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Millimeter-Wave MIMO Architectures for 5G Gigabit Wireless

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Emerging Technologies for 5G Wireless Cellular Networks
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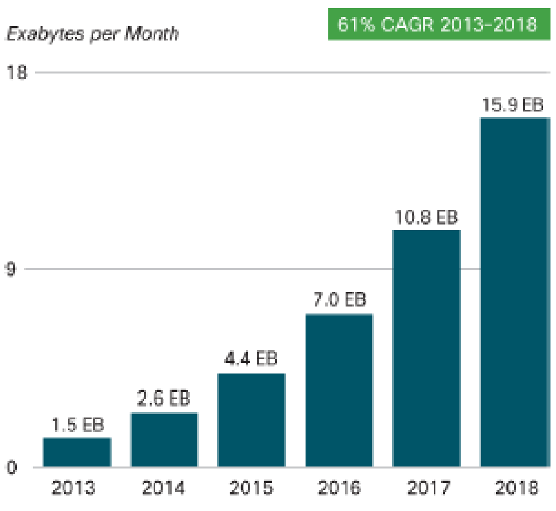
Explosive Growth in Wireless Traffic

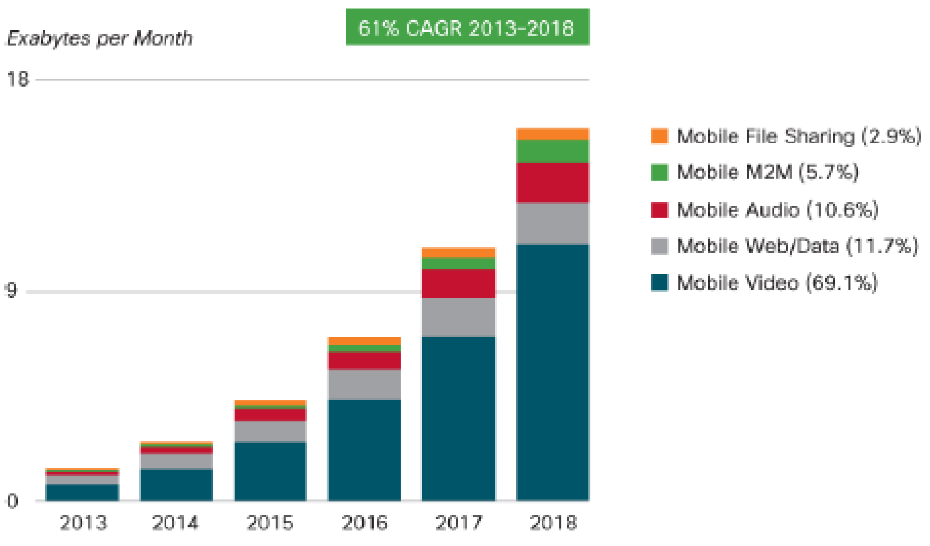
Figure 1. Cisco Forecasts 15.9 Exabytes per Month of Mobile Data Traffic by 2018



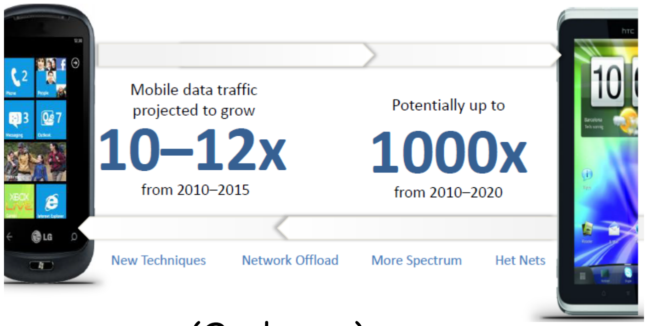
Source: Cisco VNI Mobile, 2014

(2014 Cisco visual networking index)

Figure 10. Mobile Video Will Generate Over 69 Percent of Mobile Data Traffic by 2018



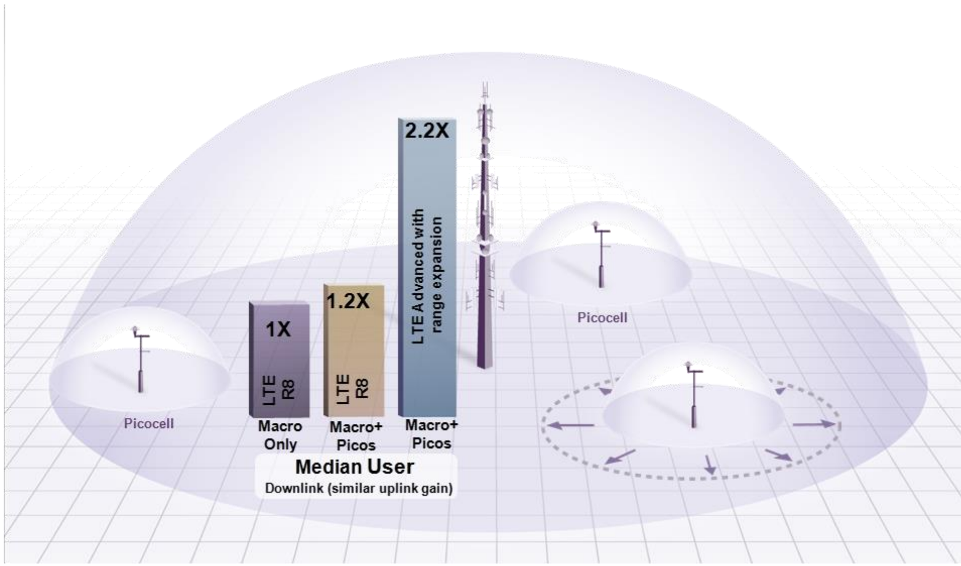
Figures in parentheses refer to traffic share in 2018.
Source: Cisco VNI Mobile, 2014



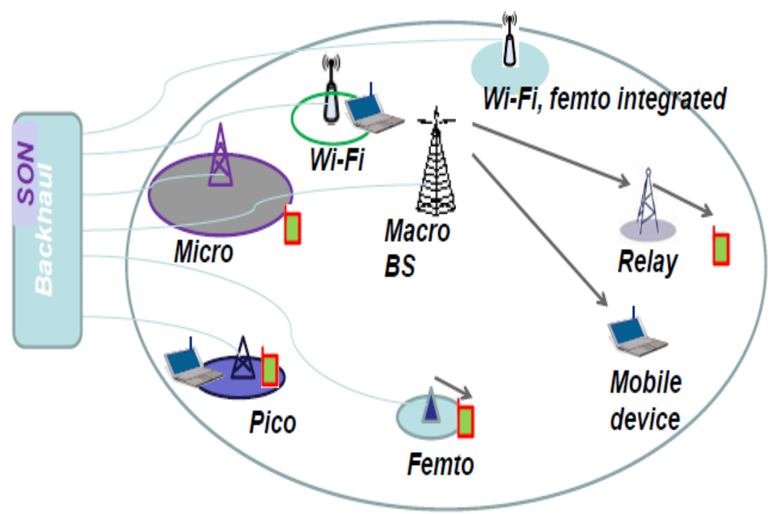
(Qualcomm)

Current Industry Approach: Small Cells & Heterogeneous Networks

Key Idea:
Denser spatial reuse of limited spectrum



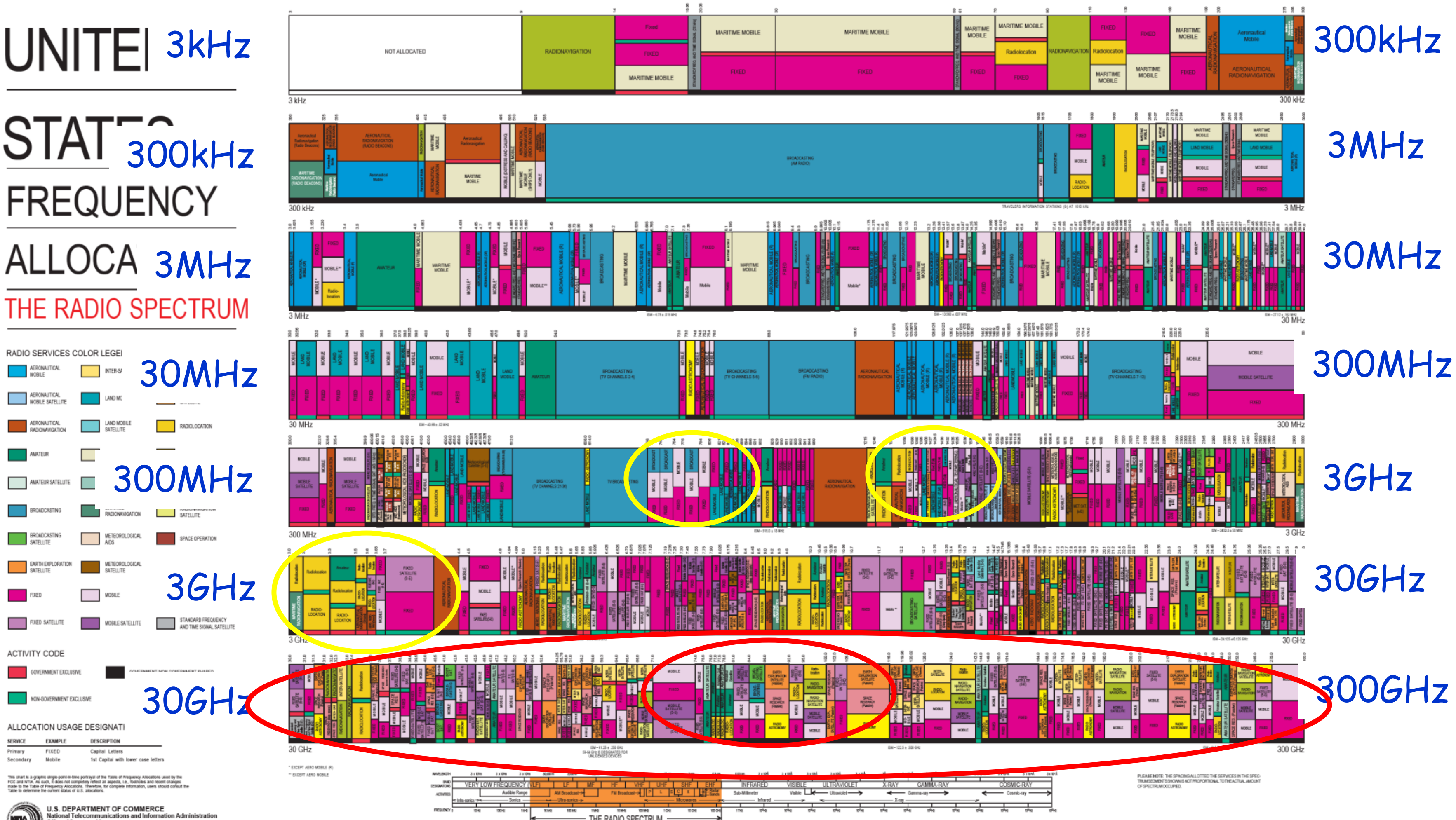
Courtesy: Dr. T. Kadous (Qualcomm)



Courtesy: Dr. J. Zhang (Samsung)

Some challenges: interference, backhaul

New Opportunity: mm-wave Band



Current cellular wireless: 300MHz - 5GHz

Mm-wave - Short range: 60GHz

Long range: 30-40GHz, 70/80/90GHz

Mm-wave Wireless: 30-300 GHz

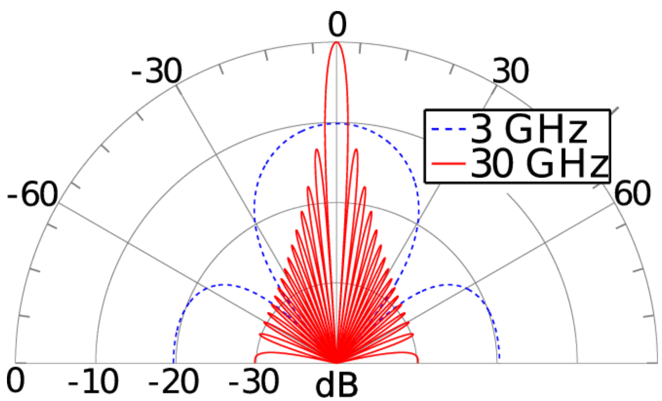
A unique opportunity for addressing the wireless data challenge

- Large bandwidths (GHz)
- High spatial dimension: short wavelength (1-100mm)

Compact high-dimensional multi-antenna arrays

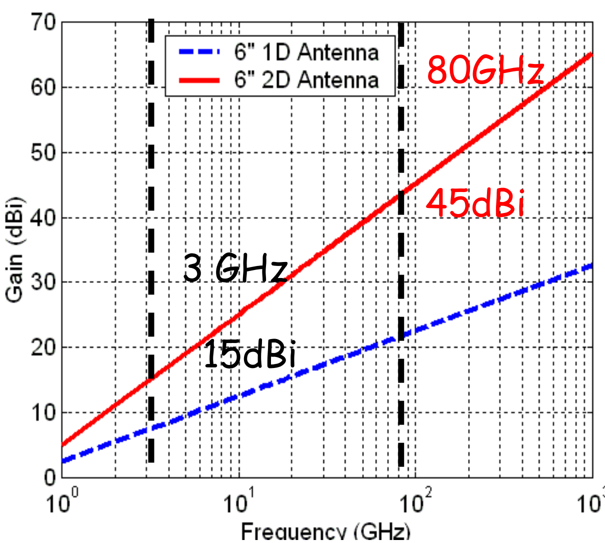
6" antenna: 6400-element antenna array (80GHz)

Highly directive narrow beams
(low interference/higher security)



Beamwidth: 35 deg @ 3GHz 2 deg @ 80GHz

Large antenna gain



Current & Emerging Applications

- Wireless backhaul; alternative to fiber
- Indoor wireless links (e.g., HDTV) IEEE 802.11ad, WiGig
- Smart base-stations for 5G mobile wireless (small cells)
- New cellular/mesh/heterogeneous network architectures
- Space-ground or aircraft-satellite links

Multi-Gigabits/s speeds
Multiple Beams

Key Opportunities and Challenges

Key Operational Functionality:

Electronic multi-beam steering & MIMO data multiplexing

Key Challenges:

- Hardware complexity: spatial analog-digital interface
- Computational complexity: high-dimensional DSP

Our Approach: Beamspace MIMO

(AS'02, AS&NB '10, JB, AS, & NB '14)

Beamspace MIMO

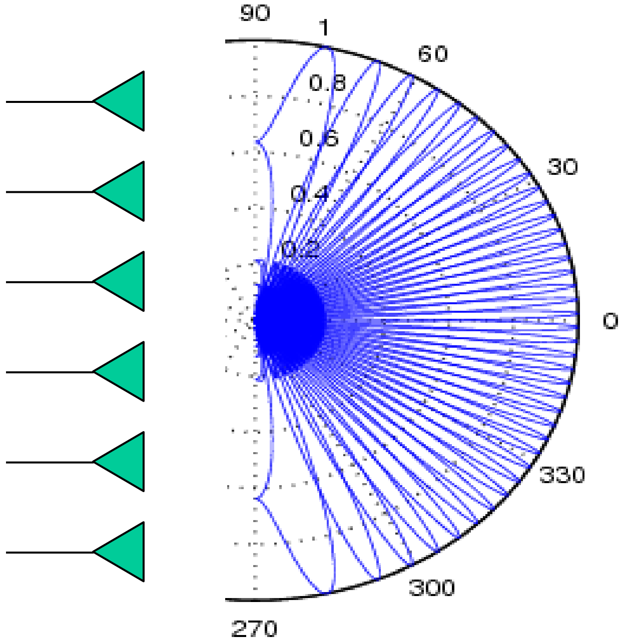
Multiplexing data into
multiple highly-directional and high-gain beams

Discrete Fourier Transform
(DFT)

Antenna space
multiplexing

Beamspace
multiplexing

n-element array
($\frac{\lambda}{2}$ spacing)



n orthogonal beams

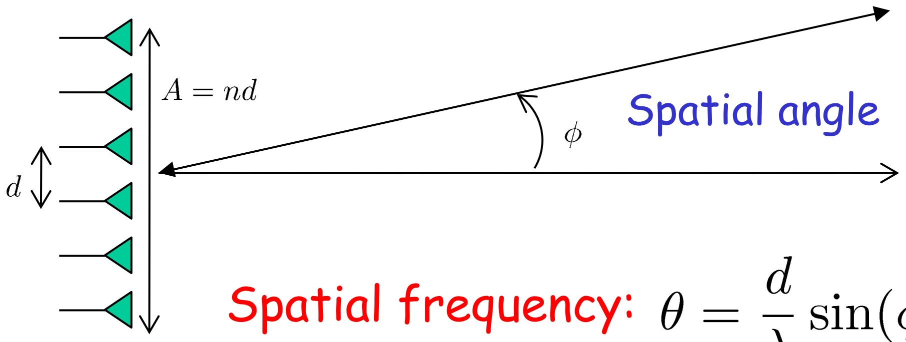
spatial channels

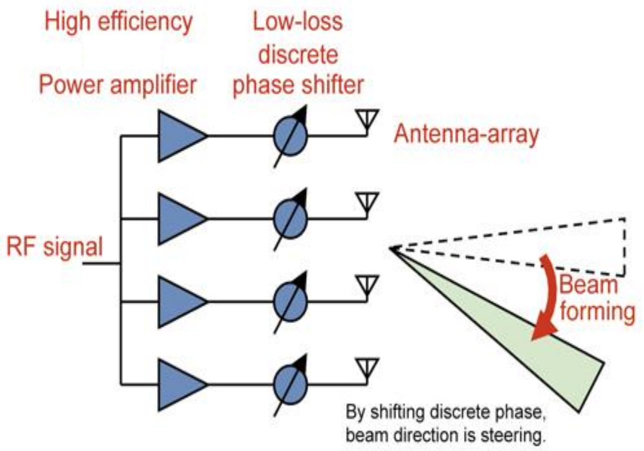
n dimensional
signal space

(AS'02, AS&NB '10, JB, AS, & NB '14)

Related: communication modes in optics (Gabor '61, Miller '00, Friberg '07)

n-element Antenna (Phased) Array





Spatial frequency: $\theta = \frac{d}{\lambda}\sin(\phi)$

$$-\frac{\pi}{2} \leq \phi \leq \frac{\pi}{2} \quad \overset{d=\frac{\lambda}{2}}{\Longleftrightarrow} \quad -\frac{1}{2} \leq \theta \leq \frac{1}{2}$$

TX: steering vector
or
RX: response vector

$$\mathbf{a}_n(\theta) = \begin{bmatrix} 1 \\ e^{-j2\pi\theta} \\ \vdots \\ e^{-j2\pi\theta(n-1)} \end{bmatrix}$$

n-dimensional spatial sinusoid

Orthogonal Spatial Beams

Spatial resolution/beamwidth:

$$\Delta\theta_o = \frac{1}{n} \longleftrightarrow \Delta\phi_o = \frac{\lambda_c}{A}$$

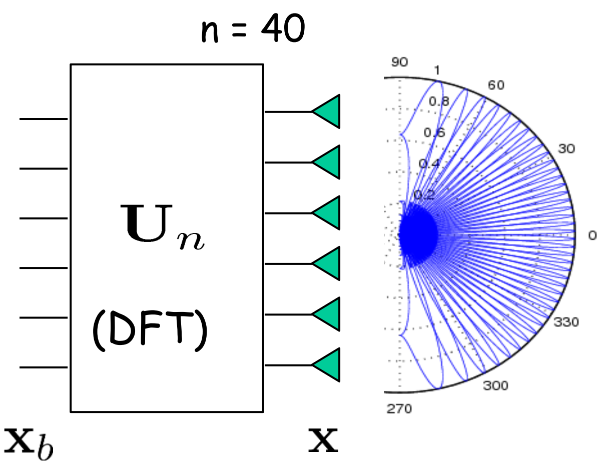
n orthogonal spatial beams

$$\theta_i = i\Delta\theta_o = \frac{i}{n} \qquad i = 0, \cdots, n-1$$

DFT spatial modulation matrix:

$$\mathbf{U}_n = \frac{1}{\sqrt{n}}\left[\mathbf{a}_n(\theta_0), \mathbf{a}_n(\theta_1), \cdots, \mathbf{a}_n(\theta_{n-1})\right]$$

(n-dimensional orthogonal basis)



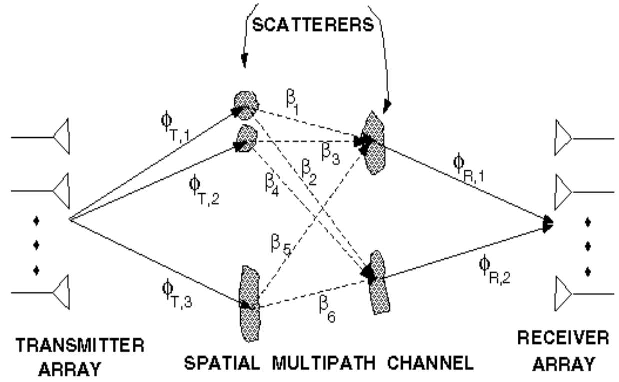
$$\mathbf{x}_b = \mathbf{U}_n^H \mathbf{x}$$
$$\mathbf{x} = \mathbf{U}_n \mathbf{x}_b$$

$$\mathbf{U}_n^H \mathbf{U}_n = \mathbf{U}_n \mathbf{U}_n^H = \mathbf{I}_n$$

Unitary

Antenna vs Beamspace Representation

n x n
MIMO system

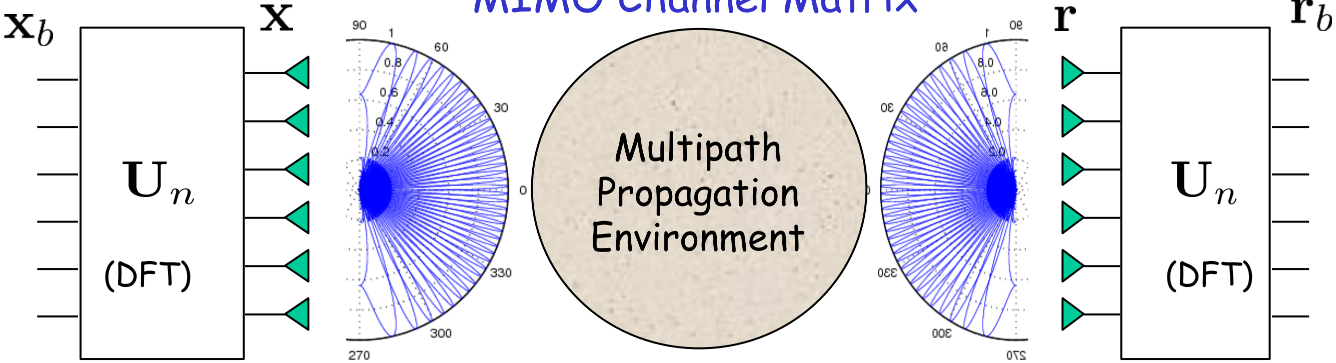


$$\text{Antenna domain: } \mathbf{r} = \mathbf{H}\mathbf{x} + \mathbf{w}$$

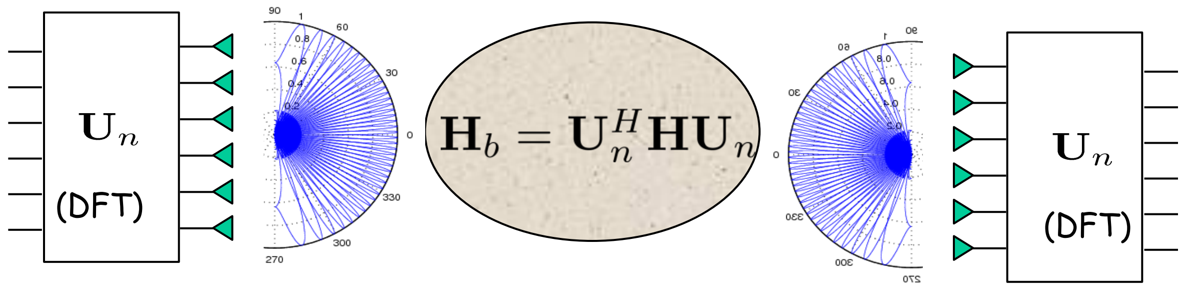
$$\text{Beam domain: } \mathbf{r}_b = \mathbf{H}_b\mathbf{x}_b + \mathbf{w}_b$$

$$\text{TX: } \mathbf{x} = \mathbf{U}_n\mathbf{x}_b \qquad \mathbf{H}_b = \mathbf{U}_n^H\mathbf{H}\mathbf{U}_n \qquad \text{RX}: \mathbf{r}_b = \mathbf{U}_n^H\mathbf{r}$$

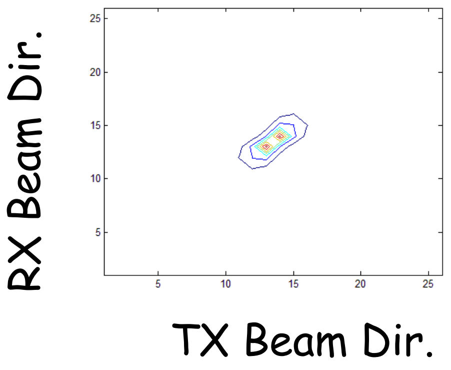
MIMO Channel Matrix



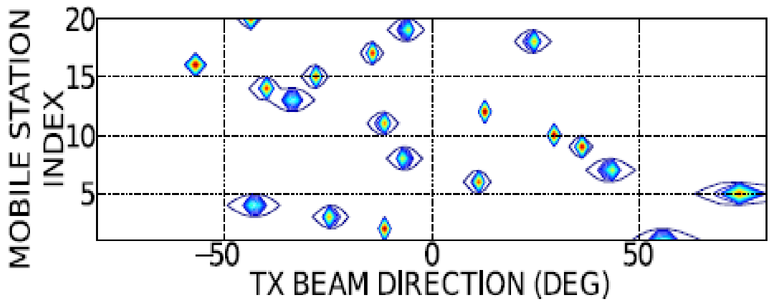
Key Characteristic at mmW: Beamspace Channel Sparsity



Point-to-point



Point-to-multipoint



- Directional, quasi-optical
- Primarily line-of-sight
- Single-bounce multipath

Communication occurs in a low-dimensional (p) subspace of the high-dimensional (n) spatial signal space

How to optimally access the communication subspace with the lowest – O(p) - transceiver complexity?

Continuous Aperture Phased (CAP) MIMO

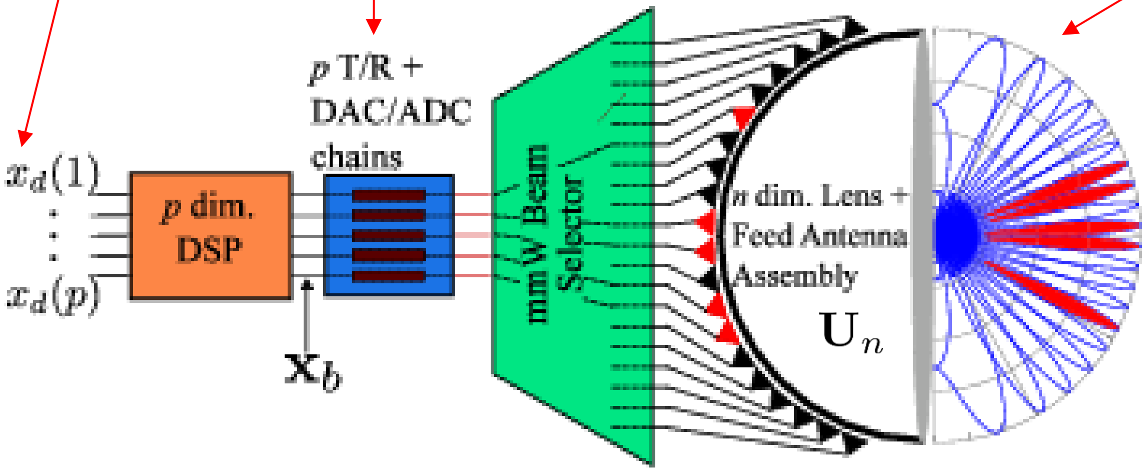
Practical Hybrid Analog-Digital Transceiver Architecture
for Beamspace MIMO (patented)

Digital modes:
p data streams

O(p) Transceiver
Complexity

Beam Selection
p << n
active beams

Analog modes:
n >> p (continuous aperture)



Comm. through beams

active beams
(data streams)

Lens computes analog spatial DFT:
direct access to beamspace

Performance-Complexity Optimization:
Optimal Performance with Lowest Hardware Complexity

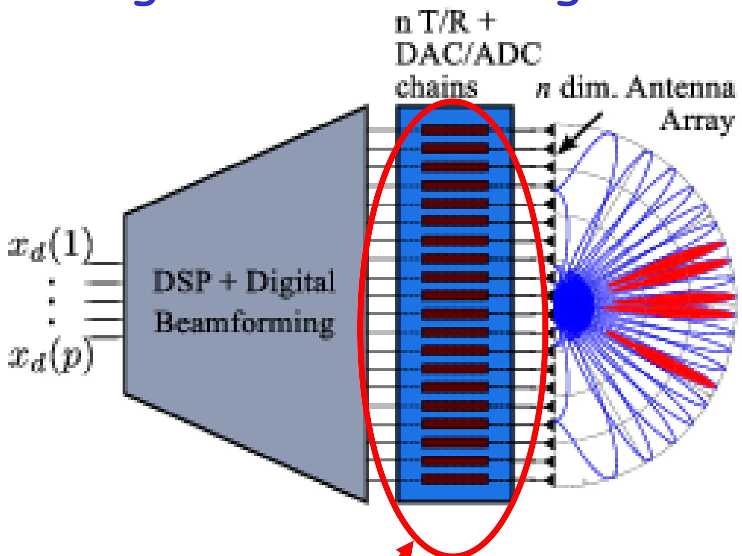
(AS & Behdad '10, '11; Brady, AS, Behdad, '12)

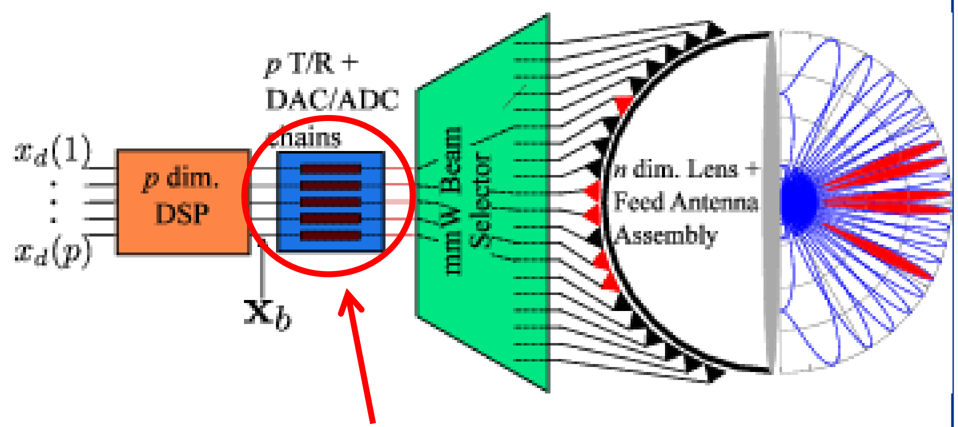
Spatial Analog-Digital Interface: Digital vs Analog Beamforming

Conventional MIMO: Digital Beamforming

Beam Selection $p \ll n$ active beams

CAP MIMO: Analog Beamforming





O(n) transceiver complexity

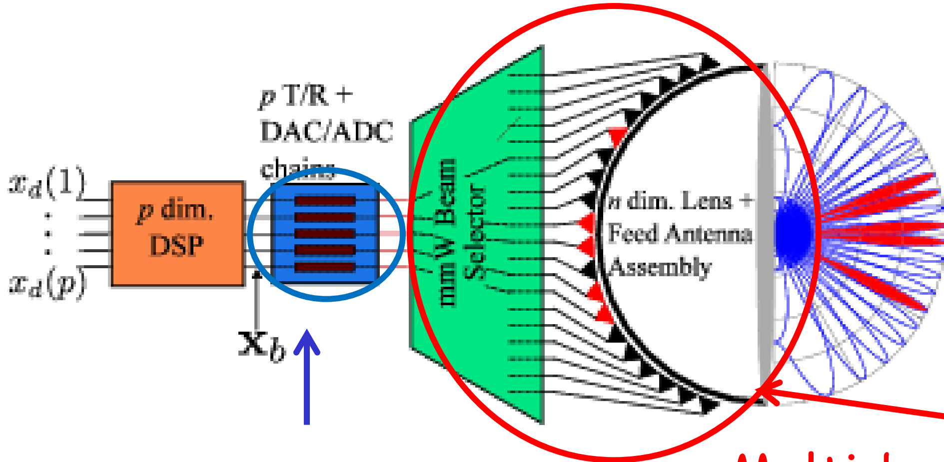
O(p) transceiver complexity

n: # of conventional MIMO array elements (1000-100,000)

p: # spatial channels/data streams (10-100)

CAP-MIMO vs Phased-Array-Based Architectures for Analog Beamforming

CAP-MIMO:

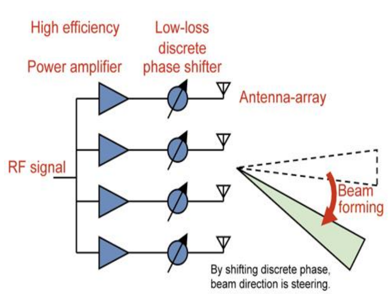


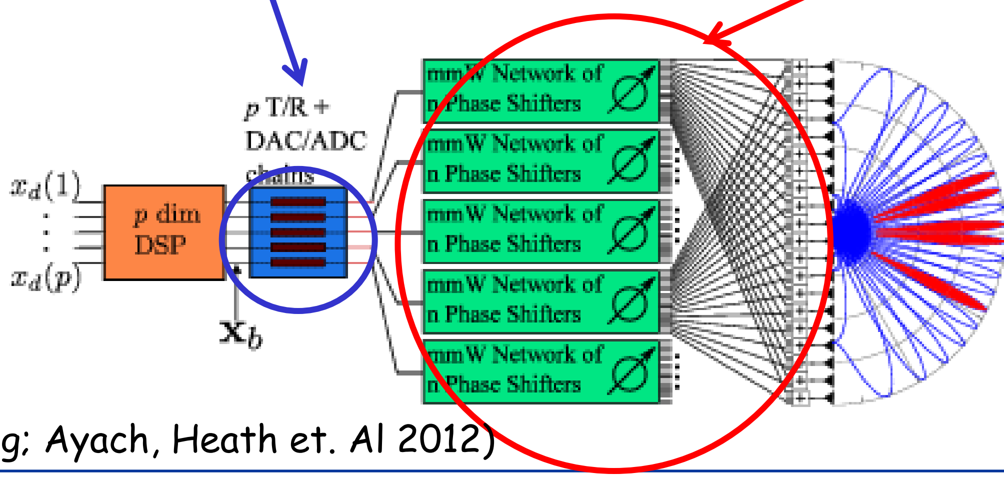
Lens
+
Beamspace Array
+
mmW Beam Selector Network

O(p) transceiver complexity

Multi-beam forming mechanism

Phased-Array Based Architecture:

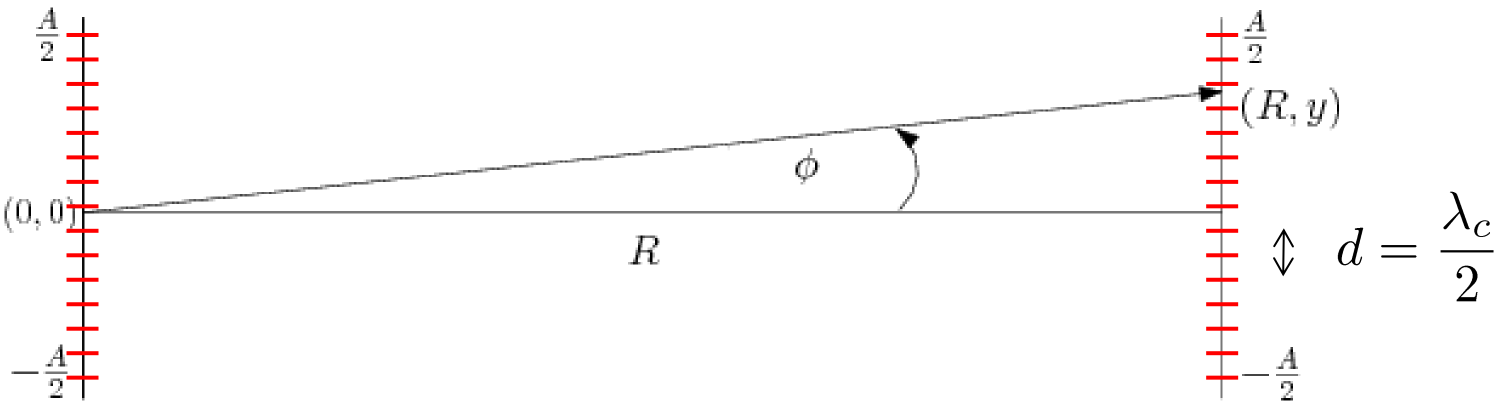




Phase Shifter Network (np)
+
Combiner Network

(e.g., Samsung; Ayach, Heath et. Al 2012)

Case Study: Line-of-Sight Link



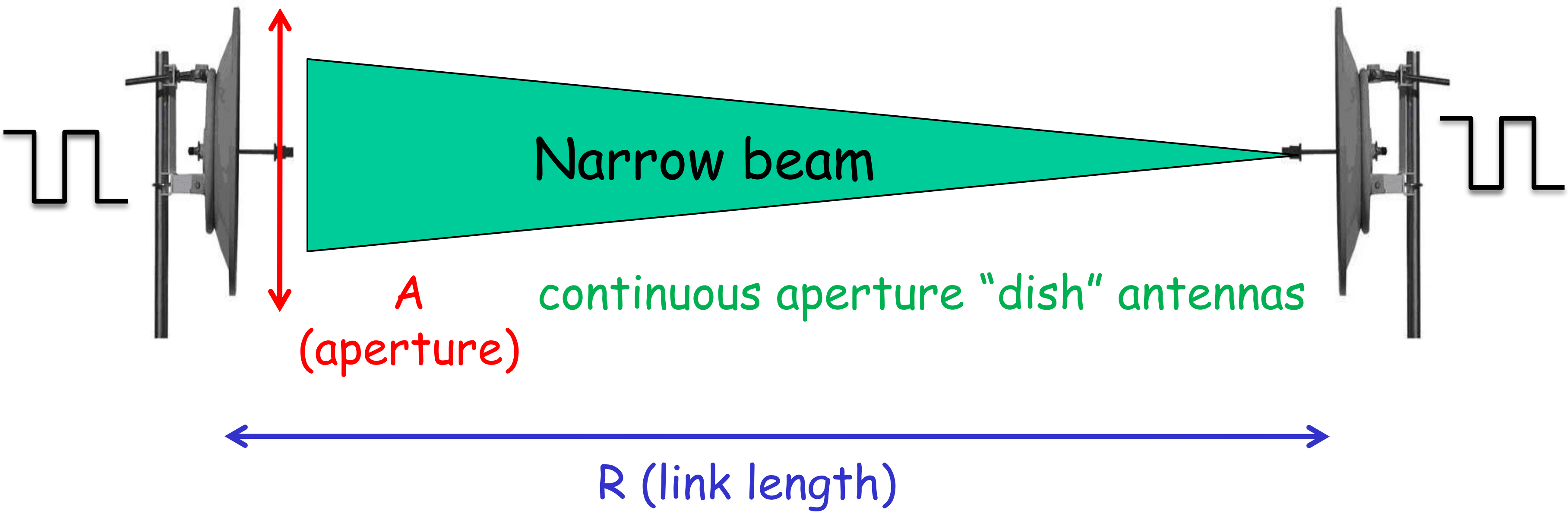
analog spatial modes: $n \approx \frac{A}{d} = \frac{2A}{\lambda_c}$ (~ antenna/array gain)

Critical sampling of aperture $\Longrightarrow n \times n$ MIMO system

Spatial domain representation: $\mathbf{r} = \mathbf{H}\mathbf{x} + \mathbf{w}$

Beamspace representation: $\mathbf{r}_b = \mathbf{H}_b\mathbf{x}_b + \mathbf{w}_b$

State-of-the-Art 1: DISH System



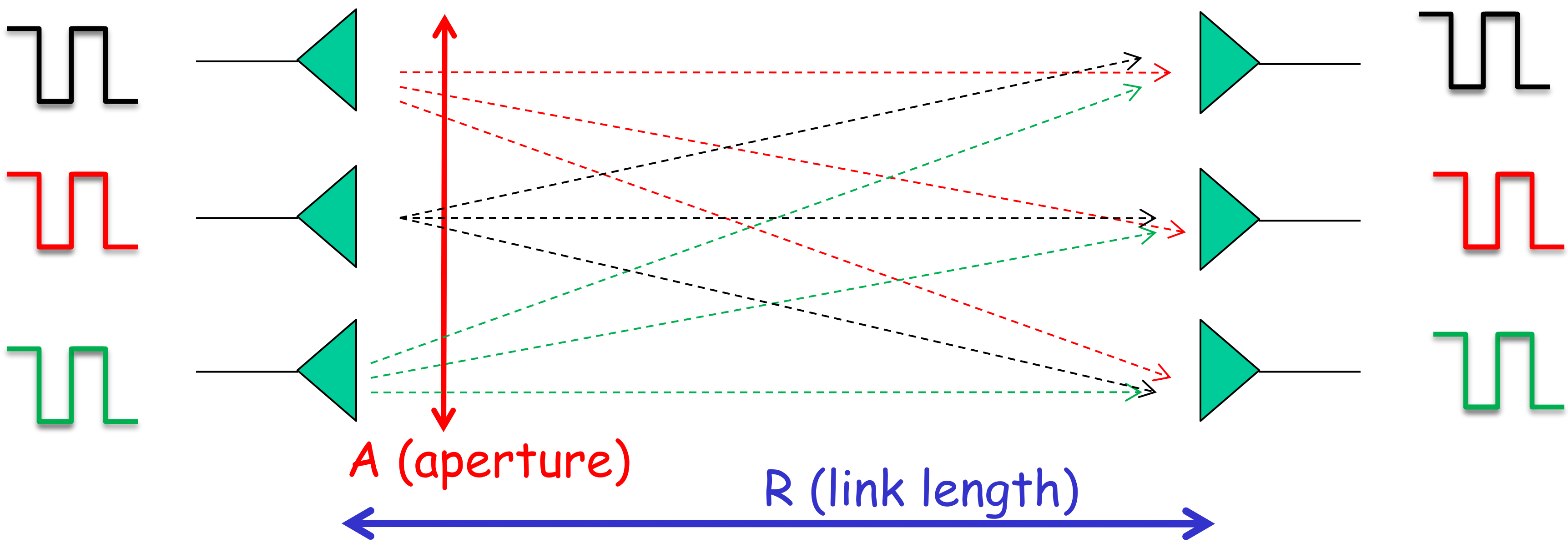
Pros: Large antenna gain (SNR gain) $G \propto \left(\frac{A}{\lambda}\right)^2$

Narrow beam (continuous aperture)

Cons: Single data stream

State-of-the-Art 2: MIMO System

Discrete Antenna Arrays (wide Rayleigh spacing)

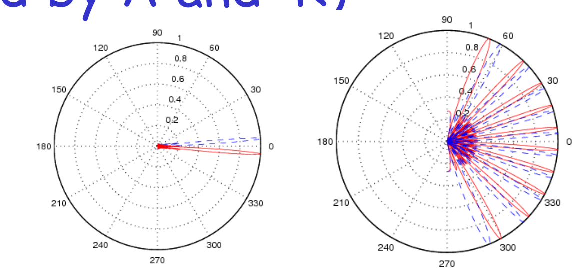


Pros: Multiplexing gain: Multiple (p) data streams

(p limited by A and R)

Cons: Reduced SNR gain

Grating lobes



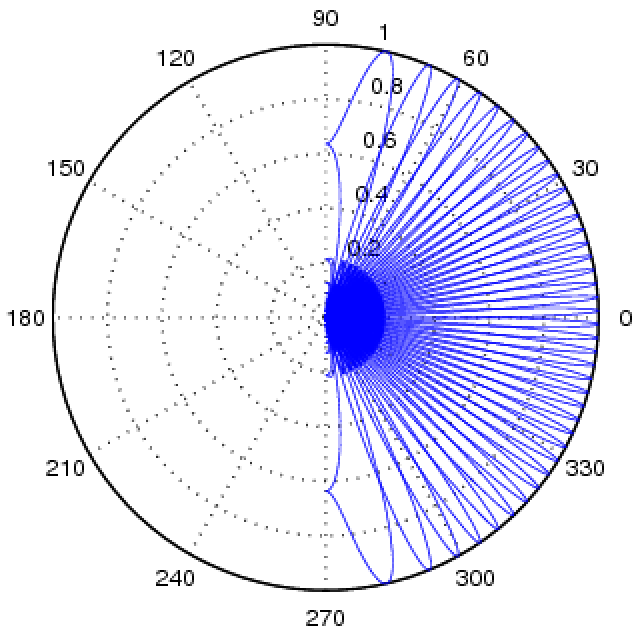
Madhow et. al. 06'

Bohagen et. al. 07'

Chalmers

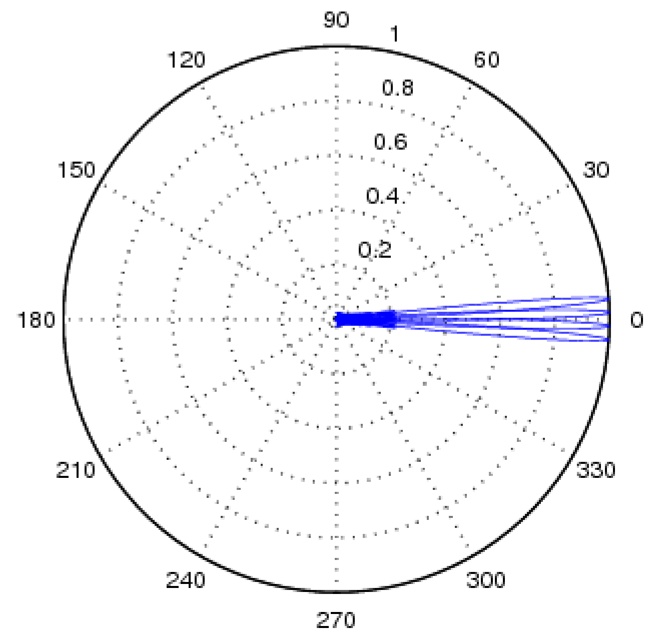
Beamspace MIMO: Coupled Orthogonal Beams

n = 40 orthogonal beams



Finite Receiver Aperture

$p_{max} = 4$ coupled beams



number of coupled beams:

(channel rank)

$$p_{max} = \frac{2\theta_{max}}{\Delta\theta_o} = 2\theta_{max} n = \frac{A^2}{R\lambda_c}$$

(Fresnel number)

Spatial BW: $2\theta_{max} = \sin(\phi_{max}) \approx \frac{A}{2R}$

Spatial Res.: $\Delta\theta_o = \frac{1}{n} = \frac{\lambda_c}{2A}$

Near-Optimality of Beamspace MIMO

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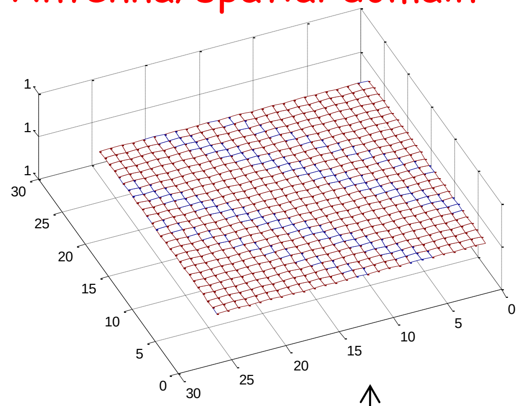
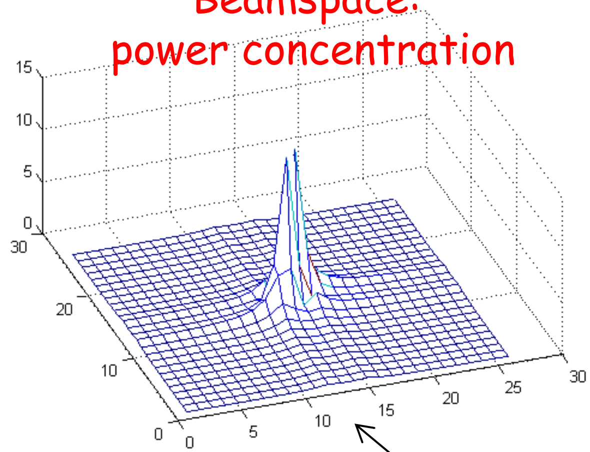
Coupled beams ~ channel eigenvectors

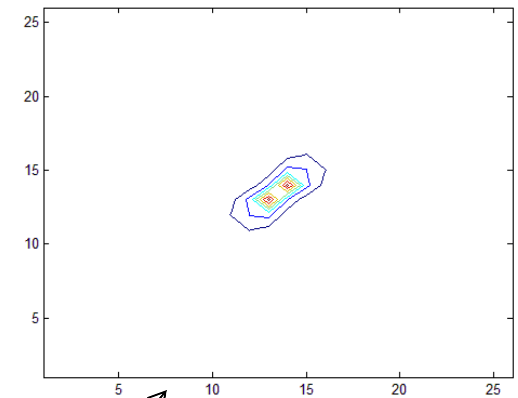
$n = 26;\ p_{max} = 2$

Antenna/spatial domain



Beamspace:
power concentration





$$\mathbf{H} = \mathbf{U}_n \mathbf{H}_b \mathbf{U}_n^H \iff \mathbf{H}_b = \mathbf{U}_n^H \mathbf{H} \mathbf{U}_n$$

$$\mathbf{H} = \mathbf{U}_n \mathbf{H}_b \mathbf{U}_n^H \approx \tilde{\mathbf{U}}_n (n \times p_{max}) \tilde{\mathbf{H}}_b (p_{max} \times p_{max}) \tilde{\mathbf{U}}_n^H (p_{max} \times n)$$

approx. eigenvectors (RX subspace) — approx. eigenvalues (diagonal) — approx. eigenvectors (TX subspace)

Subspace determination through beamspace thresholding!

Capacity Comparison with State of the Art

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Spectral Efficiency (bits/s/Hz)

CAP-MIMO:
Max. multiplexing gain & Max. SNR gain

$$C_{cap-mimo}(\rho) \approx p_{max} \log\left(1 + \rho \frac{n^2}{p_{max}^2}\right)$$

MUX gain over DISH: p_{max}

SNR gain over widely spaced MIMO: $G = \frac{n^2}{p_{max}^2}$

$$C_{dish}(\rho) \approx \log\left(1 + \rho \frac{n^2}{p_{max}}\right)$$

DISH
no multiplexing gain
Max. SNR gain

$$C_{mimo}(\rho) = p_{max} \log(1 + \rho)$$

Conv. (widely spaced) MIMO
Max. multiplexing gain
small SNR gain

Potential Gains: Backhaul and Indoor Links

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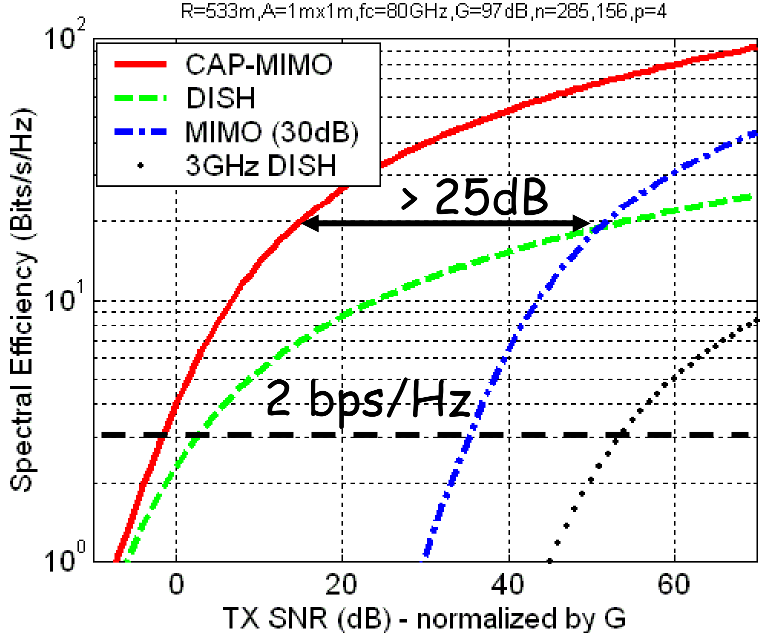
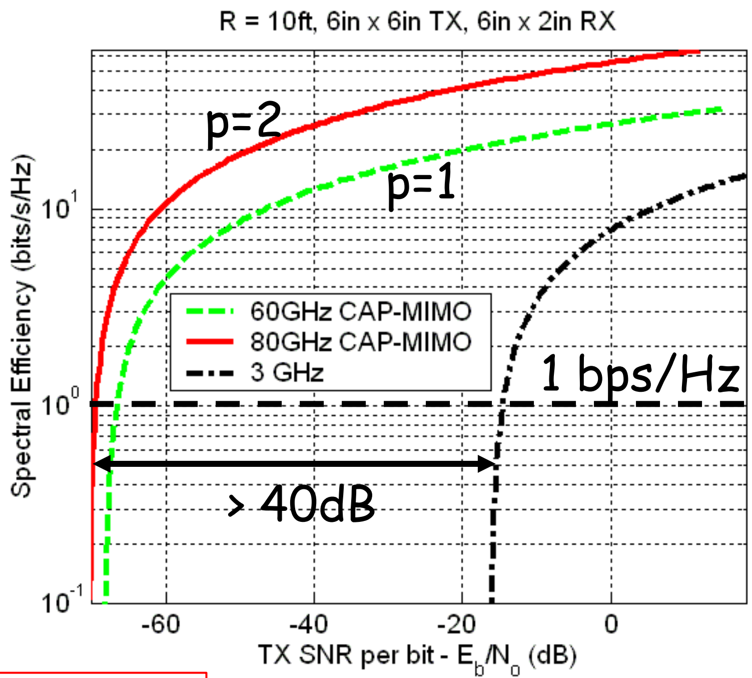
Longer (backhaul) link:
R=533m, A=1mx1m, 80GHz



Shorter (indoor) link:
R=10ft, TX: 6inx6in, RX: 6inx2in



$n \sim 300,000$

$G \sim 100\text{dB}$

$p = 4$

Spectral efficiency (bits/s/Hz):

$$C(\rho) \approx p \log\left(1 + \rho \frac{n^2}{p^2}\right)$$

ρ :SNR

n : spatial dimension

p: # data streams

3GHz

$n \sim 9,\ G \sim 15\text{dB}$

60GHz

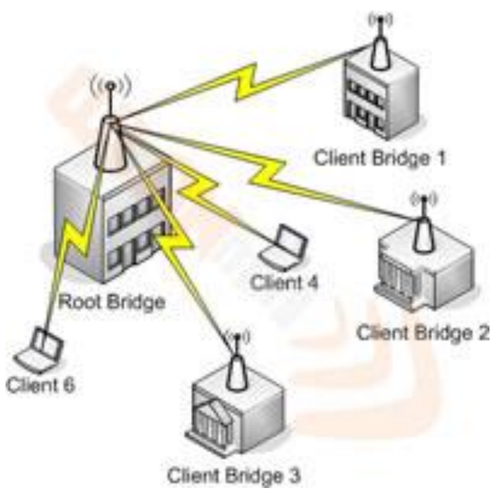
$n \sim 3000,\ G \sim 66\text{dB}$

80GHz

$n \sim 6000,\ G \sim 66\text{dB}$

Point-to-Multipoint Links

Fixed (backhaul) and dynamic (access) links



(Driverlayer.com)

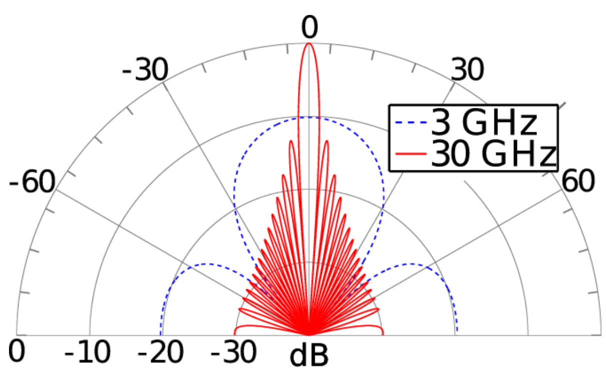
Downlink precoding: $\mathbf{r} = \mathbf{H}^H \mathbf{x} + \mathbf{w} = \mathbf{H}^H \mathbf{G} \mathbf{s} + \mathbf{w}$

Beamspace precoding: $\mathbf{r} = \mathbf{H}_b^H \mathbf{G}_b \mathbf{s}_b + \mathbf{w}$

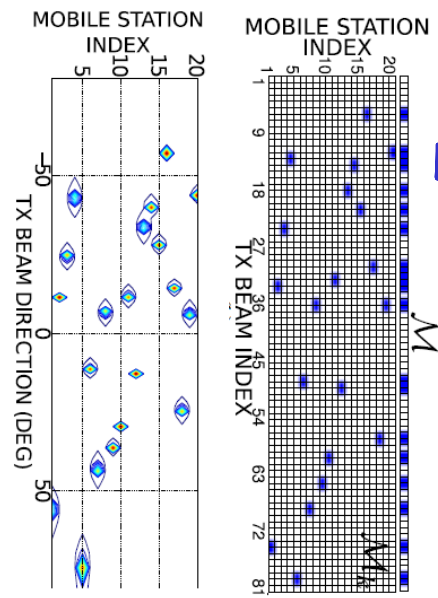
$$\mathbf{G}_b = \mathbf{U}_n^H \mathbf{G} = [\mathbf{g}_{b,1}, \mathbf{g}_{b,2}, \cdots, \mathbf{g}_{b,K}]$$

Multiuser channel: $\mathbf{H} = [\mathbf{h}_1, \cdots, \mathbf{h}_K]$, $\mathbf{h}_k = \beta_k \mathbf{a}_n(\theta_k)$

Beamspace channel: $\mathbf{H}_b = \mathbf{U}_n^H \mathbf{H} = [\mathbf{h}_{b,1}, \cdots, \mathbf{h}_{b,K}]$



Sparse Beamspace Channel



Lower-dimensional system

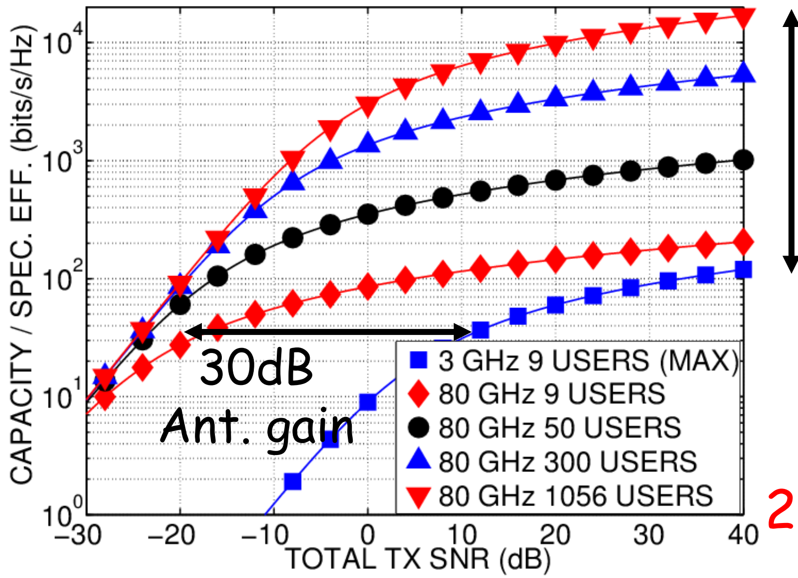
$$\mathbf{r} = \tilde{\mathbf{H}}_b^H \tilde{\mathbf{G}}_b \mathbf{s}_b + \mathbf{w}$$

$$\tilde{\mathbf{H}}_b = [\mathbf{H}_b(\ell, :)]_{\ell \in \mathcal{M}}$$

Dense Beamspace Multiplexing

Key application: small-cell access points

Idealized upper bound (non-interfering users) $C_{ub}(\rho, K, n) = K \log_2 \left(1 + \rho \frac{n}{K}\right)$

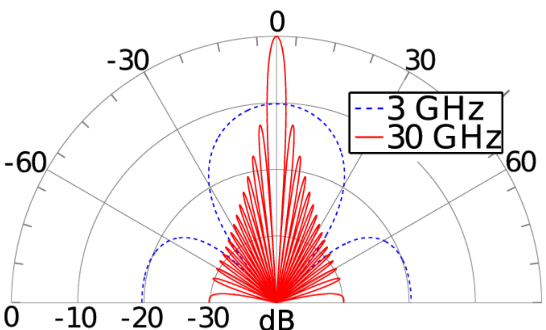


x 2-200 increase in capacity
due to beamspace multiplexing

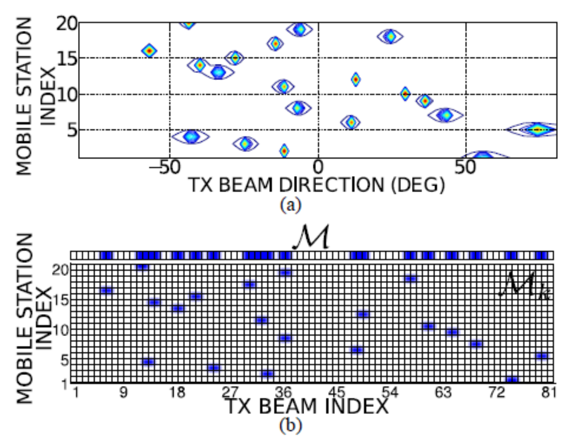
x 10-100 increase in capacity
due to extra bandwidth
(~1-10GHz vs 100MHz)

200Gbps-200Tbps (per cell throughput)
(20-200Gbps/user)

6" x 6" antenna

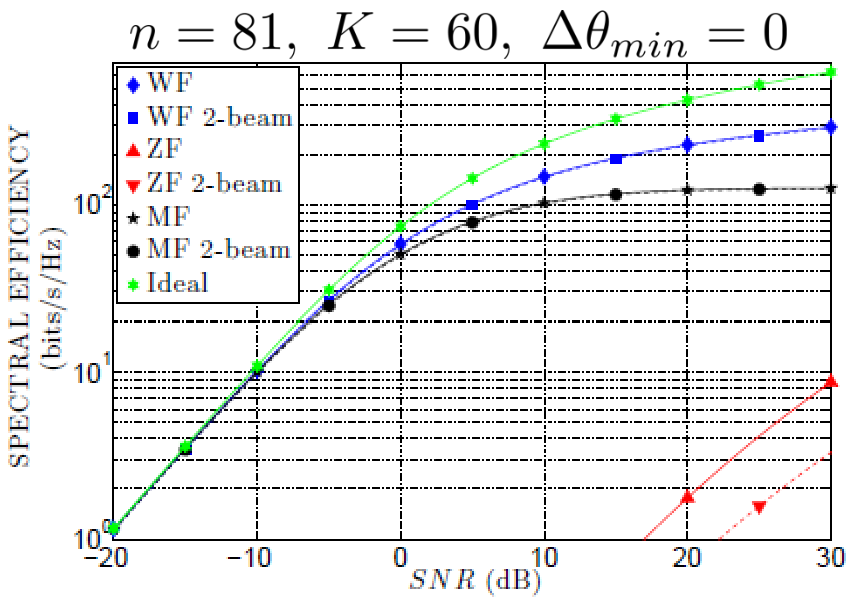


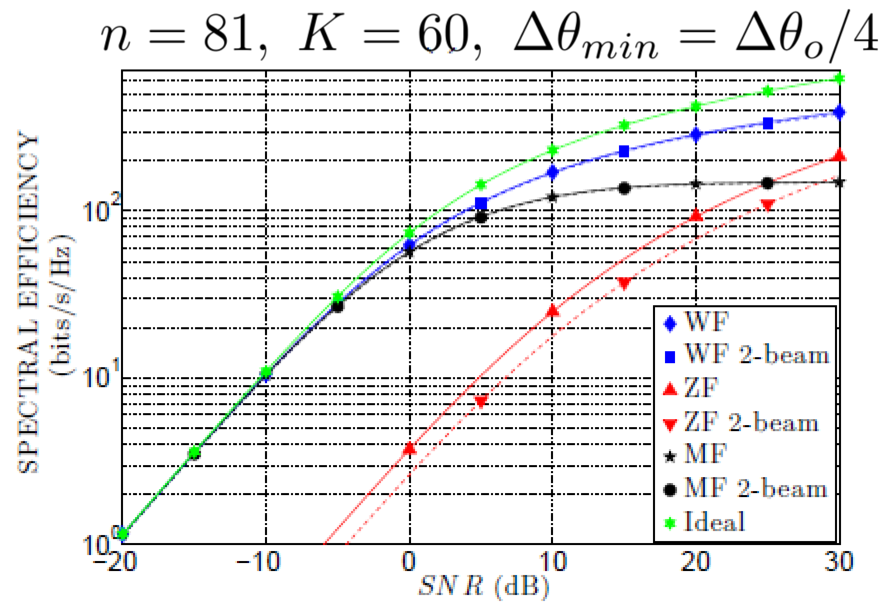
Beamspace
channel sparsity



(JB & AS '13; JB & AS '14)

Performance with Linear Precoding

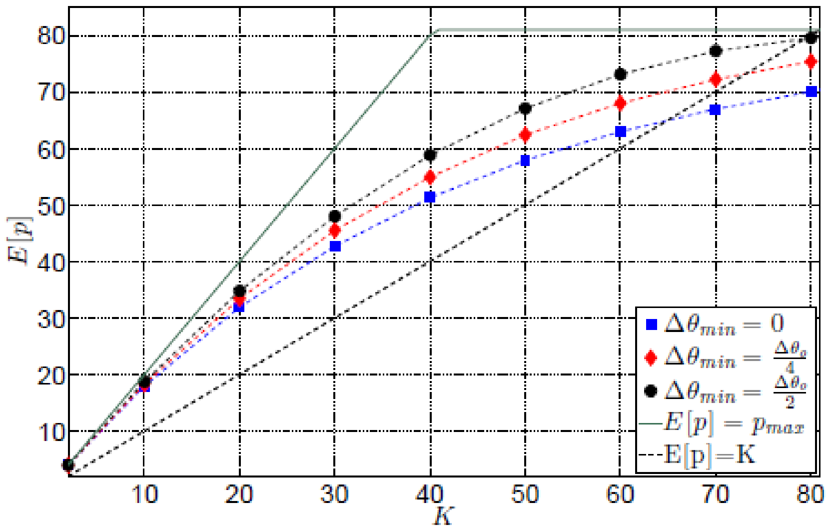




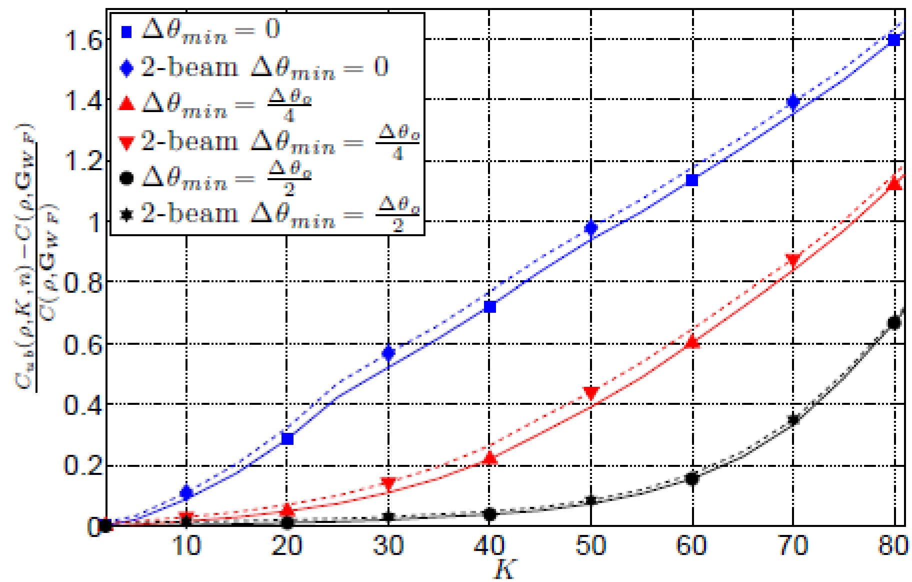
K = # users	Spectral Efficiency (bits/s/Hz)	Aggregate rate (Gbps)	Average per-user rate (Gbps)
$K = 20\ \Delta\theta_{min} = 0$	134	670	33.5
$K = 20\ \Delta\theta_{min} = \Delta\theta_o/4$	159	795	39.8
$K = 40\ \Delta\theta_{min} = 0$	192	960	24
$K = 40\ \Delta\theta_{min} = \Delta\theta_o/4$	243	1215	30.4
$K = 60\ \Delta\theta_{min} = 0$	226	1130	18.8
$K = 60\ \Delta\theta_{min} = \Delta\theta_o/4$	283	1415	23.6

(JB & AS Globecom 2013)

Number of Beams and Capacity Gap



Expected number of active beams
With 2-beam/user sparsity mask



Normalized capacity gap between the upper bound and the MMSE precoder (SNR =30dB)

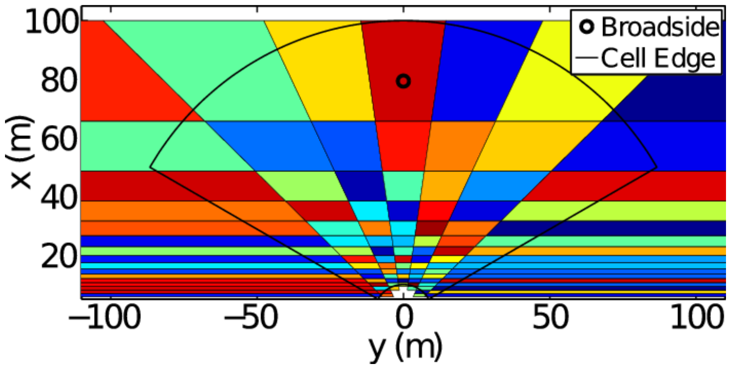
(JB & AS Globecom 2013)

(MMSE precoder:
Joham, Utschick, & Nossek 2005)

Small-Cell Design: 2D Beam Footprints

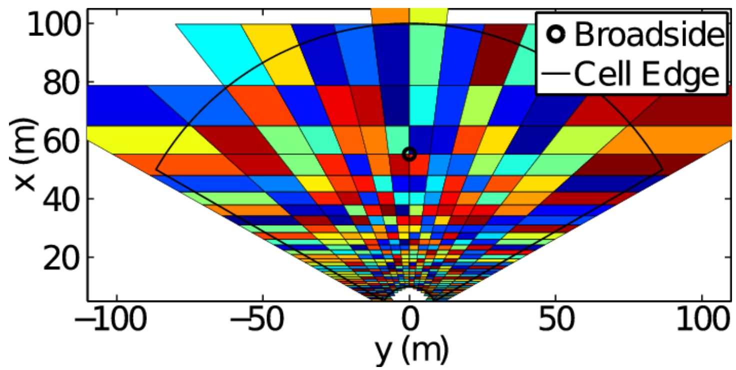
$p = K = 100$

0.45" x 2.8" antenna @ 80GHz



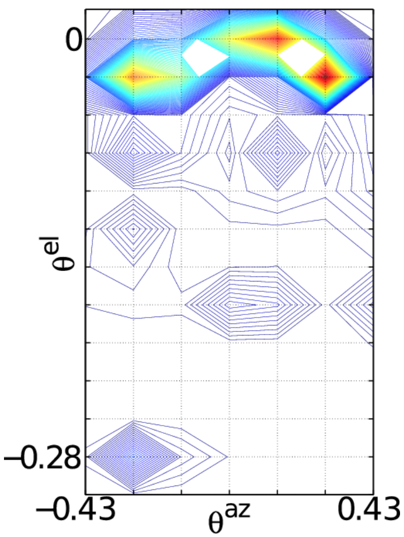
$p = 16K = 1600$

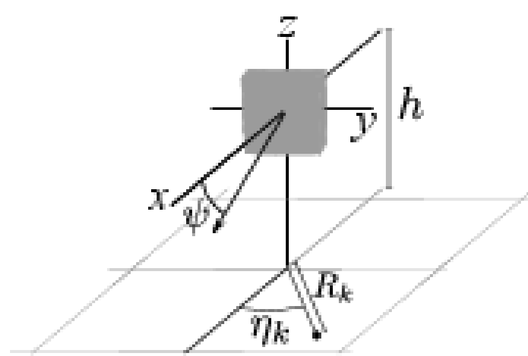
2.3" x 12" antenna @ 80GHz

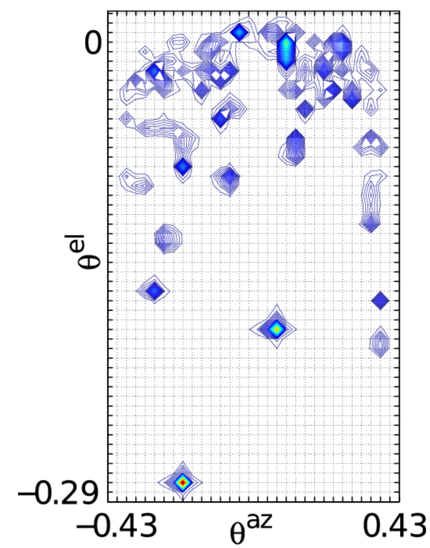


$n = 273 : \ (n_{az}, n_{el}) = (7, 39)$

$n = 5216 : \ (n_{az}, n_{el}) = (32, 163)$

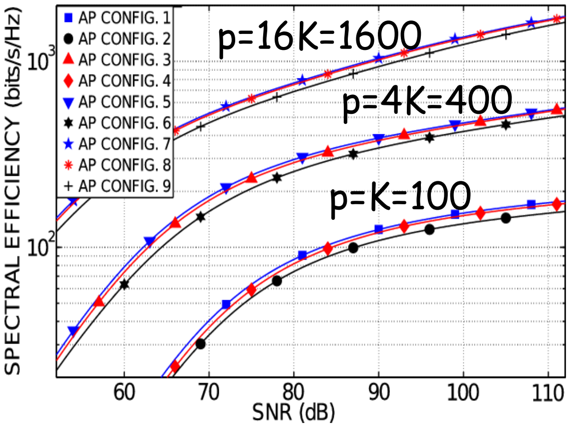


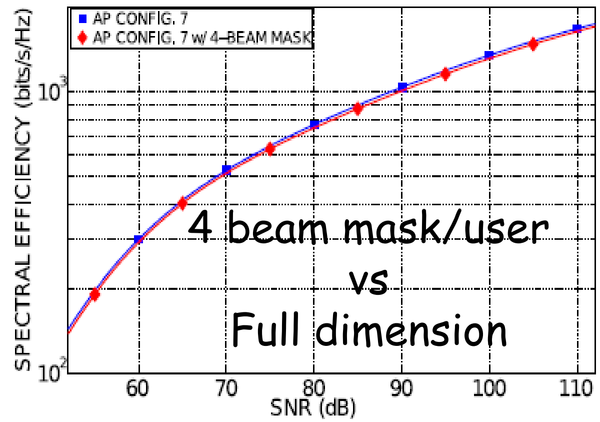




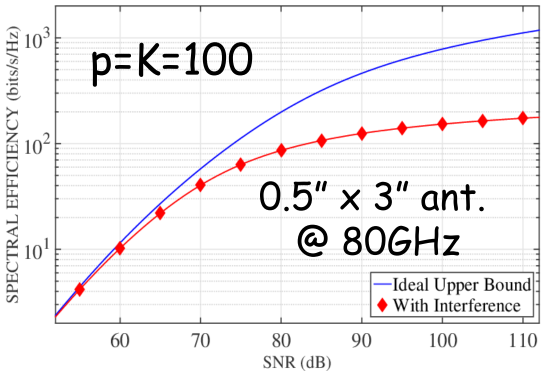
(JB & AS, SPAWC 2014)

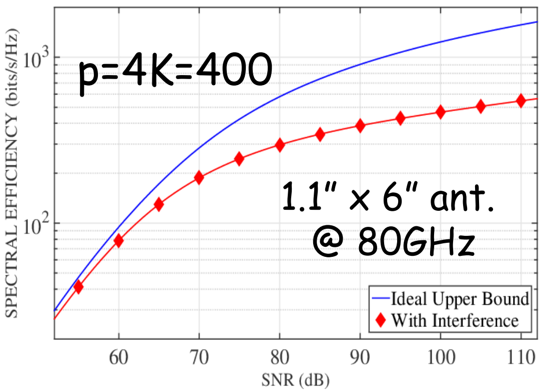
Performance of APs with 2D Arrays

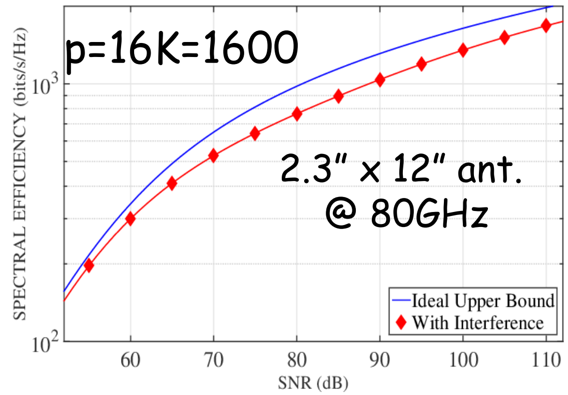




Upperbound vs MMSE precoder performance

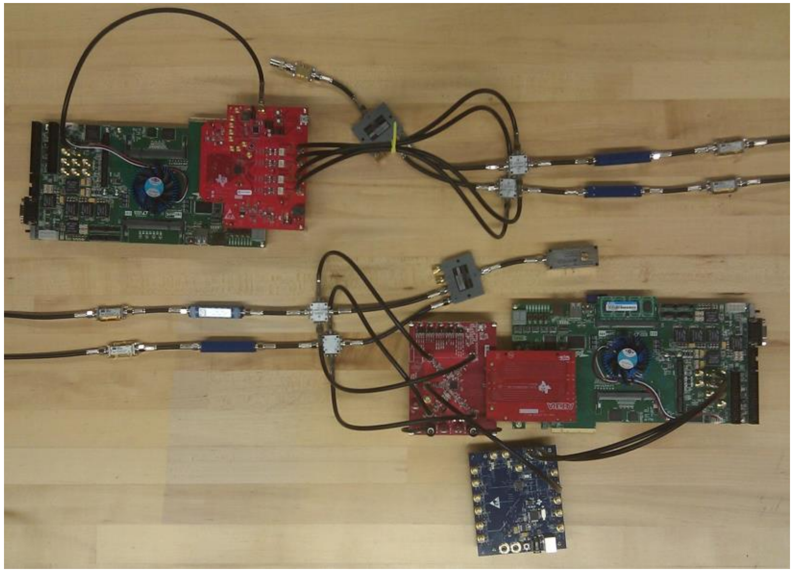


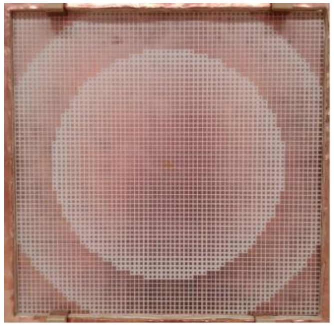




AP config.	$\psi(°)$	n_{az}	n_{el}	n	p	$\tilde{n}_{az}$	$\tilde{n}_{el}$	$\tilde{n}$	Array Size at 80 GHz
1	7.2	7	39	273	105	7	32	224	0.45"×2.81"
2	10.3	7	36	245	103	7	29	203	0.45"×2.58"
3	37	7	34	238	100	7	19	133	0.45"×2.44"
4	6.4	16	81	1296	408	15	66	990	1.11"×5.91"
5	10.3	16	76	1216	402	15	61	915	1.11"×5.54"
6	37	16	70	1120	404	16	39	624	1.11"×5.09"
7	6	32	163	5216	1610	29	138	4002	2.29"×11.96"
8	11.1	32	157	5024	1600	29	122	3538	2.29"×11.52"
9	37	32	151	4832	1614	31	81	2511	2.29"×11"

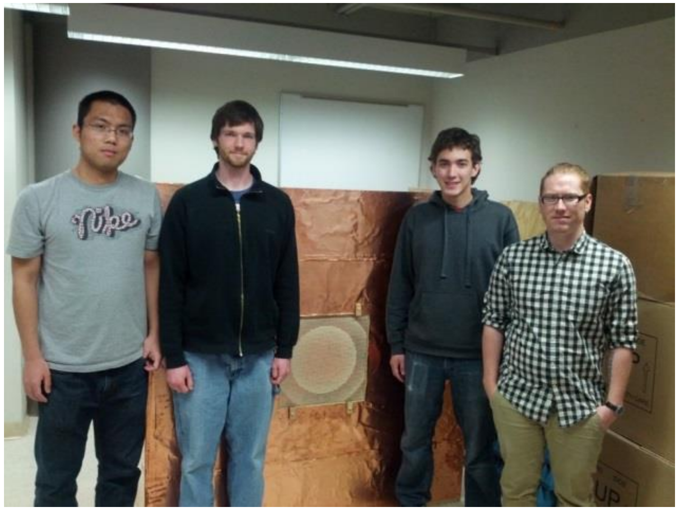
10GHz CAP-MIMO Prototype

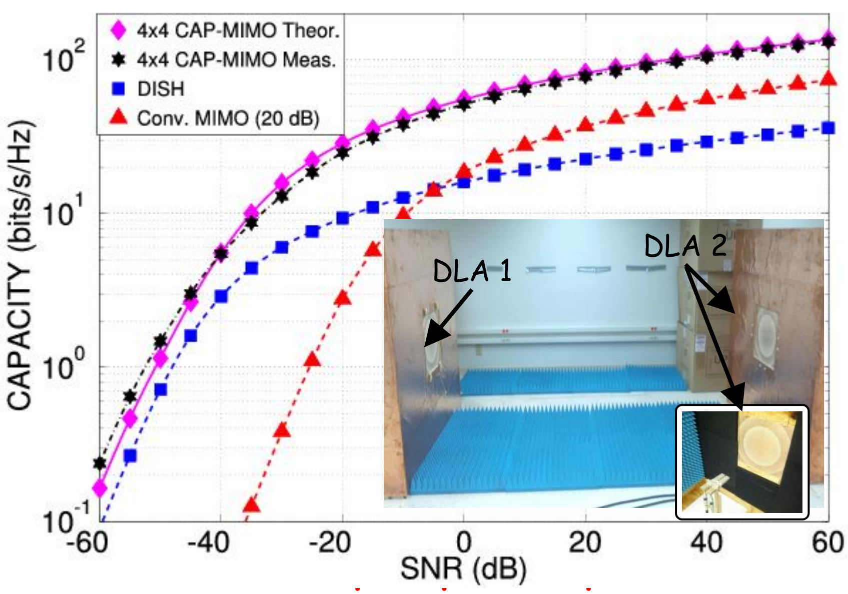




40cm x 40cm
DLA

R = 10ft,
n=676, p=4

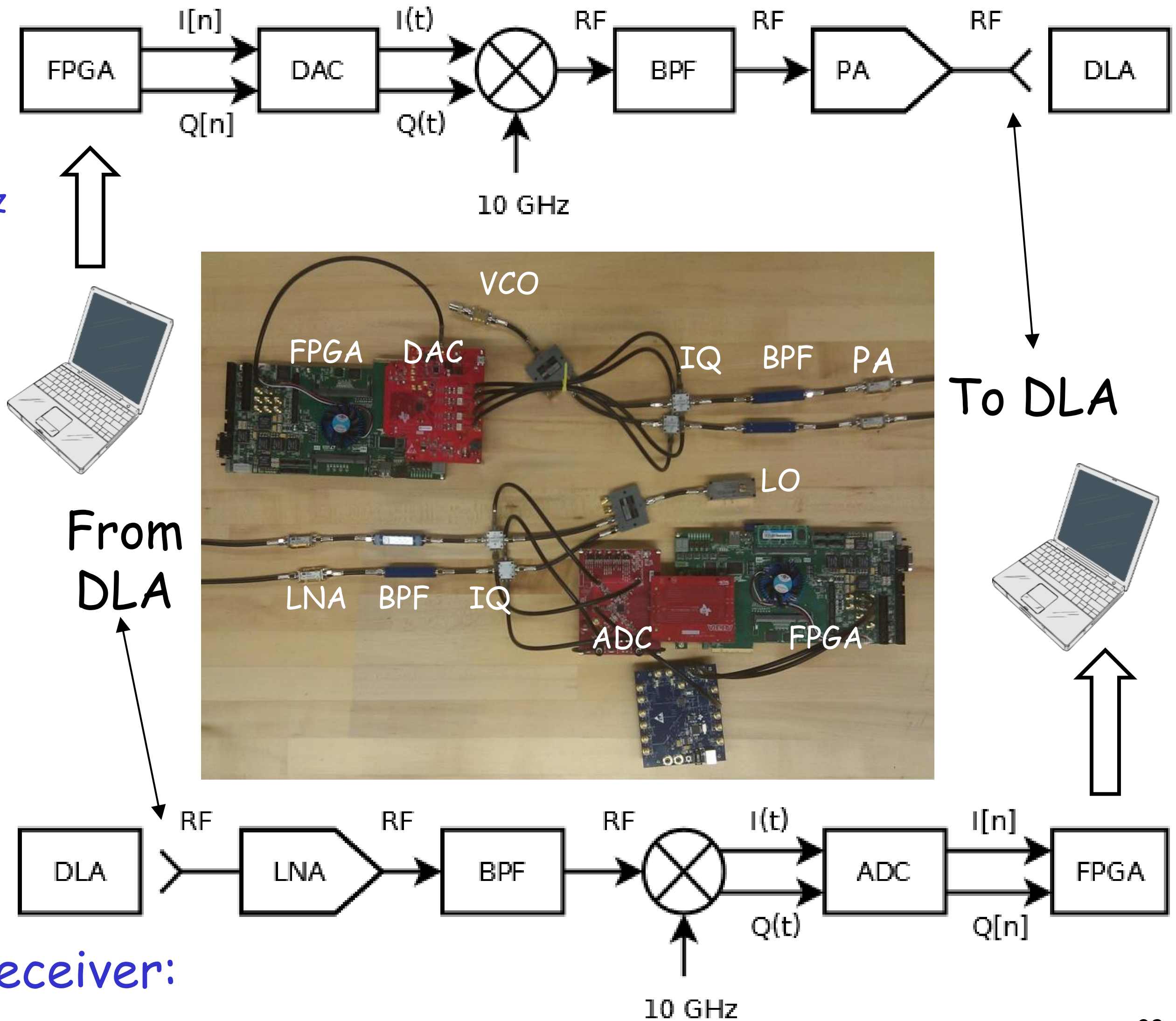




10 GHz prototype theoretical performance:
100 Gigabits/sec (1 GHz BW) at 20dB SNR
Compelling performance gains over state-of-the-art

Prototype TX/RX Hardware

Transmitter:

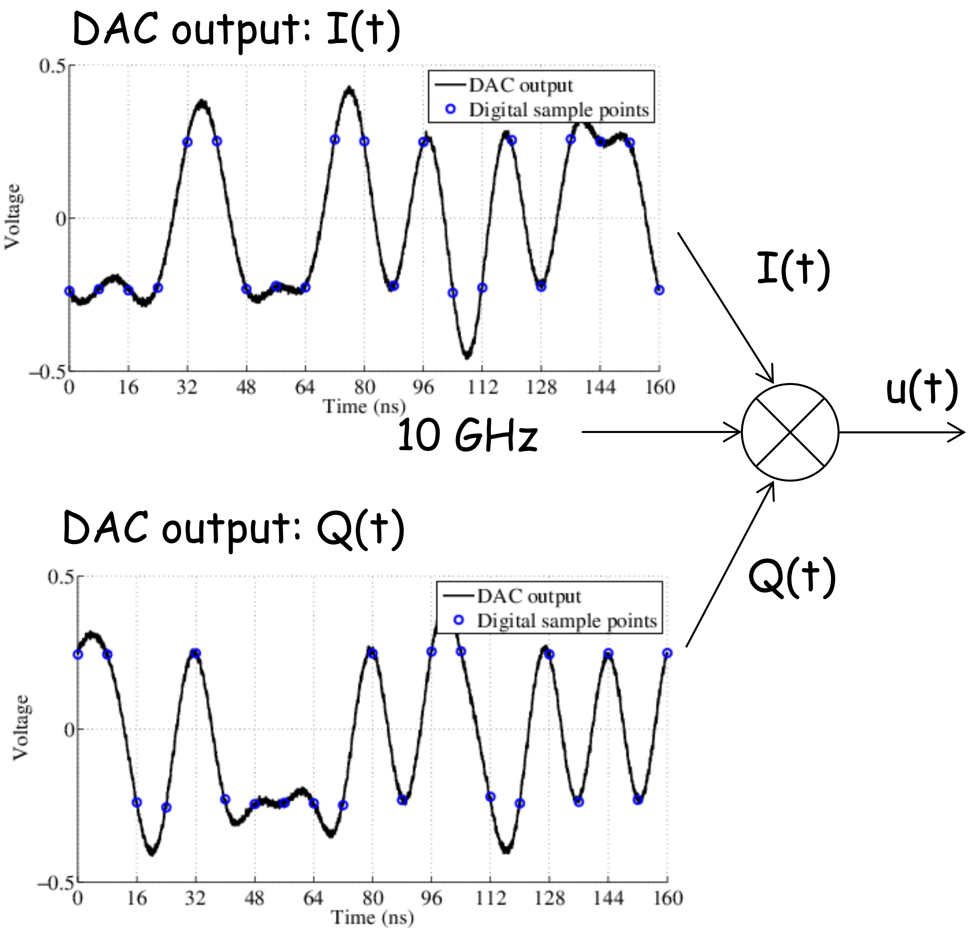


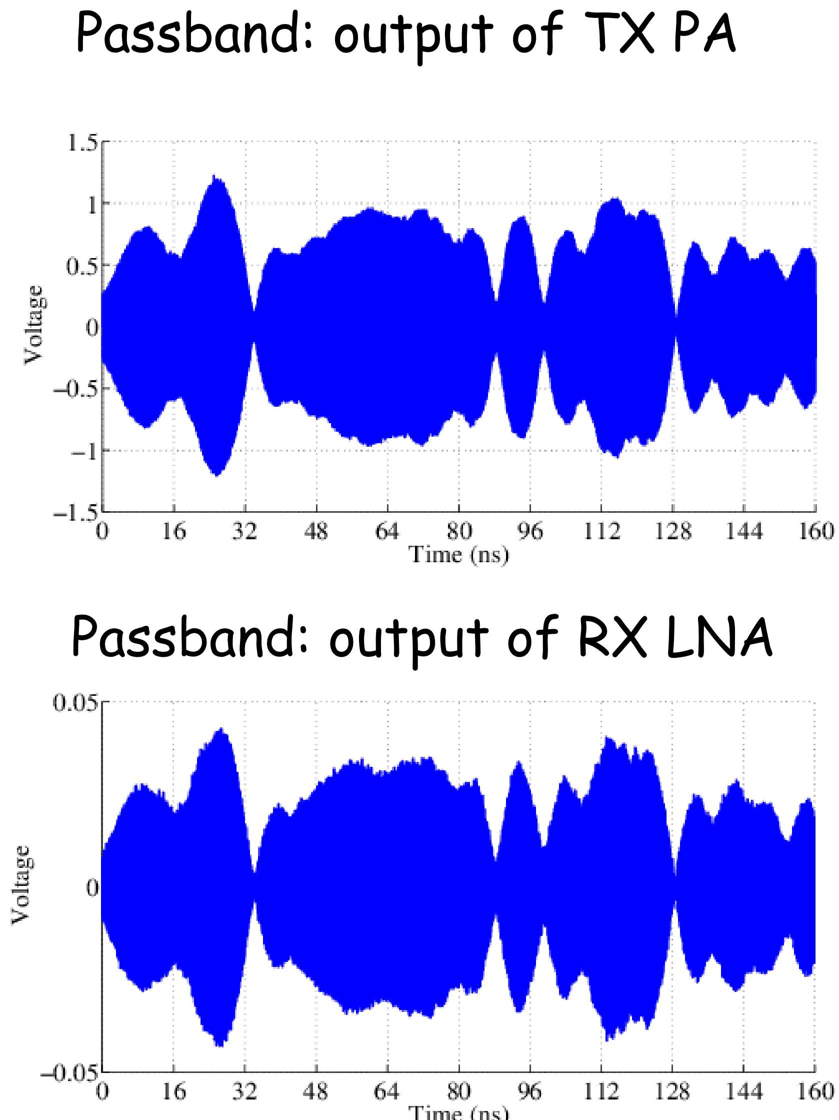
Receiver:

Prototype Specifications

- Operating frequency: 10 GHz
- Up to 4 spatial channels
- 125 MHz symbol rate
- 1 Gigabits/s with 4-QAM
- 8 bits/s/Hz spec. eff.
- TX-RX Clock/Oscillator options
  - Shared clock and oscillator
  - Separate clock or oscillator
  - Separate clock and oscillator

Baseband to Passband

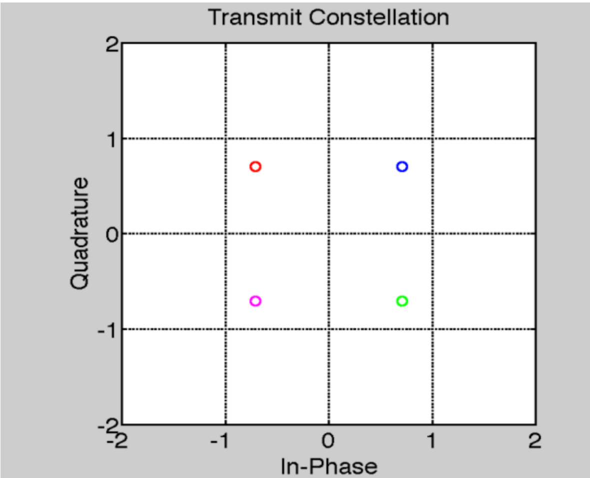




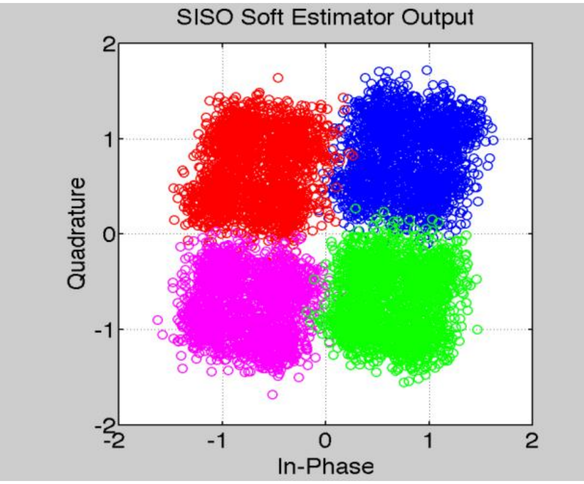
$$u(t) = I(t)\cos(2\pi f_c t) - Q(t)\sin(2\pi f_c t)$$

2x2 Spatial Multiplexing Test

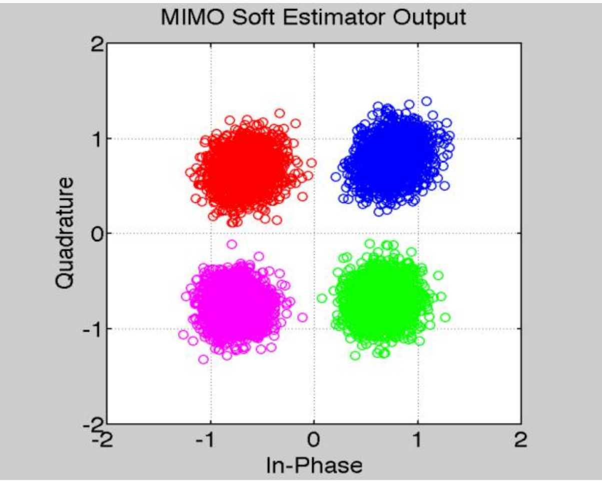
- 2 Spatial Channels
- Shared LO at TX and RX
- 500 Mbps data rate
- Separate TX and RX sample clocks



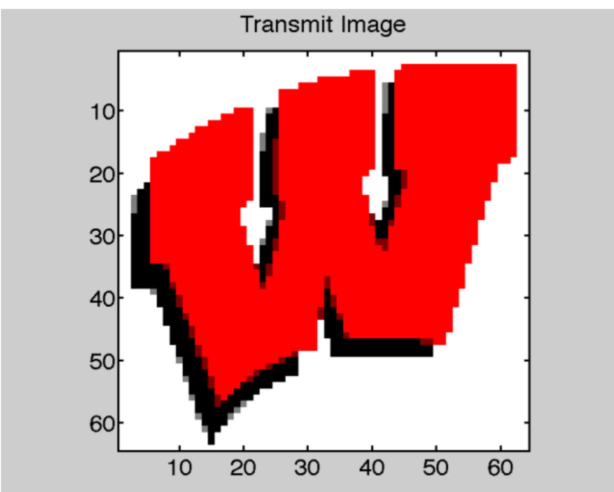
Transmitted 4-QAM Symbols



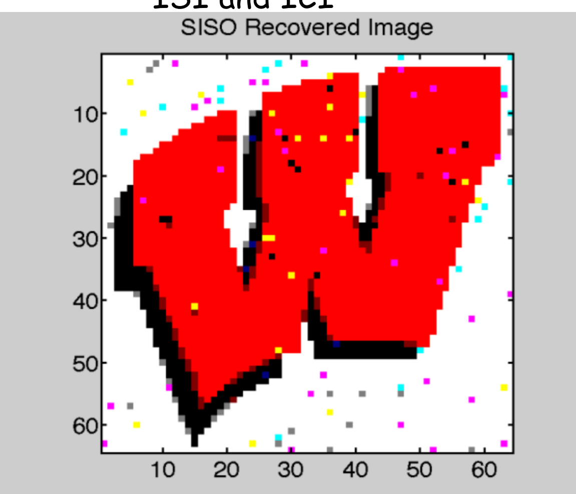
Channel 1 received symbols with ISI and ICI



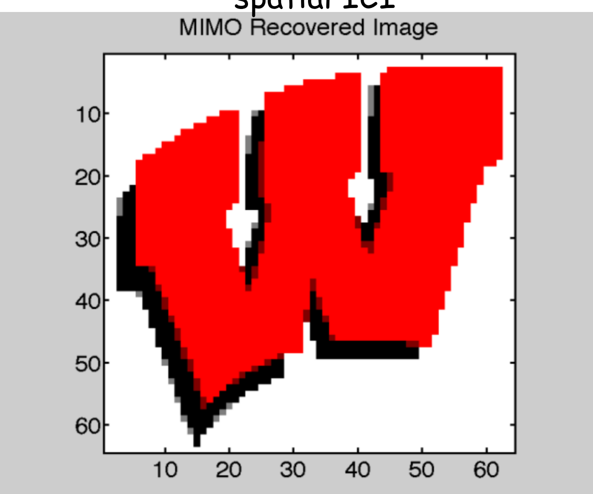
After MMSE MIMO processing to suppress spatial ICI



16 kbit test image



179 bit errors



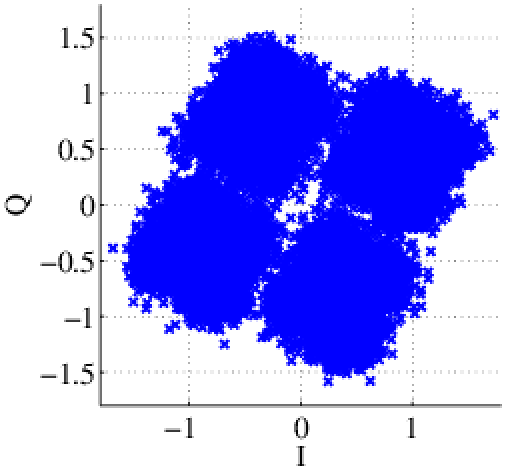
0 bit errors

Received Symbols: ICI vs ISI

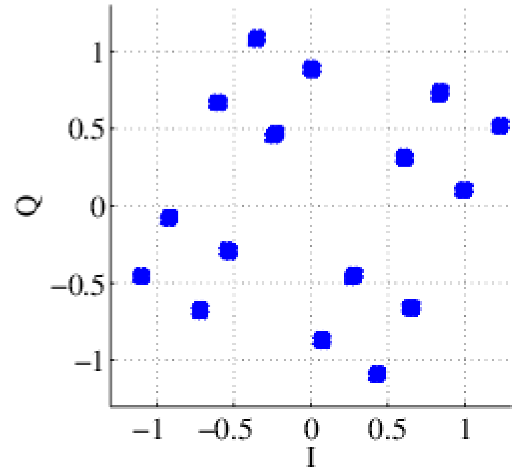
THE UNIVERSITY of WISCONSIN MADISON

ISI + ICI

Without Guard Interval

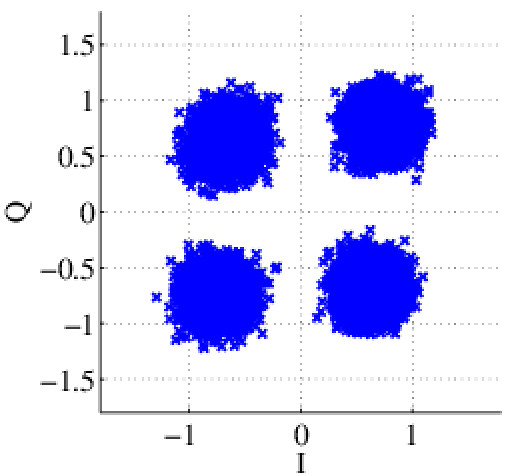


With Guard Interval (ICI only)

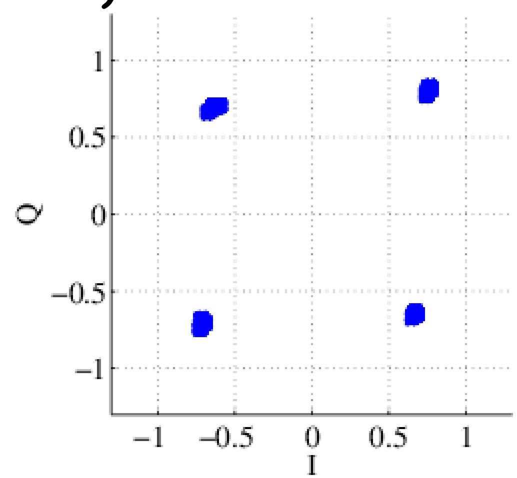


Suppressed ICI (MMSE Spatial Filter)

Without Guard Interval (ISI)

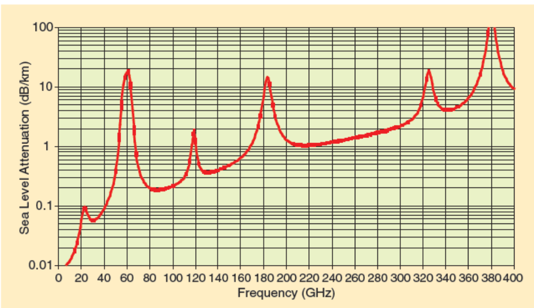


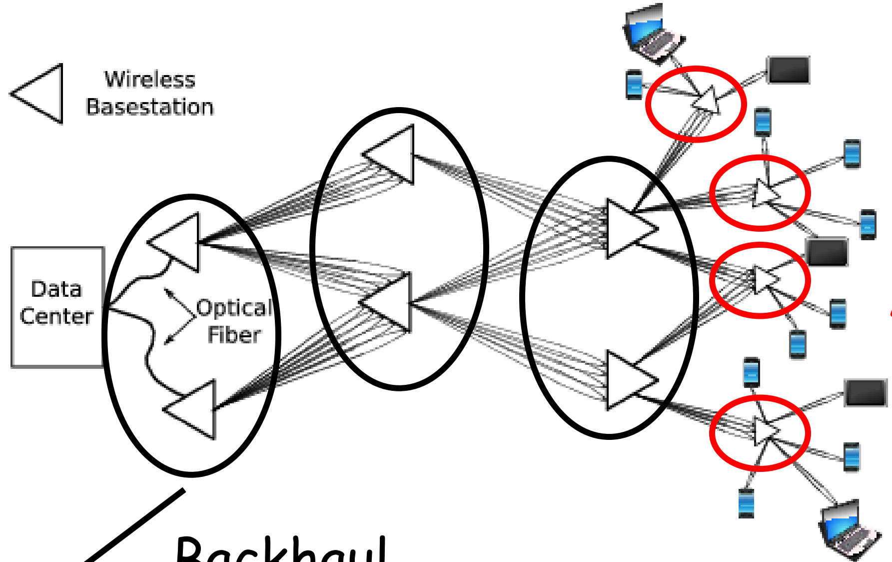
With Guard Interval (suppressed ISI & ICI)



Outlook: Multi-scale mmW MIMO Networks

Availability: Atmospheric absorption

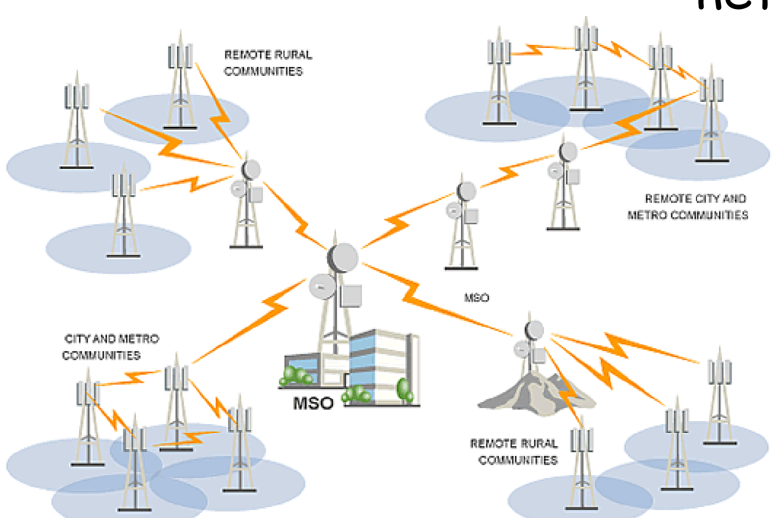




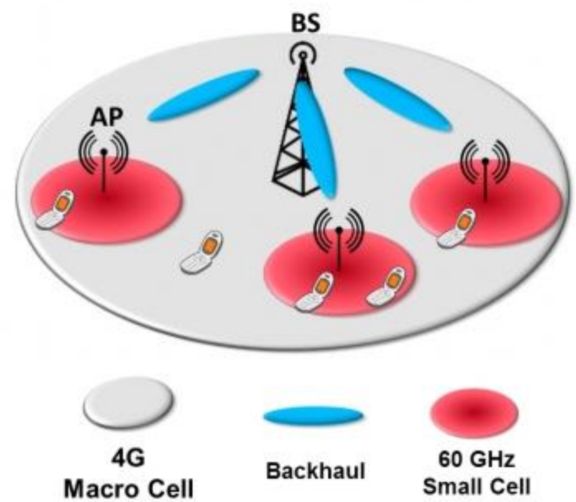
"small cell" Access Network

Multi-Gbps speeds

Backhaul network



(Source: 3G.co.uk)



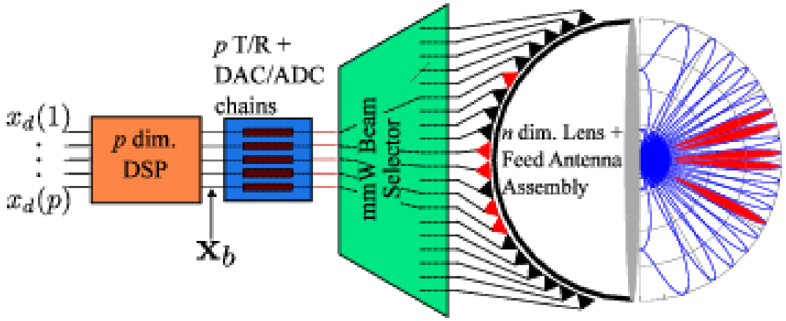
(siliconsemiconductor.net)

Going Forward

- Channel Estimation & Discovery
  - compressed sensing vs thresholding?
  - Analog subspace estimation
- Spatial Analog-Digital Interface
  - High symbol rates make DSP very power hungry
  - Move more processing into analog (mmW)?
- Wideband High-Dimensional MIMO
  - Need to revisit "narrowband" analysis
  - OFDM, SC, SC-FDMA … (limited selectivity)
- Electronic Multi-beam steering
- Channel Measurements (true beamspace)

Conclusion

- Optimal Beamspace MIMO Communication
  - Versatile theory & computational framework for system design & optimization
- CAP-MIMO: practical architecture
  - spatial A-D interface + DSP



Performance-complexity optimization

- Compelling advantages over the state-of-the-art
  - Capacity/SNR gains
  - Operational functionality
  - Electronic multi-beam steering & data multiplexing
- Timely applications (multi-Gigabits/s speeds)
  - Long-range wireless backhaul links; Indoor short-range links
  - Smart 5G Basestations: High-Gain Dense Beamspace Multiplexing
- Gen 2 prototype 28GHz – channel meas. + tech. transfer

Relevant Publications

- A. Sayeed, Deconstructing Multi-antenna Fading Channels, IEEE Trans. Signal Processing, Oct 2002
- A. Sayeed and N. Behdad, Continuous Aperture Phased MIMO: Basic Theory and Applications, Allerton Conference, Sep. 2010.
- J. Brady, N. Behdad, and A. Sayeed, Beamspace MIMO for Millimeter-Wave Communications: System Architecture, Modeling, Analysis, and Measurements, IEEE Trans. Antennas & Propagation, July 2013.
- G.-H Song, J. Brady, and A. Sayeed, Beamspace MIMO Transceivers for Low-Complexity and Near-Optimal Communication at mm-wave Frequencies, ICASSP 2013
- A. Sayeed and J. Brady, Beamspace MIMO for High-Dimensional Multiuser Communication at Millimeter-Wave Frequencies, IEEE Globecom, Dec. 2013.
- J. Brady and A. Sayeed, Beamspace MU-MIMO for High Density Small Cell Access at Millimeter-Wave Frequencies, IEEE SPAWC, June 2014.

Thank You!