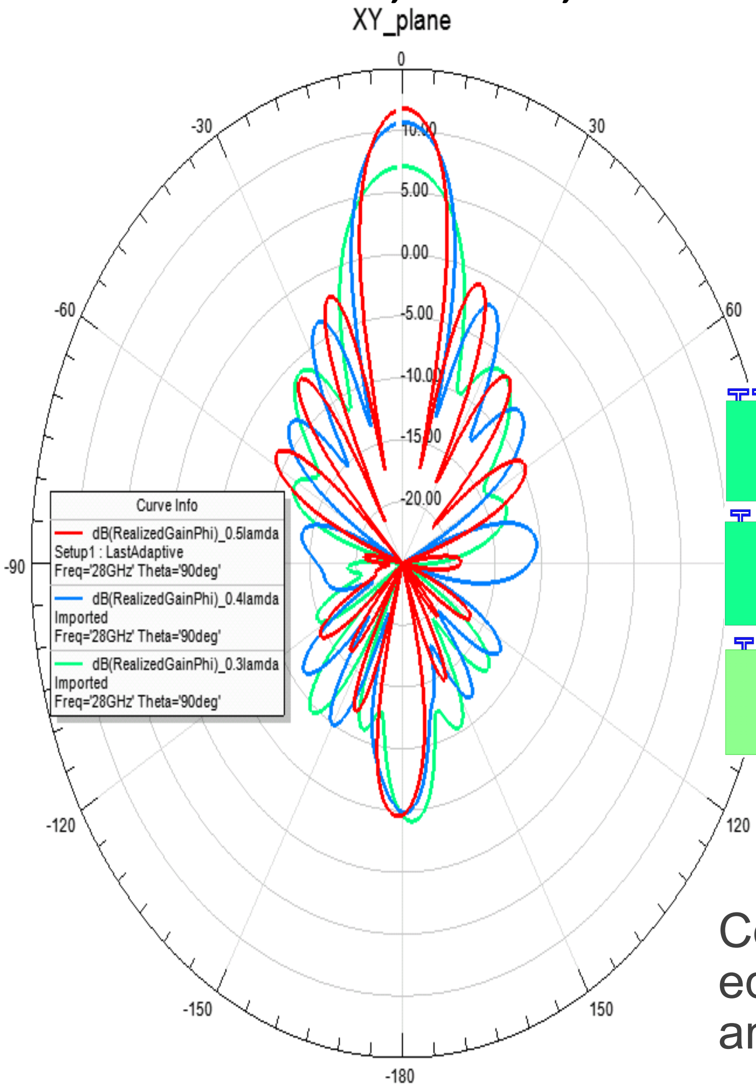
Comparison of 1x8 Dipole Array with 0.5λ, 0.4λ, 0.3λ Element Spacing at 28GHz

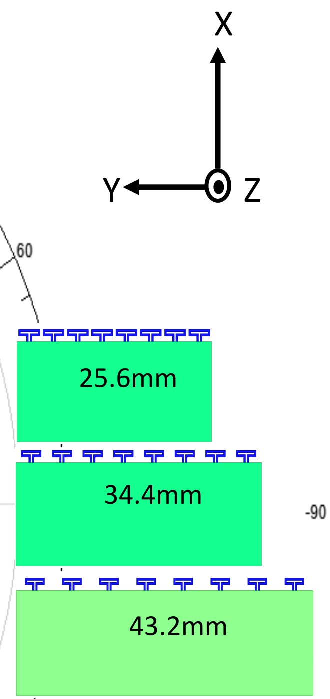


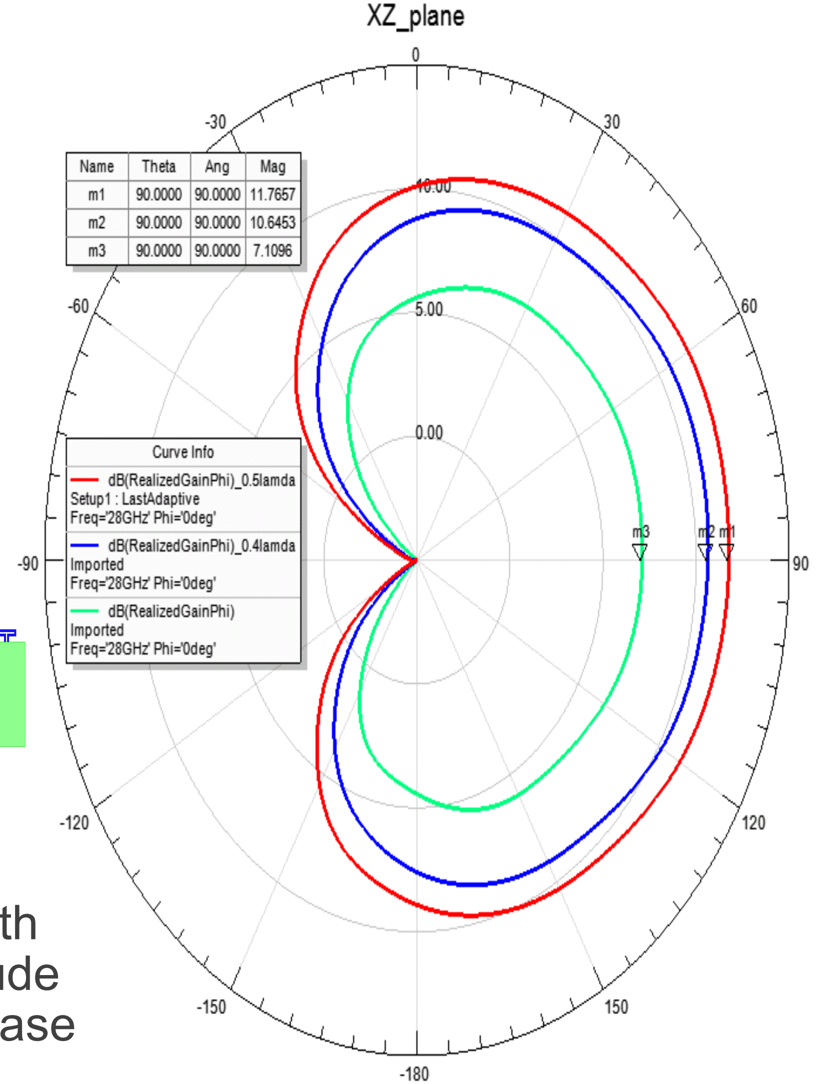


Total Aperture Area Matters not number of elements for Gain

Comparison of 1x8 Dipole Array Gain and Patterns with 0.5λ, 0.4λ, 0.3λ Element Spacing at 28GHz

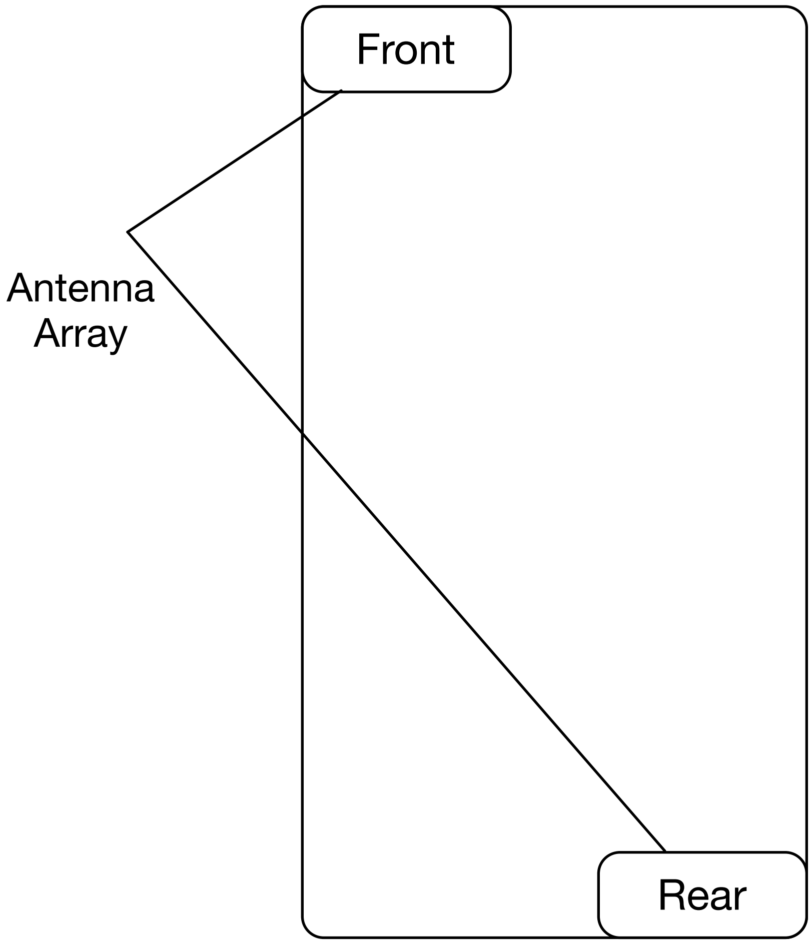






Combined with equal amplitude and equal phase

Placement of Antenna Arrays in Smart phones

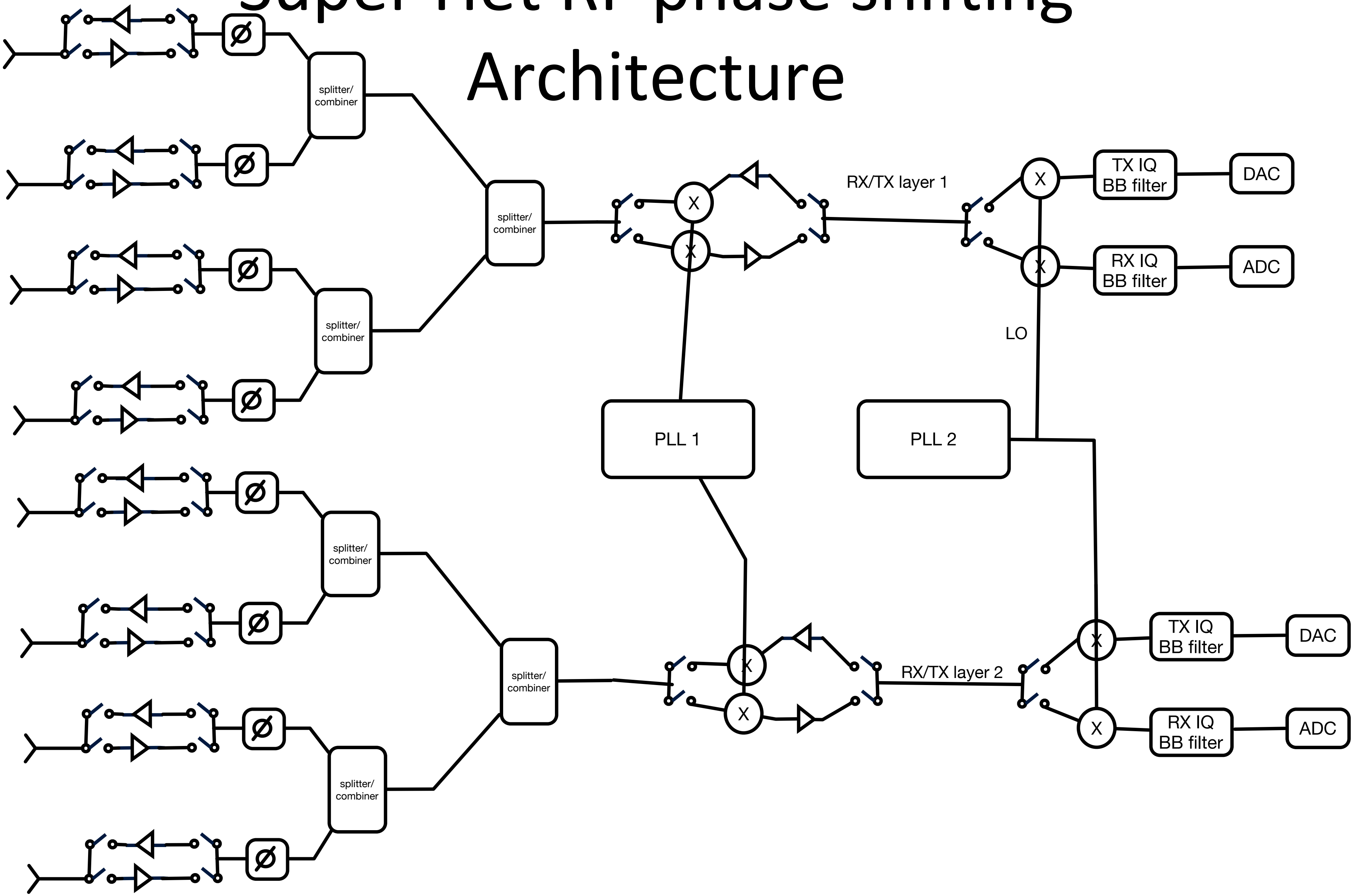


- Placement of Antenna Arrays constrained by Industrial Design
- Extra losses due to plastic / nearby metal need to be accounted for in the design
- Switched Antenna Diversity to mitigate hand /body blockage.
- Spatial and polarization MIMO within each array.

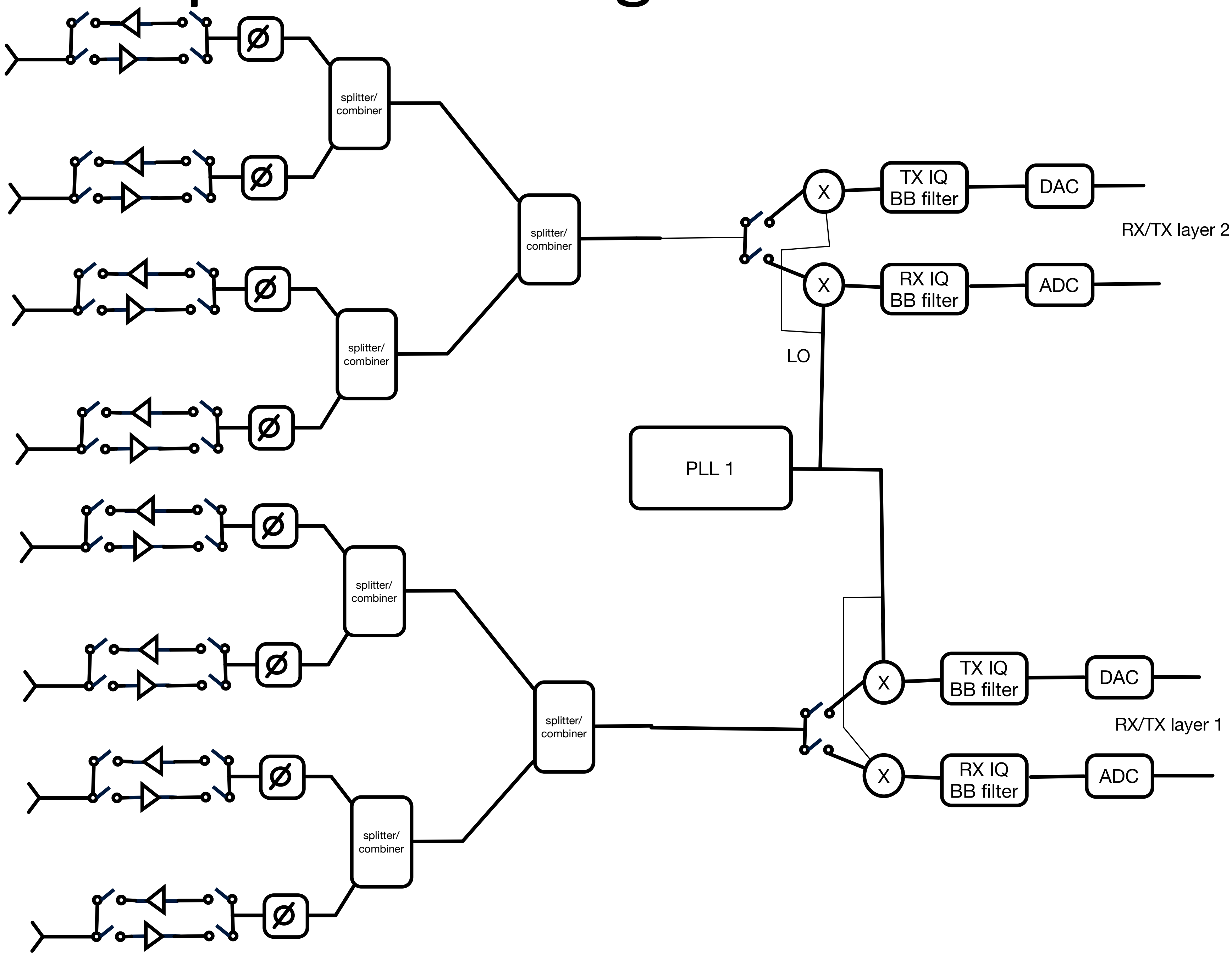
Hybrid beam forming

- Hybrid beam forming architectures
  - Antenna combining done at RF, IF into 1 or more layers.
  - MIMO processing at baseband
  - Full digital combining prohibitive at the moment for mobile devices.
- Different types of phase shifter architectures
  - Lo path phase shifter
  - RF phase shifter
  - IF/BB phase shifter
- Tradeoffs in power performance for all 3.
  - For Number of elements <= 4 all have similar power dissipation.
  - For large N RF path phase shifter best for power.
  - Lo phase shifter has higher accuracy and resolution.

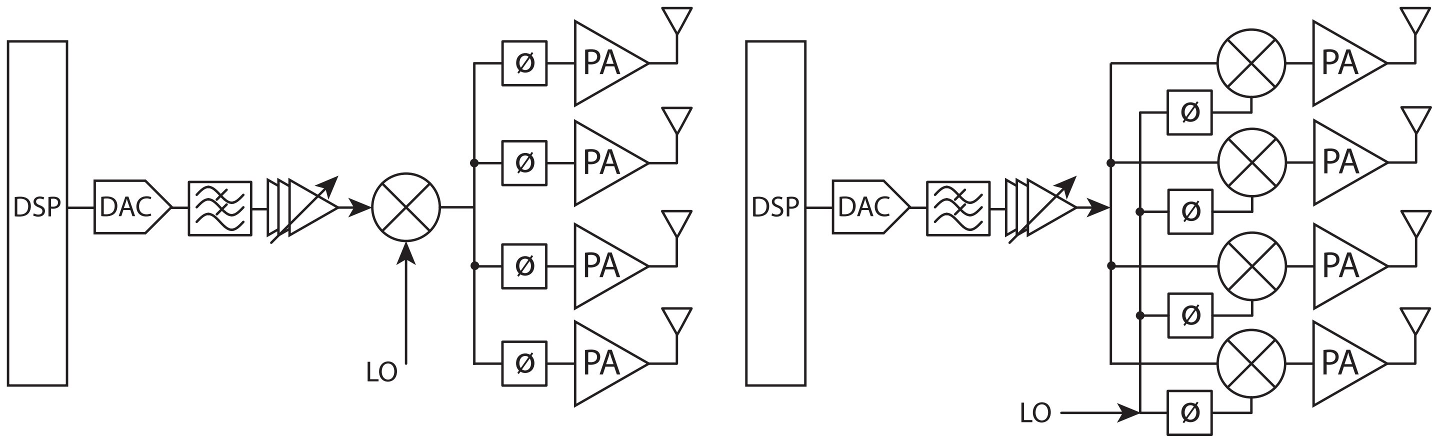
Super Het RF phase shifting Architecture



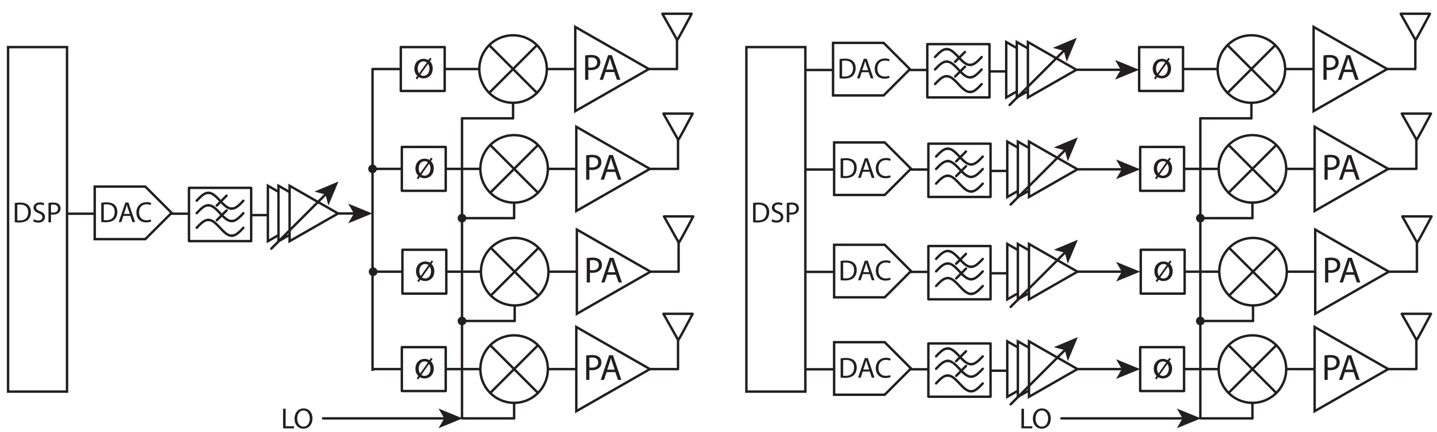
RF phase shifting ZIF architecture



TX Beam forming architectures



(a) RF Phase Shifting (b) LO Phase Shifting

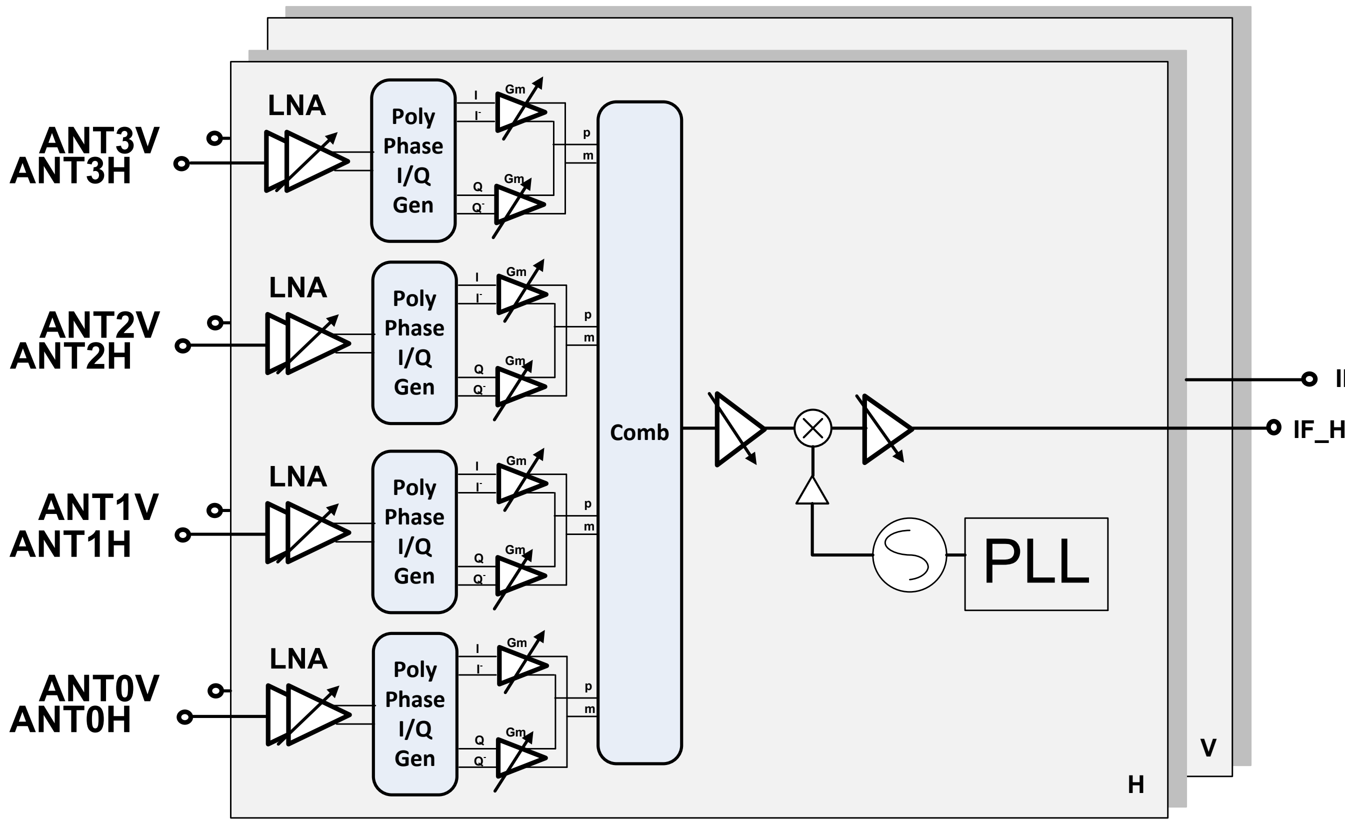


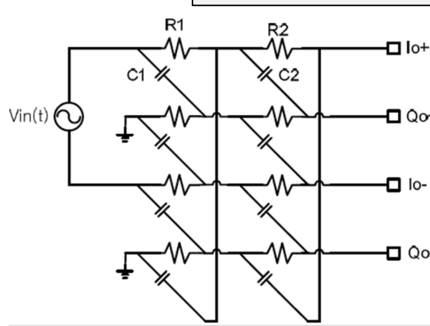
(c) Analog Baseband Phase Shifting (d) Digital Baseband Phase Shifting

Figures from UC Berkeley PHD Thesis by Jiashu Chen "Advanced Architectures for efficient mmWave transmitters " Fall 2013.

RF Phase Shift Architecture

- Vector modulator type phase shifter
- Quadrature generation via poly phase filter
- Weighing done by VGA's
- Passive or current mode combiner





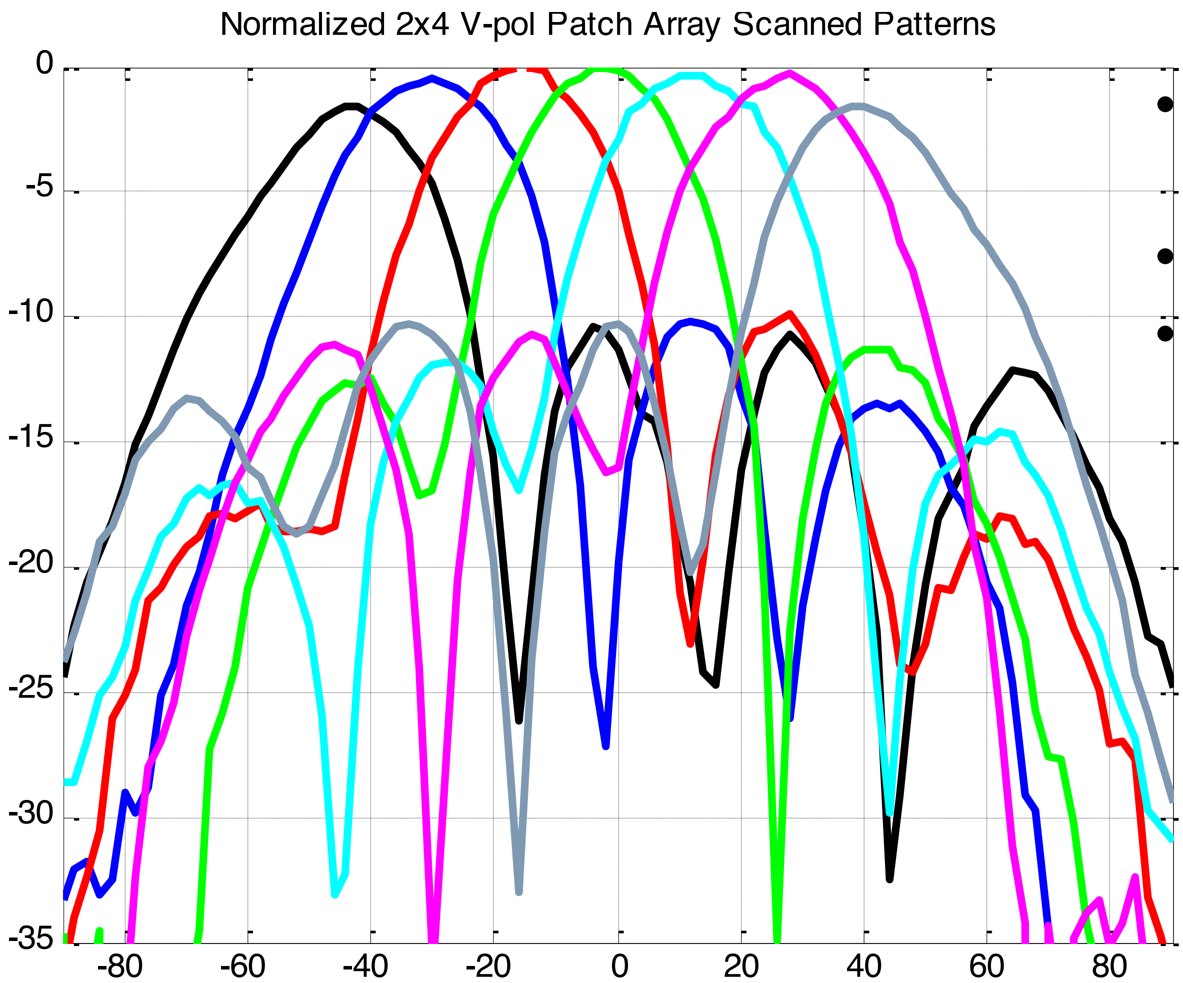
Phase shifter topology has implications on architecture choice.

- ZIF architecture would require large number of mixers if phase shifting architecture is used.
  - Larger power dissipation due to many LO chains running at RF frequency for large number of array elements.
- Super Het has less of a power penalty with phase shifting architecture.
  - Low side injection.
- Architecture choice also has PCB board level routing constraints.
  - SuperHet requires only IF lines vs Analog IQ.

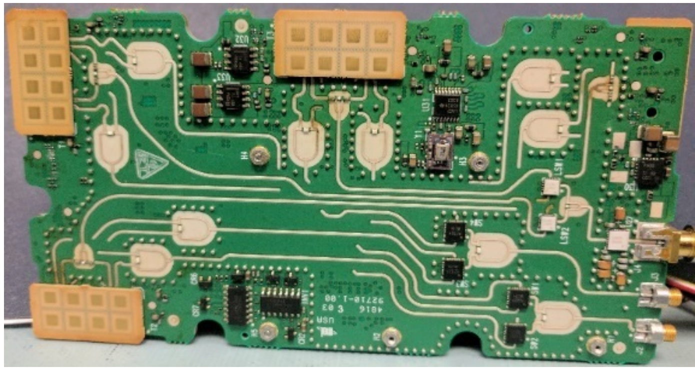
Large bandwidth Challenges

- At mm Wave frequencies, due to finite ft, the transistor gain per stage is lower.
  - Many LC tank loaded stages result in droop and cause in band signal attenuation.
- Super het architectures result in large fractional bw at IF frequencies.
- More susceptible to interference from other radios and clocks in the system.
- Digital pre-distortion (DPD) difficult due to AM/PM and AM/AM bandwidth expansion.
- Antenna Array (DPD) challenging
  - DPD on each element vs DPD on array
  - Measurement receiver capability and number
- Wide band ADC/DACs sampling at GHz frequencies

Measured results



- Element and Peak Gain agree with Simulation.
- Peak scans +/-45 degrees
- > 33 dBm EIRP achievable



antenna modules

Conclusion

- Smart phone RF front end complexity increased exponentially over the last few years.
- 5G adds additional complexity in terms of more bands, higher frequency bands, and wider bandwidths.
- Wireless Systems continue to evolve in complexity- new phase is directional communications with phased arrays.
- Phased arrays help mitigate the effects of increased path loss at mm wave frequencies.
- Many challenges remain to be solved in the next few years.
- Silicon and packaging technology enabling low cost phased arrays for consumer devices.

Acknowledgments

- Thanks to my colleagues at Qualcomm for providing Antenna Array EM sims and measurements.