Millimeter Wave Lens MIMO: A (Potential) Disruptive Technology for 5G

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Joint work with Yong Zeng and Zhi Ning Chen

Outline

- Wireless 5G and mmWave communication
- MmWave MIMO: existing techniques
- Lens MIMO and Path-Division-Multiplexing (PDM)
- Simulation results
- Conclusions

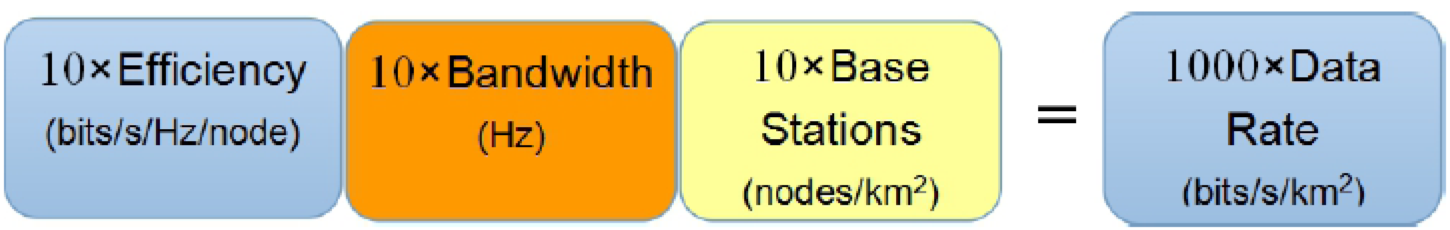
What is 5G?

❑ 5G Requirements

- Data rate (bits/s/km^2): 1000x increase from 4G to 5G
- Latency: 15ms (4G) down to 1ms (5G)
- Energy efficiency: 100x more energy efficient than 4G

❑ Key technologies for high data rate in 5G:

- Ultra-dense BSs: more active BSs deployed per unit area
- Massive MIMO: employ very large antenna arrays at BSs
- Millimeter wave (mmWave): exploit large available bandwidth



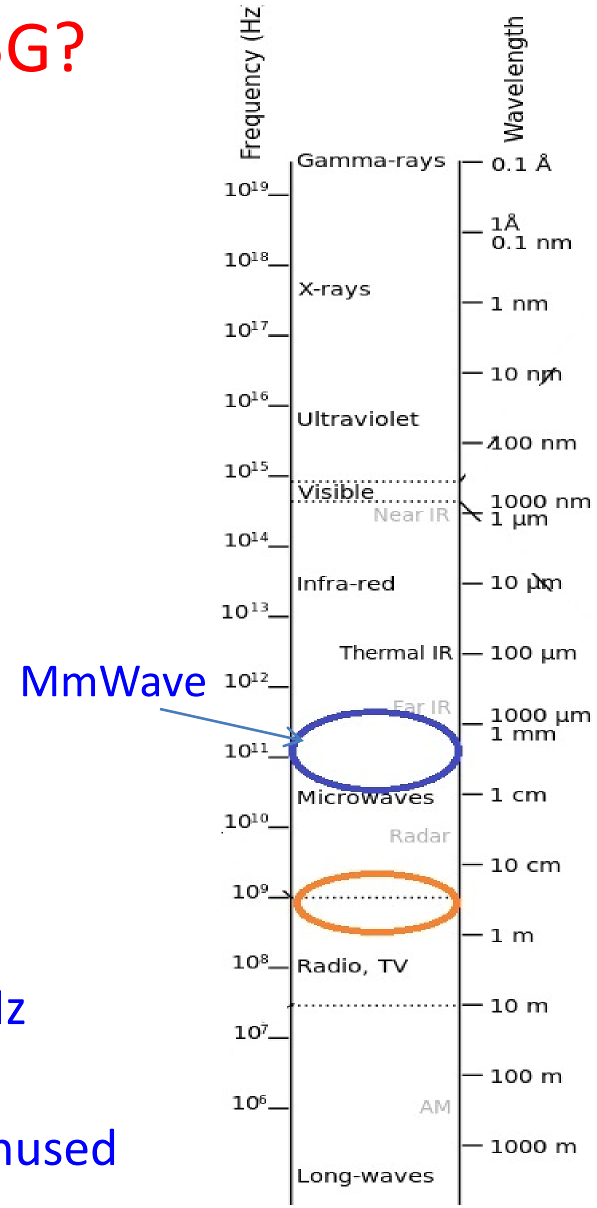
Achieving 1000× data rate

From 2G to 5G: Disruptive Technologies

	Systems	Modulation	Multiple Access	ISI mitigation technique
2G	GSM	Single Carrier (GMSK)	TDMA	Viterbi Equalizer
3G	WCDMA, CDMA2000	Single Carrier + DSSS	CDMA	Rake Receiver
4G	WiMAX, LTE, LTE-Advanced	Multi-Carrier (OFDM), Single Carrier	OFDMA, SC-FDMA	Cyclic Prefix, Frequency-Domain Equalization
5G (candidate)	–	OFDM, Filter Bank Multicarrier (FBMC)	OFDMA, Massive MIMO, NOMA	Cyclic Prefix, Equalization

Where will be the Spectrum for 5G?

Band	Uplink (MHz)	Downlink (MHz)	Carrier Bandwidth (MHz)
700 MHz	746-763	776-793	1.25 5 10 15 20
AWS	1710-1755	2110-2155	1.25 5 10 15 20
IMT Extension	2500-2570	2620-2690	1.25 5 10 15 20
GSM 900	880-915	925-960	1.25 5 10 15 20
UMTS Core	1920-1980	2110-2170	1.25 5 10 15 20
GSM 1800	1710-1785	1805-1880	1.25 5 10 15 20
PCS 1900	1850-1910	1930-1990	1.25 5 10 15 20
Cellular 850	824-849	869-894	1.25 5 10 15 20
Digital Dividend	470-854		1.25 5 10 15 20



- ❑ Current cellular spectrum: 700MHz to 2.6GHz
- ❑ Less than 780MHz for cellular use globally
- ❑ Mmwave spectrum: 30 to 300GHz, largely unused

The Key Milestone for 5G MmWave

FCC adopts new rules for the foundation of 5G networks

There's still a long way to go.

- On July 14, 2016, FCC opened up nearly 11 GHz mmWave spectrum for wireless broadband
  - 28 GHz (27.5-28.35GHz)
  - 37 GHz (37-38.6 GHz)
  - 39 GHz (28.6-40 GHz)
  - 64-71 GHz (unlicensed)

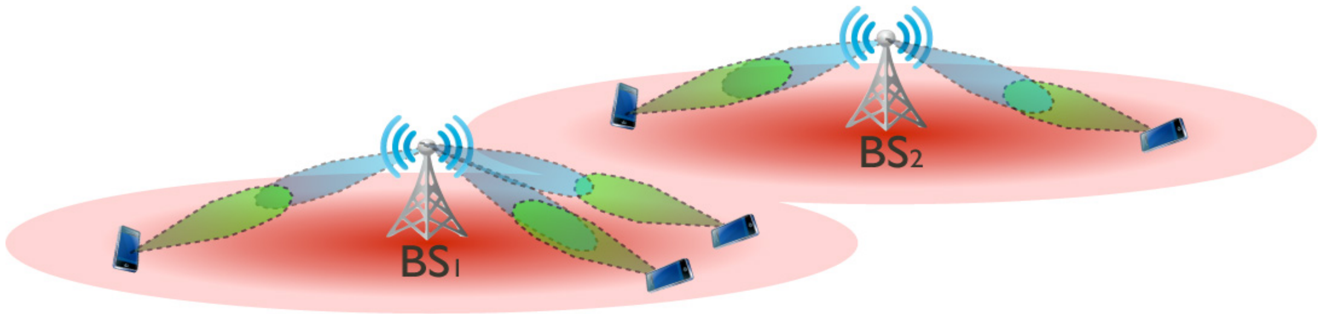
Source: https://www.engadget.com/2016/07/14/fcc-adopts-5g-rules/

FCC TAKES STEPS TO FACILITATE MOBILE BROADBAND AND NEXT GENERATION WIRELESS TECHNOLOGIES IN SPECTRUM ABOVE 24 GHZ

New rules will enable rapid development and deployment of next generation 5G technologies and services

Source: https://www.fcc.gov/document/fcc-adopts-rules-facilitate-next-generation-wireless-technologies

MmWave for 5G: Potentials and Challenges



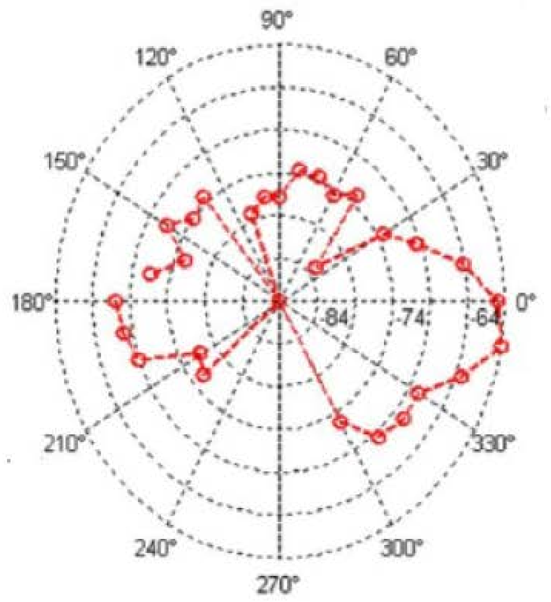
Major benefits of 5G mmWave:

- Large bandwidth (e.g., 2.16 GHz for WPAN versus 20MHz for LTE)
- Tiny antenna size due to small wavelength, massive MIMO compatible
- Reduced interference with directional beamforming

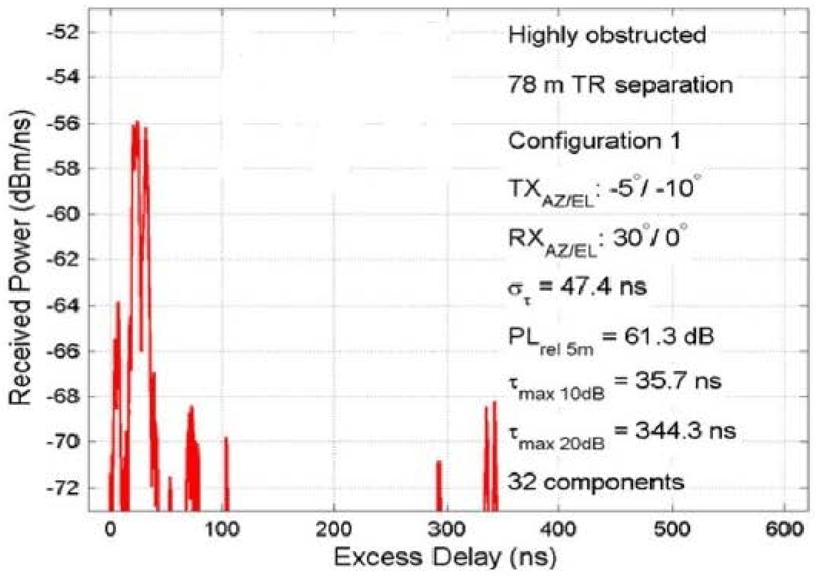
New challenges for mmWave communications:

- High free-space path loss, requires large antenna array
- Severe shadowing and high penetration loss, limited indoor coverage
- Wide-band and frequency-selective channel, inter-symbol interference (ISI)
- Increased hardware cost, power consumption, signal processing complexity
- Beamforming and channel estimation with cost-effective hardware

MmWave Channel Characteristics



AoA power profile



Power delay profile

- ❑ Multi-path/angular sparsity: on average 2.5 lobes based on measurements in New York City
- ❑ Frequency-selective: wide signal bandwidth + large delay spread

T. S. Rappaport, R. W. Heath, R. C. Daniels, and J. N. Murdock, “Millimeter wave wireless communications," Prentice Hall, Sep. 2014.

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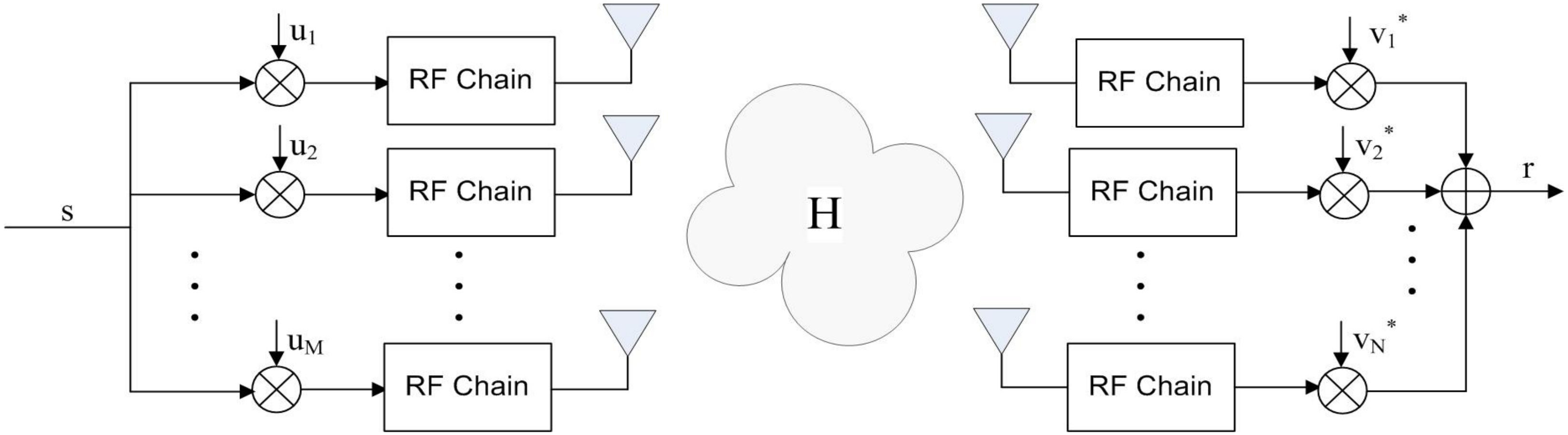
MmWave MIMO: Fully Digital Processing



❑ Fully digital MIMO processing

- ➢ Transmit/receive beamforming implemented in baseband, both signal phase and magnitude varied at each antenna
- ➢ One radio-frequency (RF) chain is needed for each antenna

❑ **Impractical** for mmWave MIMO

- ➢ High signal processing complexity due to large signal dimensions: large array + large signal bandwidth (over hundreds of MHz)
- ➢ Prohibitive hardware and power consumption cost: large number of RF chains operating at tens of GHz

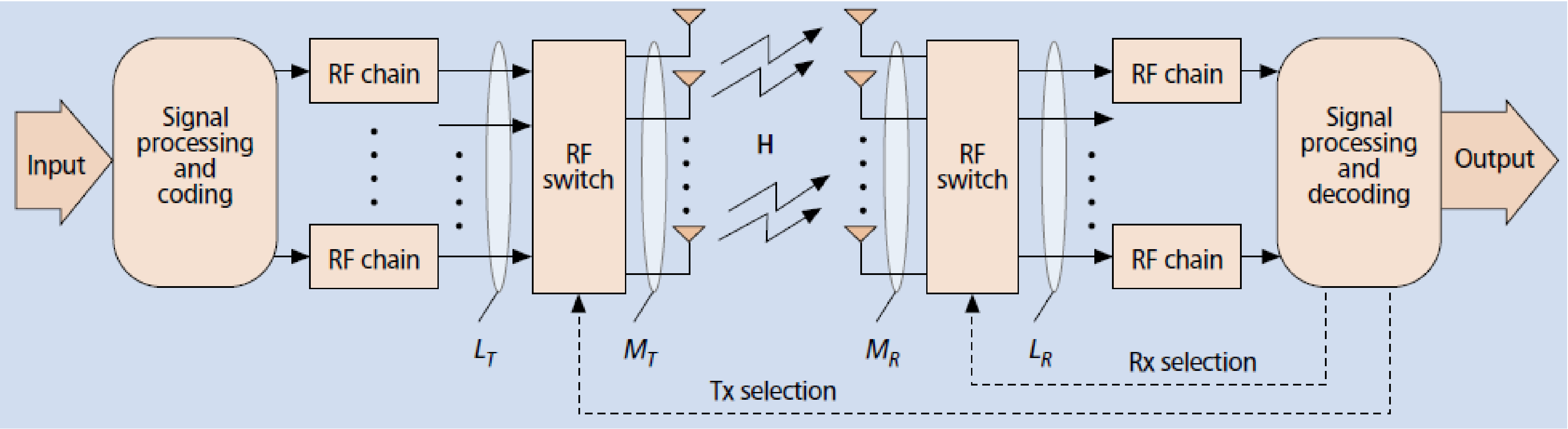
Cost-Aware MmWave MIMO: Existing Techniques

- Existing techniques: use fewer or inexpensive RF chains
  - Antenna selection
  - Analog beamforming
  - Hybrid analog/digital processing
  - Low-resolution (one-bit) ADCs

  (but all of the above result in performance compromise due to low-cost/complexity processing)

Antenna Selection

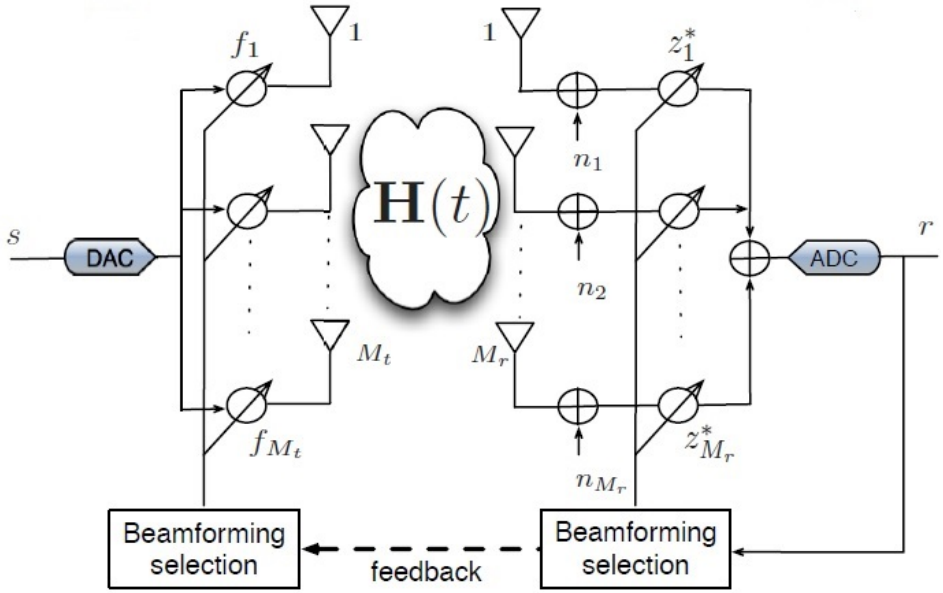
- Select the "best" subset of transmit/receive antennas
- Low complexity/cost: reduced RF chains
- Limited array gain
- Poor performance in correlated channels
- Ineffective in frequency-selective channels



S. Sanayei and A. Nosratinia, "Antenna selection in MIMO systems" *IEEE Commun. Mag.*, Oct. 2004.

Analog Beamforming

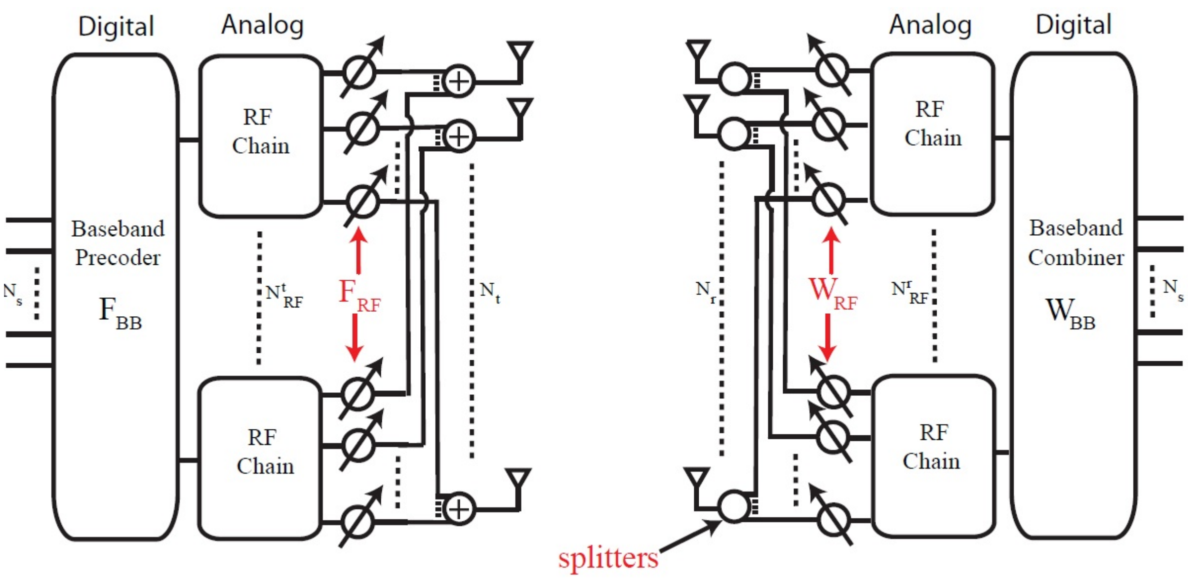
- Performed in RF domain using phase shifters only
- One RF chain for both transmitter/receiver: low cost
- Degraded beamforming performance (vs. fully digital)
- Limited design degrees of freedom: no signal magnitude variation
- Cannot support spatial multiplexing



S. Hur, et al., "Millimeter wave beamforming for wireless backhaul and access in small cell networks," *IEEE Trans. Commn.*, Oct. 2013.

Hybrid Analog/Digital Processing

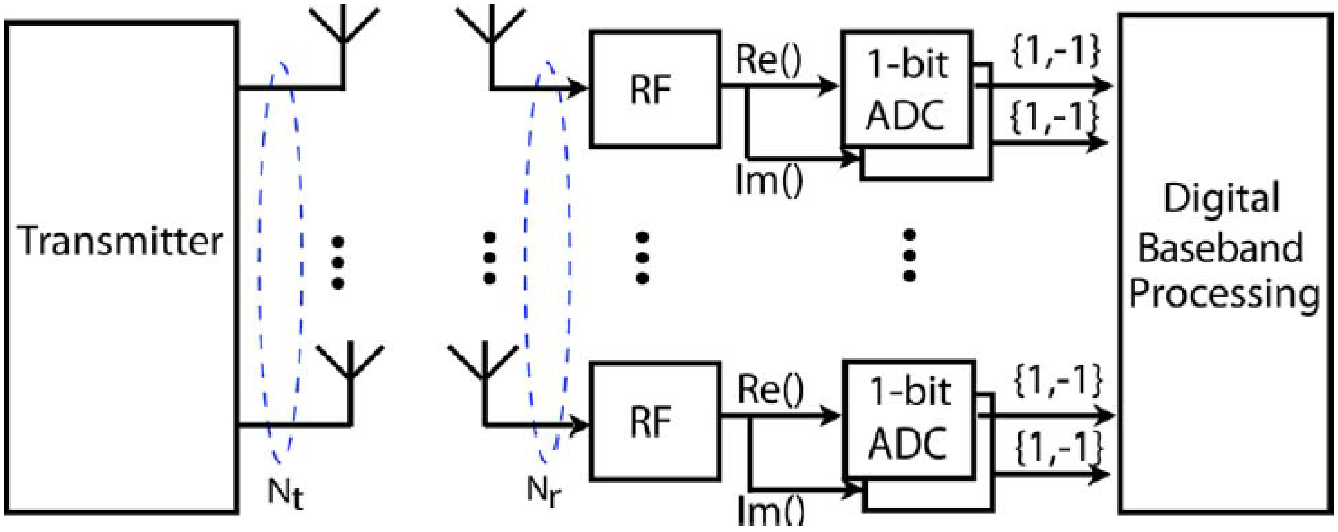
- Two-stage (baseband and RF) processing, with limited RF chains
- More flexible trade-off between performance and cost
- Complicated MIMO precoder/combiner optimization
- More challenging in channel estimation
- Very large number of RF phase shifters: additional cost & power consumption



O. E. Ayach, S. Rajagopal, S. A. Surra, Z. Pi, and R. W. Heath, "Spatially sparse precoding in millimeter wave MIMO systems," *IEEE Trans. Wireless Commn.*, Mar. 2014.

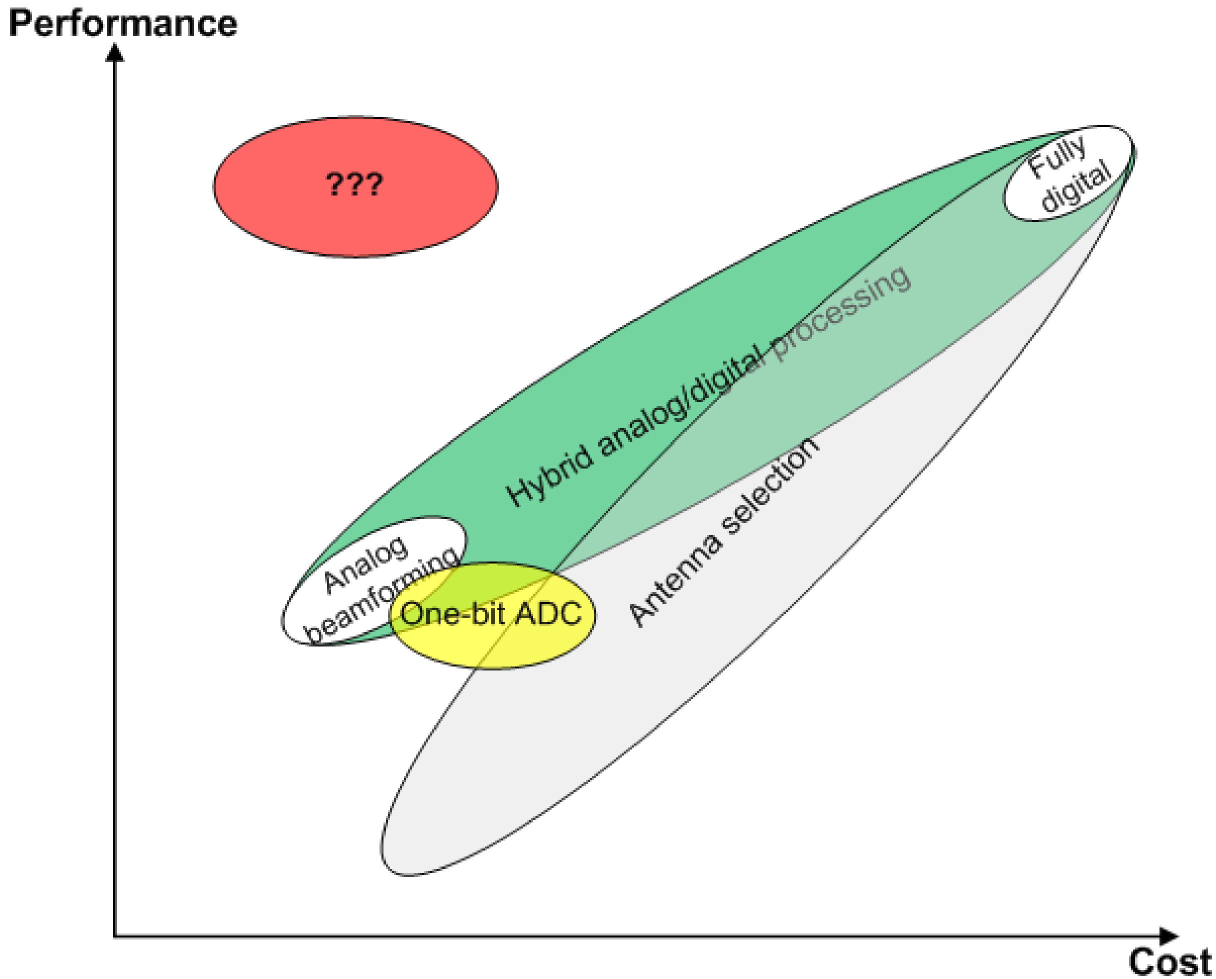
Low-Resolution (One-Bit) ADCs

- Use low-resolution ADC at receiver: less expensive and more power-efficient
- Limited performance: data rate limited by finite ADC output levels
- More challenges in beamforming design and channel estimation
- Frequency-selective channels? Transmitter DACs?



J. Mo and R. W. Heath, "Capacity analysis of one-bit quantized MIMO systems with transmitter channel state information," *IEEE Trans. Signal Process.*, Oct. 2015.

Existing mmWave MIMO Techniques: Cost-Performance Trade-off



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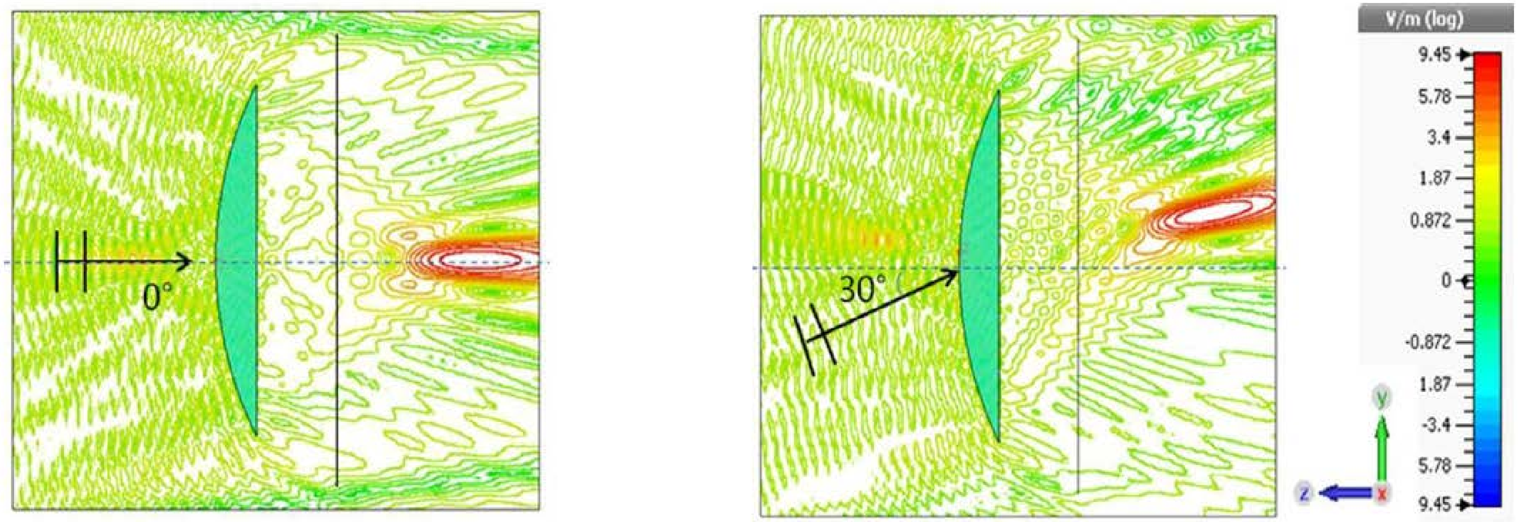
Proposed Technique: MmWave Lens MIMO

- Capacity-optimal, yet with significantly reduced RF chain cost and signal processing complexity
- Electromagnetic (EM) lens: angle-dependent energy focusing

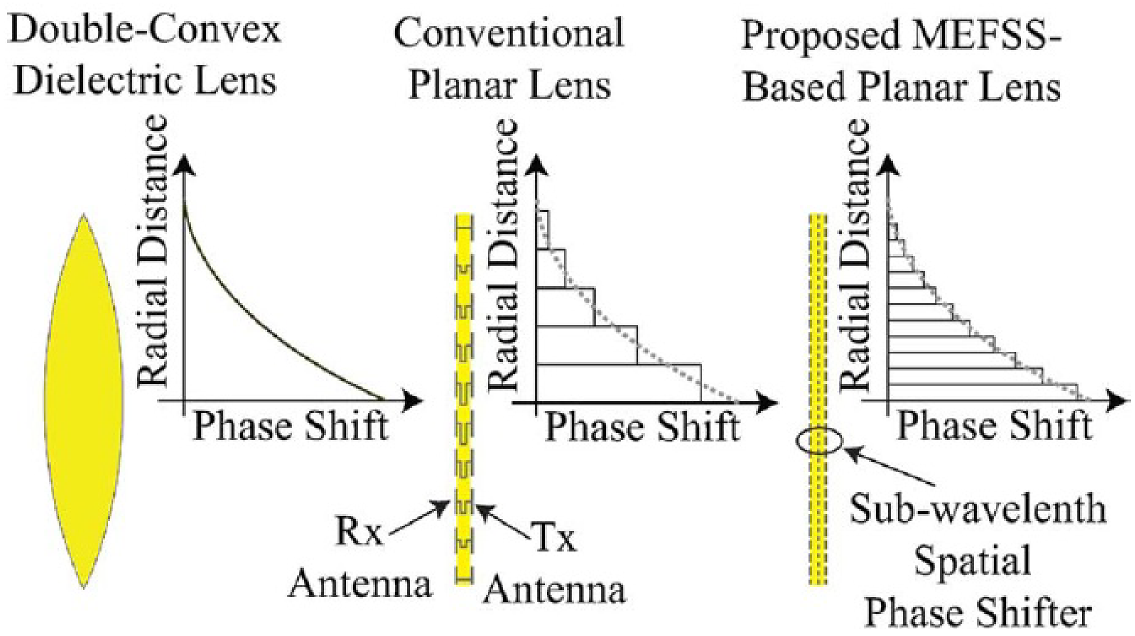


E-field distribution with AoA $\theta = 0^\circ$

E-field distribution with AoA $\theta = 30^\circ$

P. Y. Lau, Z. N. Chen, and X. M. Qing, "Electromagnetic field distribution of lens antennas," in *Proc. Asia-Pacific Conf. on Antennas and Propag.*, Aug., 2013.

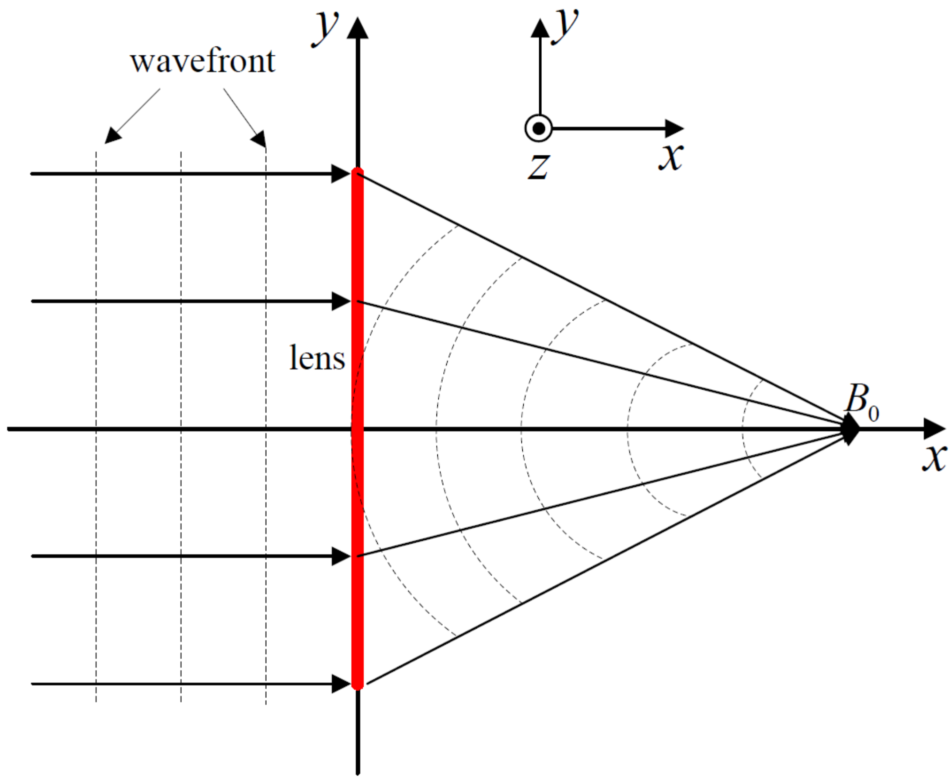
Three Types of EM Lenses



- Dielectric lens
- Conventional planar lens
- Modern planar lens: ultra thin, semi-continuous phase shifting, negligible insertion loss

M. A. Joumayly and N. Behdad, "Wideband planar microwave lenses using sub-wavelength spatial phase shifters," *IEEE Trans. Antennas and Propag.* Dec. 2011.

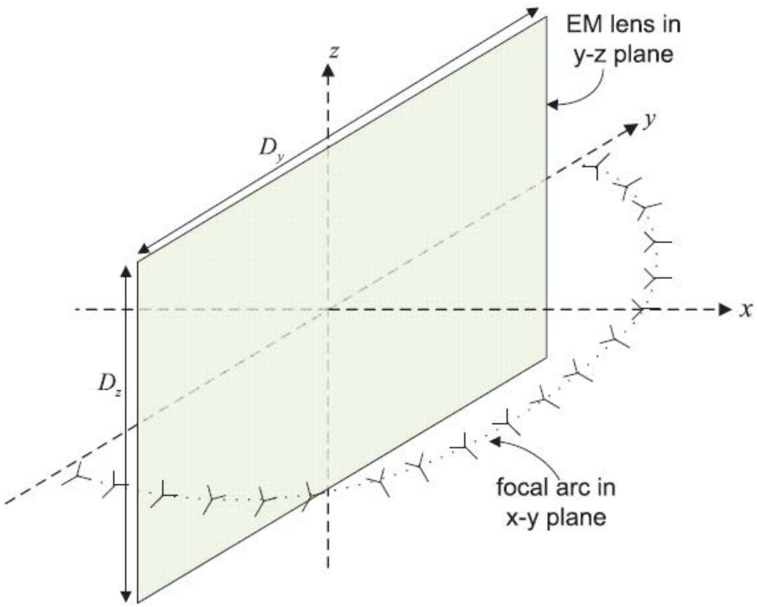
EM Lens: Principle of Operation



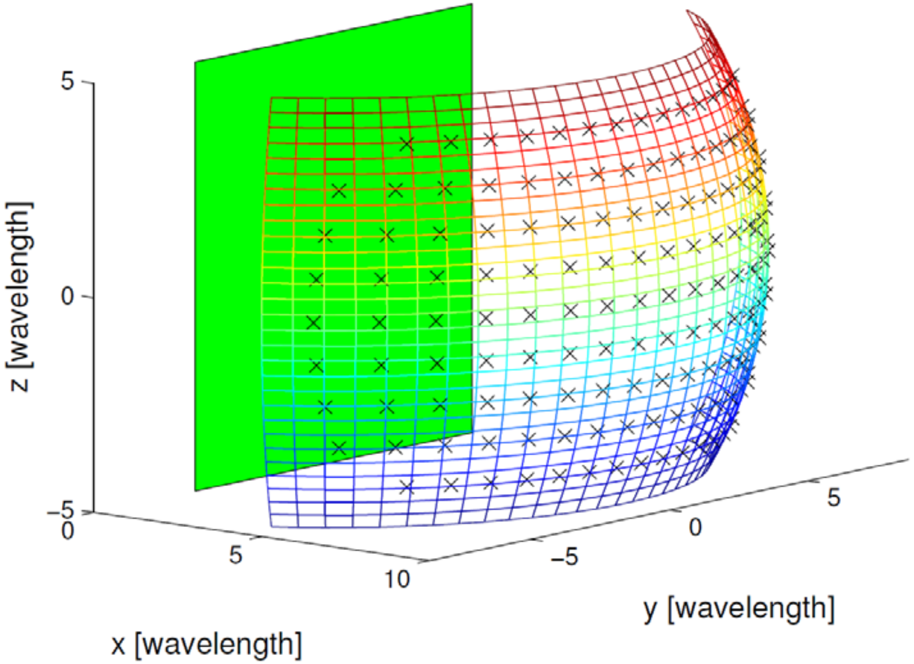
- EM lens: provide different phase shift across the lens aperture to achieve constructive superposition at focal points
- E.g., larger phase shift at the lens center than edge

Lens Antenna Array: Configuration

- **Lens Antenna Array:** EM lens + antenna array on focal arc/surface



(a) 2D lens array

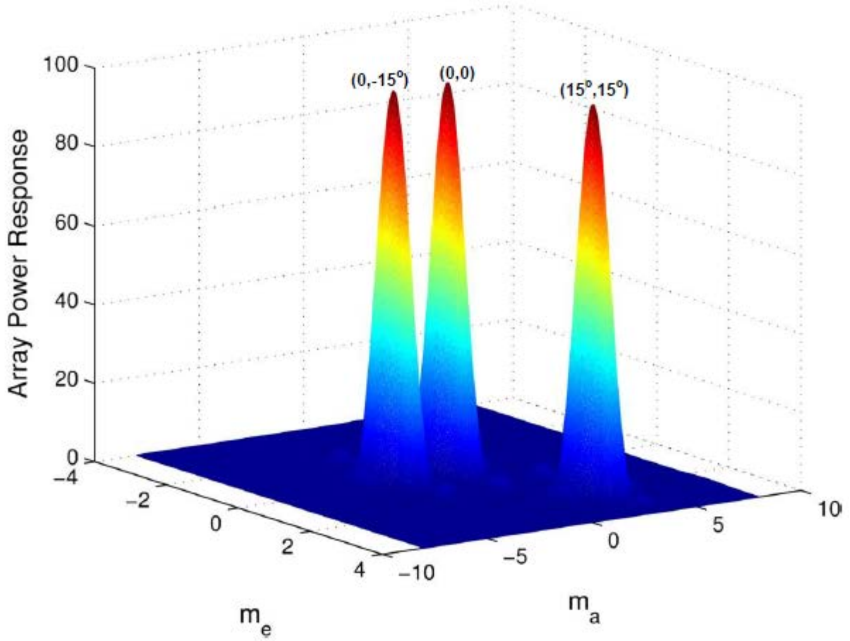


(b) 3D/Full-dimensional lens array

(a) Y. Zeng and R. Zhang, "Millimeter wave MIMO with lens antenna array: a new path division multiplexing paradigm," *IEEE Trans. Commun.*, April 2016.
(b) Y. Zeng and R. Zhang, "Cost-effective millimeter wave communications with lens antenna array", submitted to *IEEE Wireless Commun.*

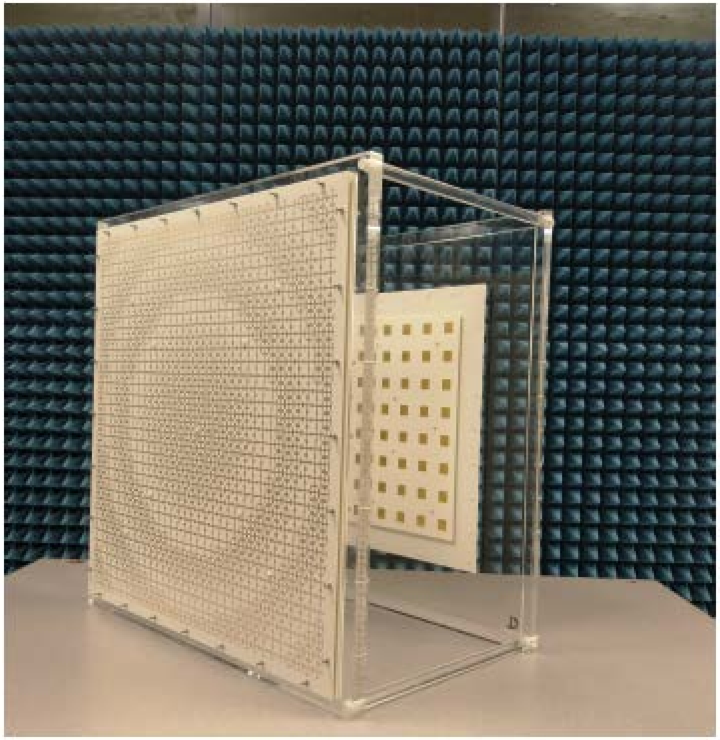
Array Response of Full-Dimensional Lens Array

- Array response: $a_m(\theta,\phi) \approx \sqrt{\tilde{D}_y \tilde{D}_z}\,\mathrm{sinc}(m_e - \tilde{D}_z \sin\theta)\,\mathrm{sinc}(m_a - \tilde{D}_y \cos\theta \sin\phi)$
- Angle-dependent energy focusing: antenna selection without performance degradation
- Multi-path separation: path division multiplexing without ISI



Y. Zeng and R. Zhang, "Cost-effective millimeter wave communications with lens antenna array", submitted to *IEEE Wireless Commun.*

Lens Array: Prototype and Measurement Results

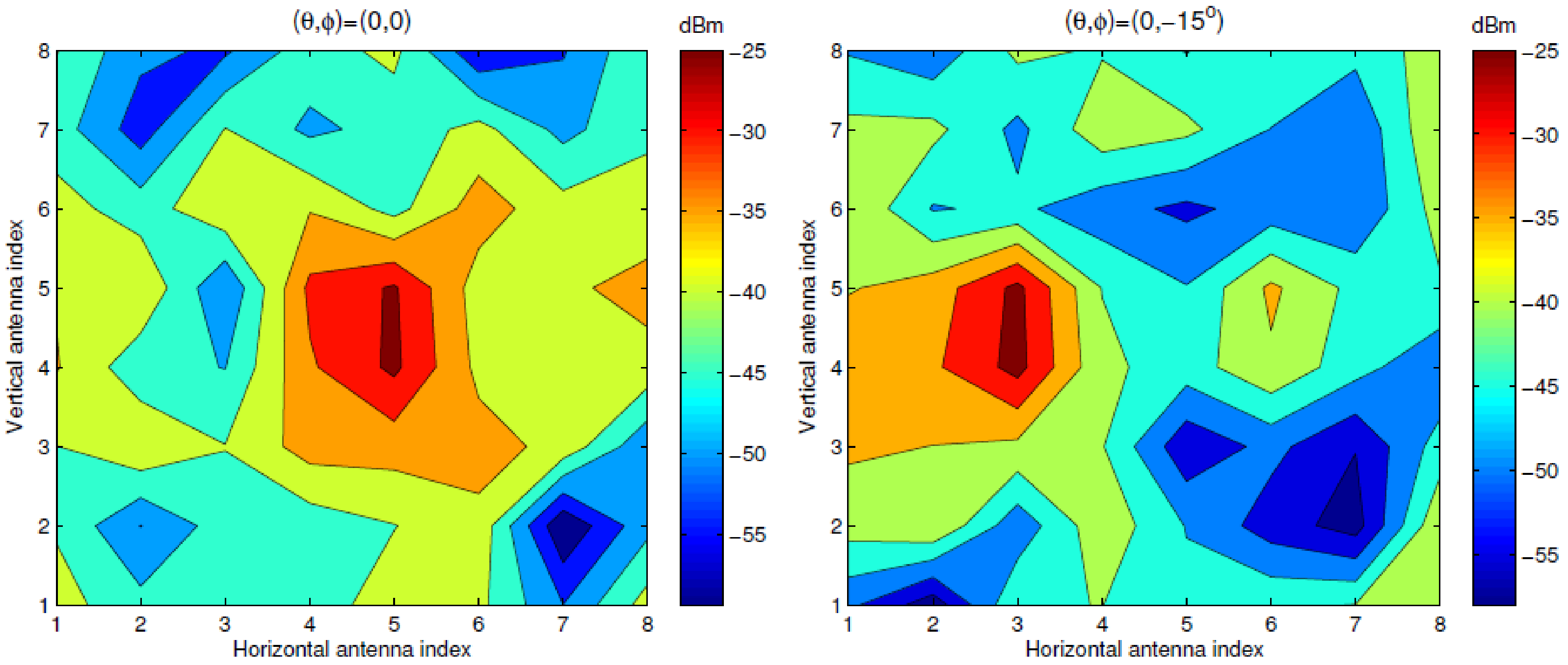


Lens array prototype developed at the National University of Singapore

- Central frequency: 5.8GHz
- EM lens: 52.8cm x 52.8cm (10λ x 10λ)
- 8 x 8 patch antenna array on a flat plane (for ease of fabrication)
- Lens-array separation: 25cm

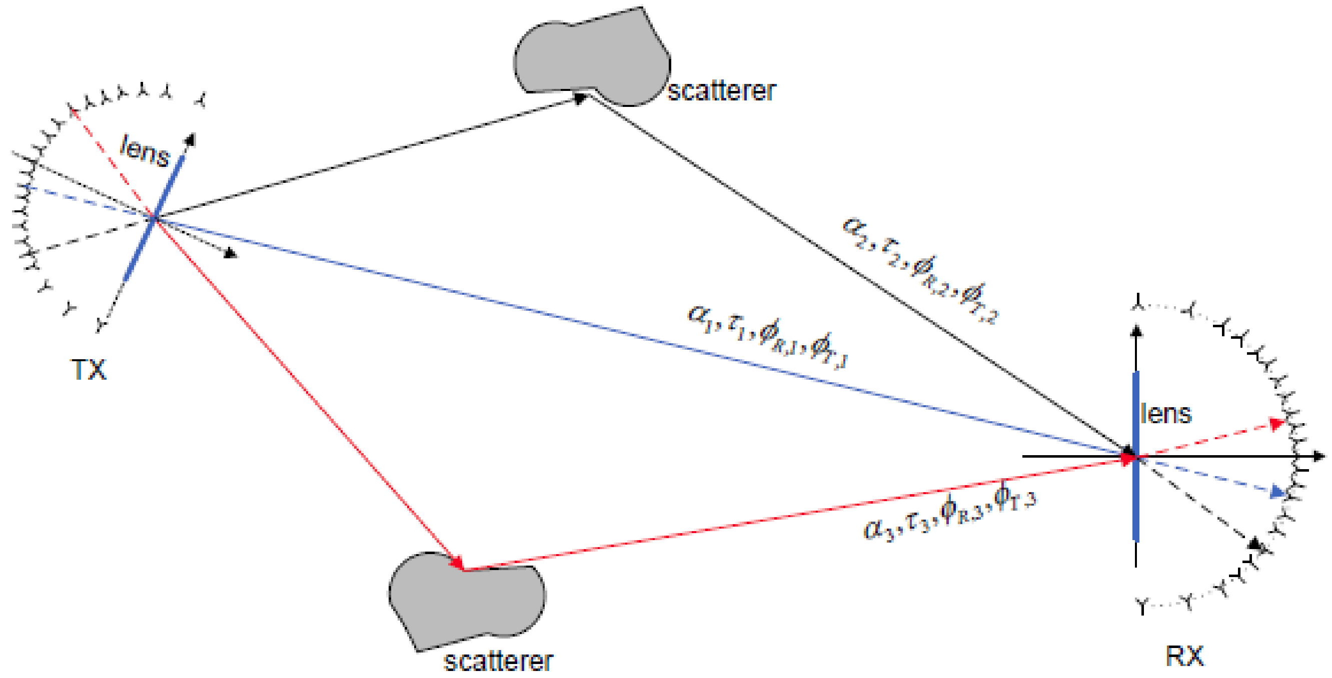
Lens Array: Prototype and Measurement Results

- Measurement setup:
  - Transmitter (tx): horn antenna, 10dBi gain, 10dBm tx power
  - Receiver (rx): 8 x 8 lens antenna array
  - Tx-rx distance: 5m, two signal arriving directions



Y. Zeng and R. Zhang, "Cost-effective millimeter wave communications with lens antenna array", submitted to *IEEE Wireless Commun.*

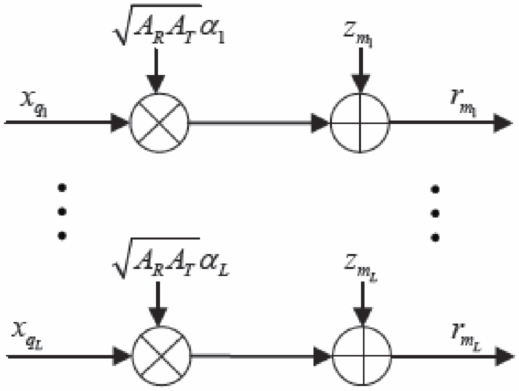
MmWave MIMO with Double-Sided Lens Array



- Lens arrays at both transmitter and receiver
- *L* multi-paths, usually small (less than 4) due to multi-path sparsity in mmWave channels
- Number of RF chains only need to be equal to *L*

Orthogonal Path Division Multiplexing (OPDM)

- Multi-path signals with different angles of arrival/departure are perfectly separated by the EM Lens
- Reduce to *L* parallel SISO channels, regardless of narrow- or wide-band communications
- Inter-symbol interference (ISI) is inherently eliminated
- Single-carrier (SC) transmission is capacity optimal, sophisticated MIMO-OFDM or equalization is no longer necessary



Y. Zeng and R. Zhang, "Millimeter wave MIMO with lens antenna array: a new path division multiplexing paradigm," *IEEE Trans. Commun.*, April 2016.

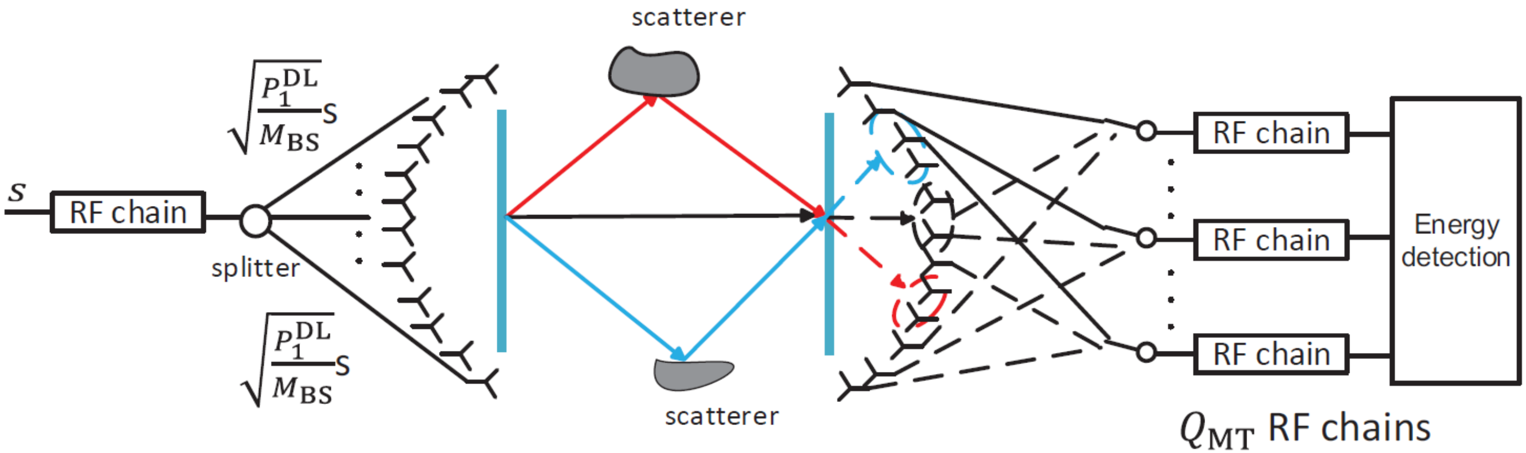
Lens MIMO vs Conventional UPA (Uniform Planar Array)

- **Lens MIMO:** OPDM with antenna selection ($L \ll M$)
- **UPA MIMO:** Fully-digital MIMO-OFDM ($M \times M$ with N subcarriers)

	Signal processing complexity		**Hardware cost**		
	MIMO processing	Channel estimation	No. of Antennas (for same aperture)	No. of RF chains	EM lens
Lens MIMO	$O(L)$	$O(L)$	$< 2M$	$2L$	Yes
UPA MIMO	$O(M^3N + MN\log N)$	$O(M^2N)$	$2M$	$2M$	No

MmWave Lens MIMO: Channel Estimation

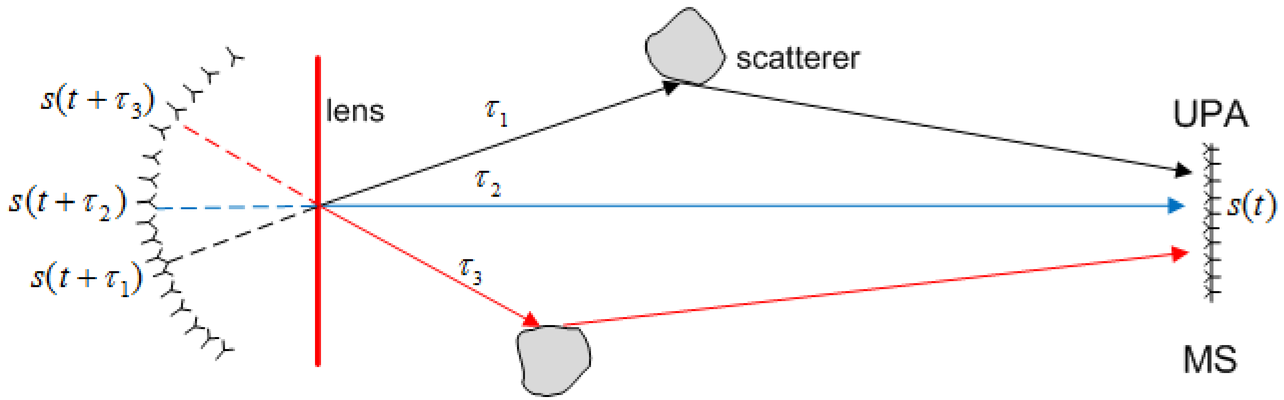
- MIMO channel estimation **with limited RF chains**
  - Complicated in mmWave MIMO with analog or hybrid processing
  - Significantly simplified in lens MIMO systems for both TDD and FDD



- Phase 1: antenna selection at MS via energy comparison
- Phase 2: antenna selection at BS via energy comparison
- Phase 3: reduced MIMO channel estimation

L. Yang, Y. Zeng, and R. Zhang, "Efficient channel estimation for millimeter wave MIMO with limited RF chains," in *Proc. IEEE Int. Conf. Commun. (ICC),* 2016.

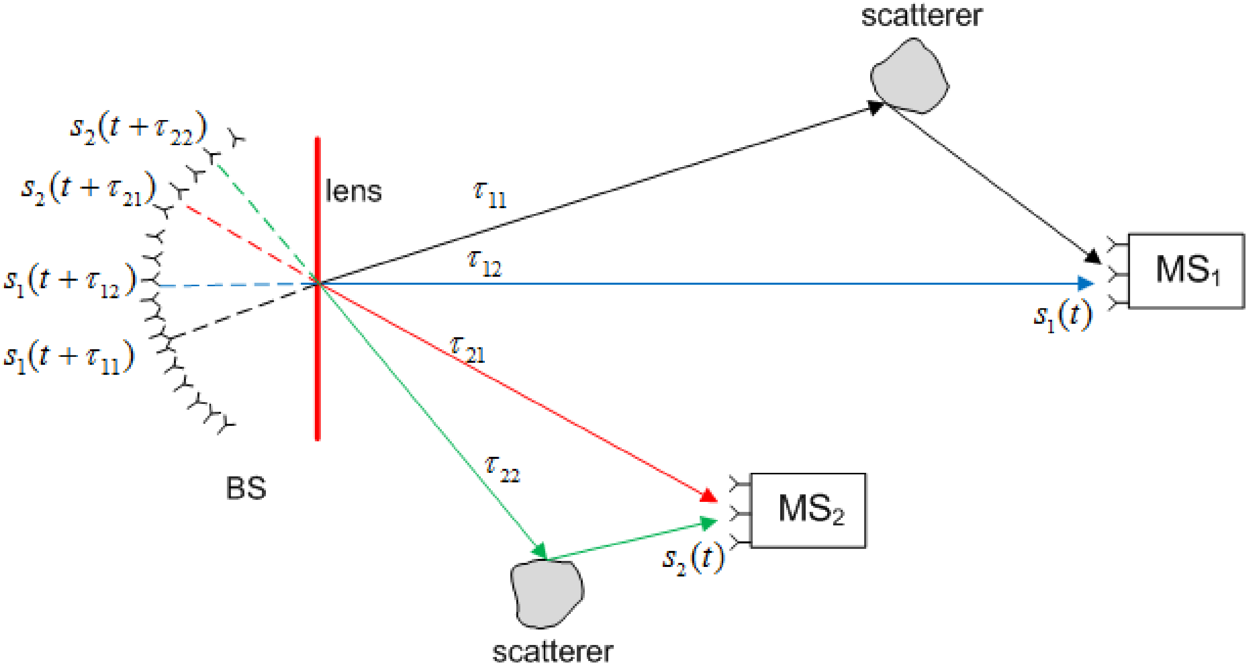
MmWave MIMO with Single-Sided Lens Array



- Lens array at BS, conventional array (e.g., UPA) at MS
- *L* multi-paths are well separated at the BS
- Perfect ISI elimination via path delay compensation at BS
- Small MIMO processing over "frequency-flat" channels
- Sophisticated MIMO-OFDM or equalization is not needed

Y. Zeng and R. Zhang, "Cost-effective millimeter wave communications with lens antenna array", submitted to *IEEE Wireless Commun.*

Multi-User MmWave Lens MIMO: Path Division Multiple Access



- Large lens array at the BS: high angle resolution
- Different paths of all users are well separated at the BS
- Inter-user interference is inherently eliminated: path division multiple access

Y. Zeng, R. Zhang, and Z. N. Chen, “Electromagnetic lens-focusing antenna enabled massive MIMO: performance improvement and cost reduction,” *IEEE J. Sel. Areas Commun.*, June 2014.

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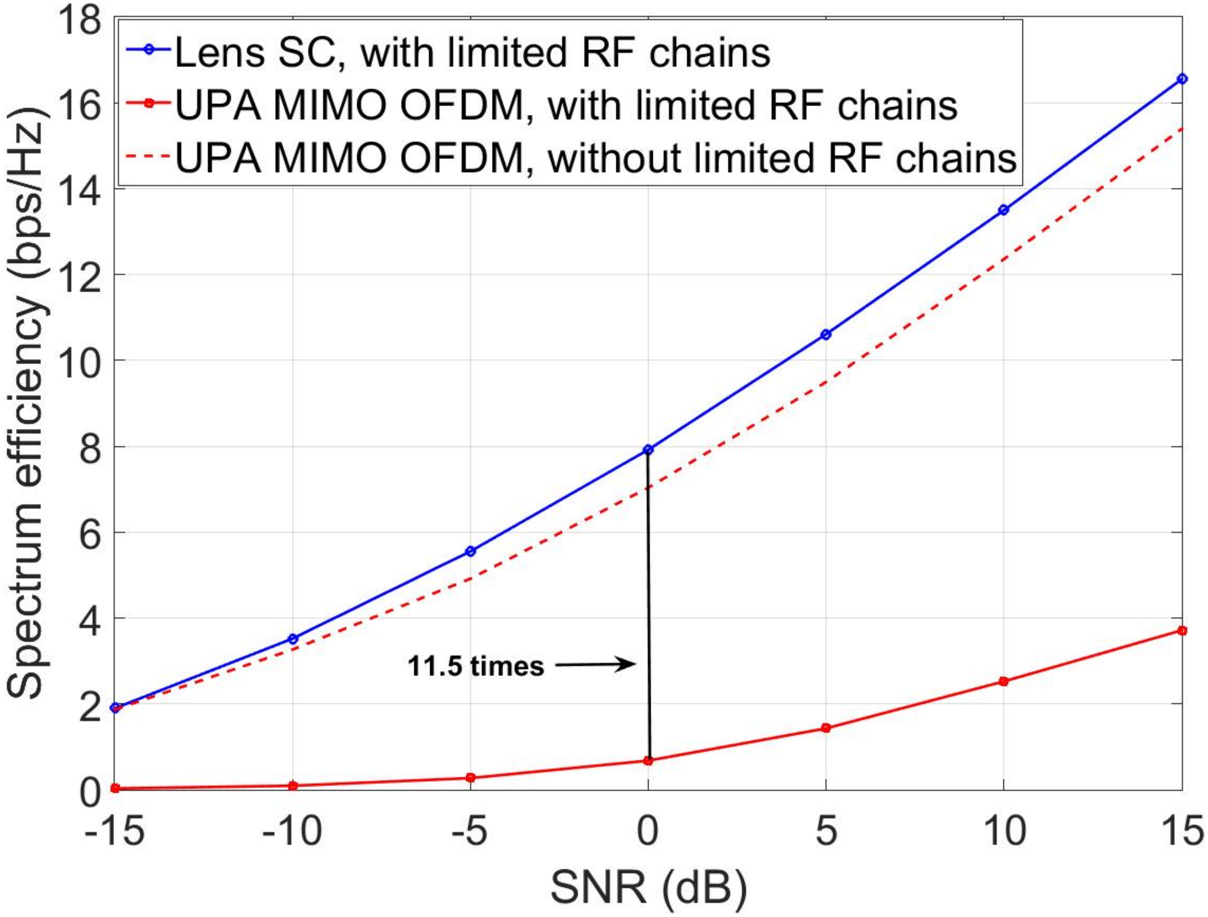
Double-Sided Lens MIMO vs. UPA MIMO-OFDM

- Frequency: 28GHz, bandwidth: 500MHz
- Number of multi-paths *L*: uniformly distributed between 1 and 3

	Lens MIMO with Antenna Selection		**UPA MIMO with Antenna Selection**	
	Base station **(2D Lens Array)**	Mobile station **(2D Lens Array)**	Base station (UPA)	Mobile station (UPA)
No. of antenna elements (for same aperture)	31	5	120	20
No. of RF chains	5	3	5	3
Modulation	Single-carrier (SC), with path delay compensation at BS and small MIMO processing		MIMO-OFDM, with 512 subcarriers and cyclic prefix length 50	

Double-Sided Lens MIMO vs. UPA MIMO-OFDM (with and without Limited RF Chains)

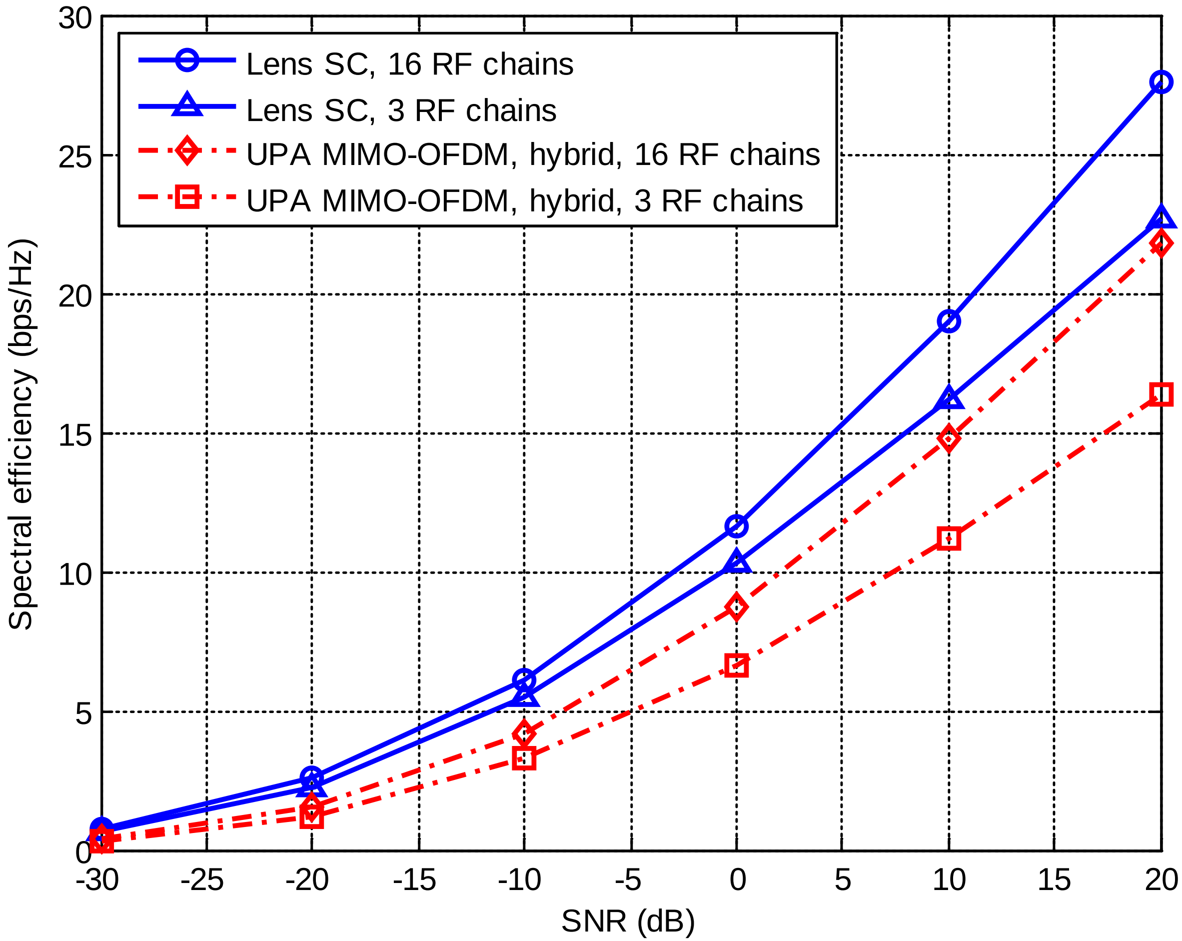


Single-Sided Lens MIMO vs UPA MIMO-OFDM with Hybrid Analog/Digital Precoding

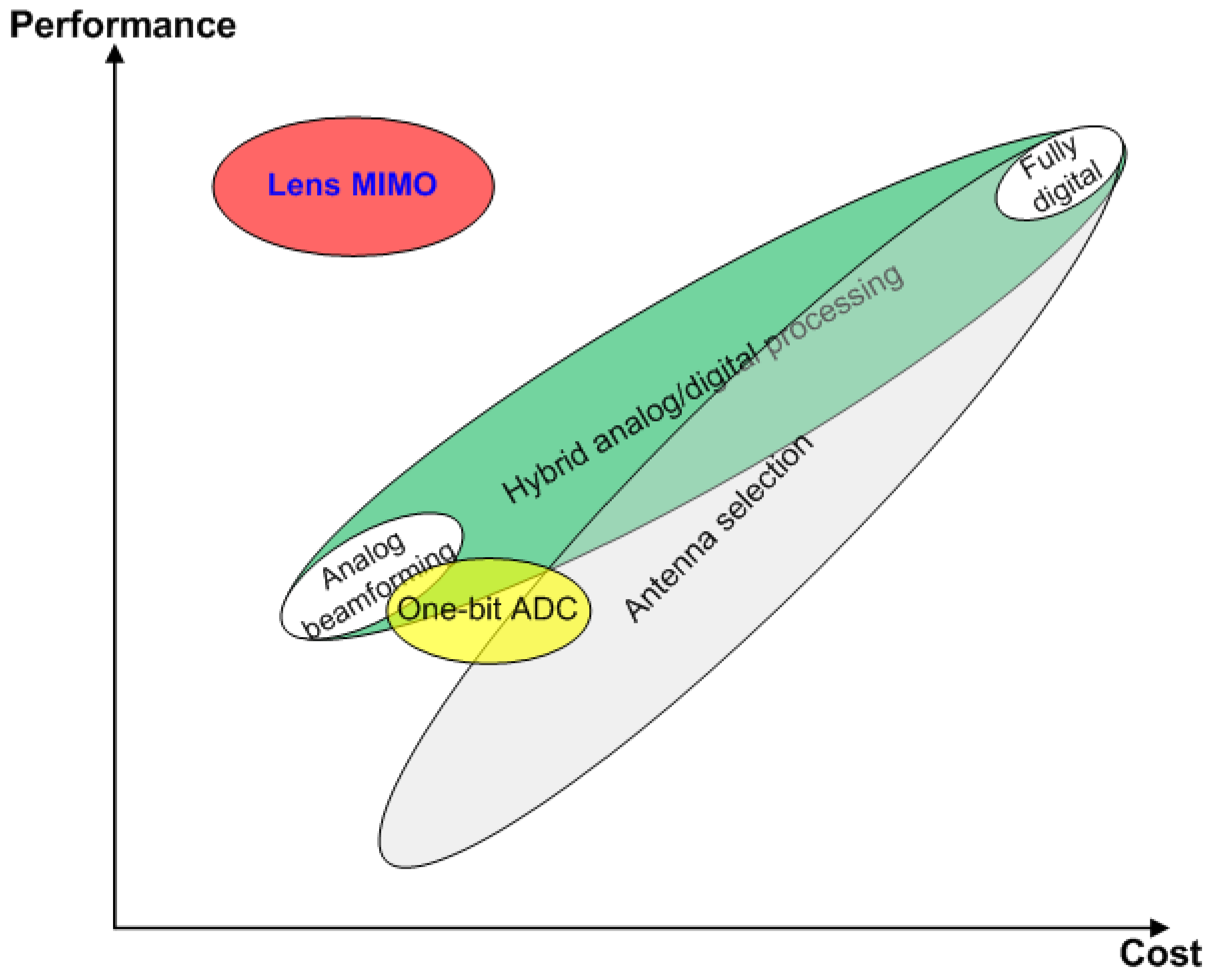
- Frequency: 28GHz, bandwidth: 500MHz
- Number of multi-paths *L*: 3; maximum path delay: 100ns

	Lens MIMO with Antenna Selection		**UPA MIMO with Hybrid Precoding**	
	Base station **(3D Lens Array)**	Mobile station **(UPA)**	Base station (UPA)	Mobile station (UPA)
No. of antenna elements (for same aperture)	149	4	400	4
No. of RF chains	3 or 16	4	3 or 16	4
Modulation	Single-carrier (SC), with path delay compensation at BS and small MIMO processing		MIMO-OFDM, with 512 subcarriers and cyclic prefix length 50	

Single-Sided Lens MIMO vs. UPA MIMO-OFDM with Hybrid Analog/Digital Precoding



MmWave MIMO: Cost-Performance Trade-off (Revisit with Lens MIMO added)



Conclusions

MmWave Lens MIMO

- Exploits both angle-dependent energy focusing of lens array and angular sparsity of mmWave channels
- Capacity-optimal and low-cost:
  - ✓ Signal processing: single-carrier transmission with path division multiplexing and small MIMO processing: *O(L)*
  - ✓ ISI Mitigation: "Frequency-selective" wideband channel converted to "frequency-flat" narrowband channel by lens antenna and path delay compensation
  - ✓ RF chain hardware & power consumption cost: *O(L)*
  - ✓ Channel estimation overhead: *O(L)*

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2G	GSM	Single Carrier (GMSK)	TDMA	Viterbi Equalizer
3G	WCDMA, CDMA2000	Single Carrier + DSSS	CDMA	Rake Receiver
4G	WiMAX, LTE, LTE-Advanced	Multi-Carrier (OFDM), Single Carrier	OFDMA, SC-FDMA	Cyclic Prefix, Frequency-Domain Equalization
5G (candidate)	_	OFDM, Filter Bank Multicarrier (FBMC)	OFDMA, Massive MIMO, NOMA	Cyclic Prefix, Equalization
5G (proposed)	**MmWave Lens MIMO**	**Single Carrier**	**Path Division Multiple Access (PDMA)**	**Lens Array, Path Delay Compensation**

Thank You

Q & A ?