Comments on FCC NOI 15-154 regarding mmW spectrum (>24GHz)

My comments are mainly limited to the antenna technology and corresponding beamspace MIMO (multiple input multiple output) transceiver architectures. They have been prepared a bit hastily given that we found out about NOI comment deadline a bit late (today!) – my apologies. Thus, I have also included a copy of a presentation on mmW MIMO transceiver architectures that I recently presented at a 5G workshop (http://wcsp.eng.usf.edu/5g/2014/) at the 2014 Globecom conference. I would be happy to answer any questions.

Akbar Sayeed
University of Wisconsin-Madison
December 16, 2014.

Comments:

Section III A.

17.

1. Yes, the work of the mmW community, including our own indicates that it will be feasible.
2. The main issue would be that of availability under harsh conditions, e.g., very heavy rain or snowfall. Even under such conditions mmW communication could work, albeit at much lower rates.
3. I think all these considerations will come into play. In particular, electronic multi-beam steering and data multiplexing (MBDM) capability is going to be a key functionality and the impact of various factors from the viewpoint of realizing this capability will be important.
4. Propagation characteristics from the viewpoint of coverage and availability.
5. The highly directional nature of propagation at mmW frequencies means that we can substantially control the interference to other devices using the same band.
6. These frequencies could be very relevant for sensing applications, e.g., automotive radar.
7. I think the electronic multi-beam steering and data multiplexing (MDBM) capability is a key operational characteristics of emerging mmW mobile systems, both from the viewpoint of enabling Gigabit mobile access and also from the viewpoint of minimizing in-band and adjacent-band interference.

1. Antenna Technology.

a. Base station antennas:

General comments.

Antenna technology is a key enabler for realizing the full potential of mmW mobile broadband technology. In particular, the electronic multi-beam steering and data multiplexing (MBDM) capability enables beamspace MIMO communication – multiplexing data streams in distinct beams. MIMO systems represent a particularly promising opportunity at mmW frequencies: high-dimensional MIMO

operation is possible with physically compact antennas due to small wavelengths. The large number of MIMO degrees of freedom can be exploited for a number of critical capabilities, including :

• *higher antenna or beamforming gain* for dramatically enhanced power efficiency;

• *higher spatial multiplexing gain* for dramatically enhanced spectral efficiency; and

• *highly directional communication with narrow beams* for dramatically enhanced spatial reuse.

However, despite the intensive MIMO research in the last fifteen years, conventional state-of-the-art approaches fall significantly short of harnessing these opportunities because of their failure to address fundamental *performance-complexity* tradeoffs inherent to high-dimensional MIMO systems. In particular, the hardware complexity of the mmW beamforming front-end and the software complexity of the back-end digital signal processing challenge the current paradigm and result in significant technology gaps that requires a fresh look at the design of the high-dimensional spatial analog-digital interface.

In an NSF-funded PFI-TT (Partnership for Innovation – Technology Translation) project, we are developing a prototype for a new wireless transceiver architecture – *Continuous Aperture Phased MIMO (CAP-MIMO)* – that combines the directivity gain of traditional antennas, the beam-steering capability of phased arrays, and the spatial multiplexing gain of MIMO systems to realize the multi-Gbps capacity potential of the mmW technology as well as the unprecedented operational functionality of dynamic multi-beam steering and data multiplexing. It is based on the concept of *beamspace MIMO communication* – multiplexing data into multiple orthogonal spatial beams – for optimally exploiting the spatial antenna dimension. The CAP-MIMO prototype leverages beamspace MIMO theory through two key translational elements for filling the technology gaps in realizing the full potential of mmWtechnology: i) *a lens-based front-end antenna for analog beamforming,* and ii) *a multi-beam selection architecture that enables joint hardware-software optimization of transceiver complexity*. As a result, CAP-MIMO promises significant advantages over current and emerging competing technologies, including:

• Significant improvements in data capacity, power efficiency, and operational functionality

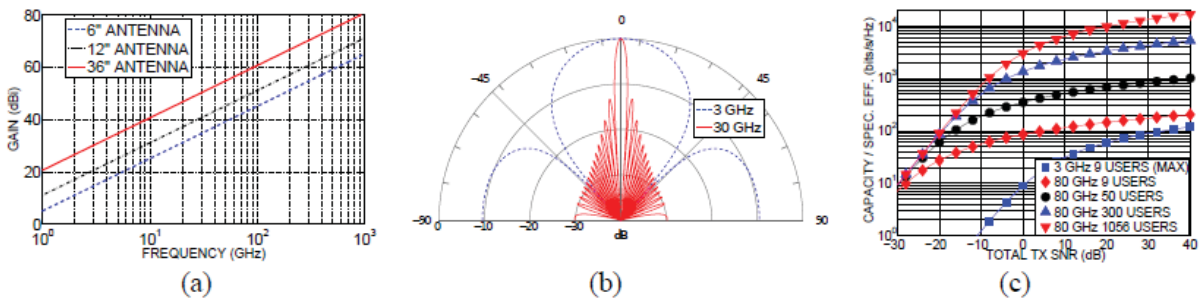
• Optimum performance with the lowest transceiver complexity - number of transmit/receive (T/R) modules or transceiver chains and digital signal processing (DSP) complexity.

CAP-MIMO also offers a broad application footprint due a number of advanced operational capabilities:

• Point-to-point (P2P) and point-to-multipoint (P2MP) network operation

• Operation in Line-of-sight (LoS) and/or multipath (MP) propagation conditions

• Beam agility (BA) and electronic multi-beam steering and data multiplexing (MBDM) for channel discovery and alignment and for creating dynamic mobile P2MP links.



(a) (b) (c)

Figure 1: *(a): Antenna gain vs. frequency. (b): Antenna beampatterns for a 6" antenna at 3GHz vs. 30GHz. (c): Potential spectral efficiency gains due to spatial multiplexing at 80GHz vs. 3GHz with a 6" antenna.*

Fig. 1 illustrates the potential of beamspace CAP-MIMO transceivers for exploiting the large number of *spatial degrees of freedom* at mmWfrequencies. The large *antenna directivity gains* shown in Fig. 1(a) more than offset the increased path loss and atmospheric absorption at mmW frequencies, and result in higher power efficiency compared to lower frequencies. The extremely *narrow beamwidths* at mmW frequencies, illustrated in Fig. 1(b), offer dramatically enhanced spatial reuse through *dense spatial multiplexing*: the spectrum resources can be reused across distinct and narrow beams. The resulting spatial multiplexing gain promises unprecedented gains in spectral efficiency illustrated in Fig. 1(c). Fig. 1(c) shows idealized spectral efficiency (b/s/Hz) upper bounds for downlink communication from an access point (AP) with a 6"x6" antenna: while at 3GHz a maximum of 9 users can be spatially multiplexed, at 80GHz orders-of-magnitude improvements are possible in signal-to-noise ratio (SNR) due to antenna gain, and in spectral efficiency due to spatial multiplexing gain. These gains in power and spectral efficiency, coupled with with larger available bandwidths, promise very large gains in overall network throughtput. Indeed, 100-10,000 Gbps aggregate rates, over 100-300 users, seem attainable with the 1-10GHz of available mmW bandwidth. In contrast, much lower aggregates rates of 30-50Gb/s, over a maximum of 9 users, are possible with 300-500MHz of potential bandwidth at 3GHz. Furthermore, the required total transmit (TX) SNR at 3GHHz is about 30dB higher than that at 80GHz.

Item 19. We think that the CAP-MIMO transceiver architecture which uses a lens-based front-end for analog multi-beamforming is the most attractive architecture for achieving dense spatial multiplexing (dense spatial reuse) at base stations. CAP-MIMO is compared with the two main competing transceiver architectures in Fig. 3 below.

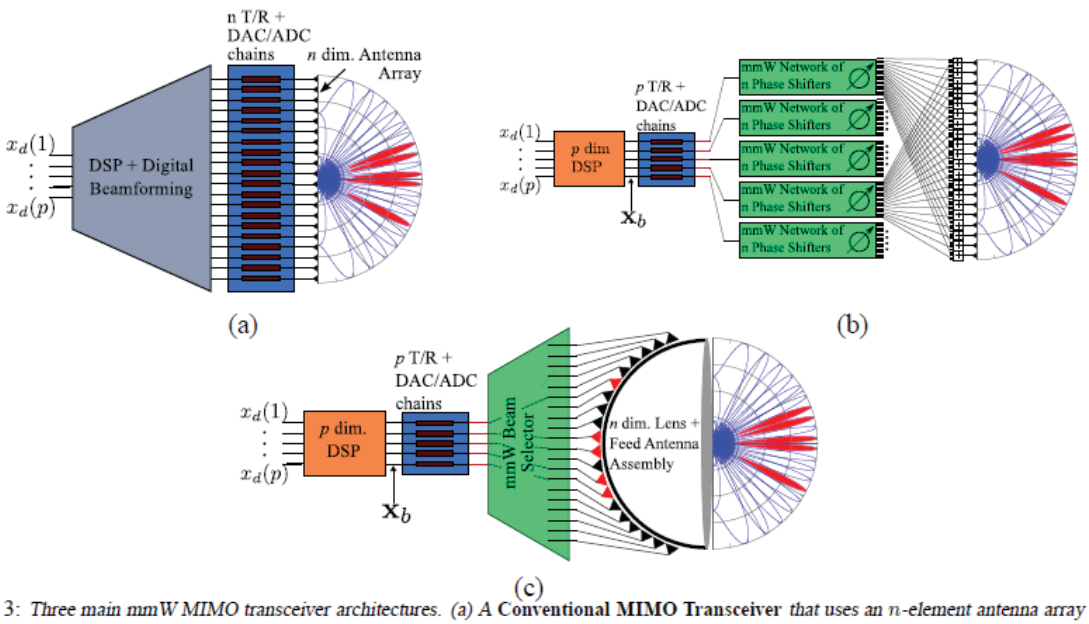


Figure 3: *Three main mmW MIMO transceiver architectures. (a) A* **Conventional MIMO Transceiver** *that uses an n-element antenna array and baseband* **Digital Beamforming**. *(b) A* **Phased-Array-Based Transceiver** *that uses a network of n-element* mmW phased shifters, *one for each of the p data streams, to drive the n-element antenna array for generating p beams. (c) The proposed* **CAP-MIMO Transceiver** *that uses Lens-Based* **Analog Beamforming** *to directly map the p data streams to $O(p)$ beams via the* **mmW Beam Selector**.

In conventional MIMO with digital beamforming, an antenna array with a larger number of elements is used, where each antenna has its own transceiver chain (T/R) consisting of a power amplifier, mixer, filter, ADC/DAC etc. This leads to a very high complexity since the number of antennas, say n, is very large; e.g., n=6400 for a 6” x 6” antenna aperture with half-wavelength spaced antennas at 80GHz. On the other hand, the number of users/data streams, say p, is small, on the order of 10-100. In CAP-MIMO, different beams are excited by feed antennas on the focal surface of the antenna (Fig. 3 c) – the number of active antenna is on the order of p and so is the number of T/R chains to drive them. In phased-array-based designs, a network of n phase shifters is associated with each beam/data stream. Thus, in total a network of np phase shifters is needed for p data streams. This complexity becomes challenging as p gets large.

Item 20. We think that mmW basestations could be used for both mobile access (small cells – 100m-200m radius) as well as for longer range backhaul networks. Thus, potentially both low-power and high-power base stations may be used. In CAP-MIMO technology the number of power amplifiers (PA’s) will track the number of users/beams rather than the effective number of antennas. Each PA will drive a particular beamspace feed antennas (Fig. 3c).

Item 21. In CAP-MIMO technology the EIRP will be managed by controlling the power associated with a few (1-4) feed antenna associated with a high-gain beam. In contrast, in a phased-array-based design, all array elements will have to be sufficiently phase-coherent to yield the desired antenna gain (a challenging propoposition for large number of effective antennas). We think a 120 degree sector in azimuth is sufficient. The elevation sector will be determined by the height of the base-station and the size of the cell.

Item 22. The main consideration of the base-station antenna will be the size of the coverage area that will determine the aperture of the antenna and the number of feed antennas. Thus, this could be different for indoor versus outdoor configurations. The orientation of handset is important. In particular, occlusion of the line-of-sight component is a challenge. In this case either multipath beams can be exploited opportunistically or coordination across multiple base-station antennas may be used.

b. **Mobile station antennas.** Phased-arrays or lens arrays may be used at handsets.

c. **Operation**. Exact solutions to items 27,28,29 remain to be determined but are doable. A key operational functionality would be "network channel discovery, tracking, and management". Coordination across multiple base stations may be needed, for managing interference and occlusions. Multipath will be handled as part of dealing with frequency selectivity.

2. Bandwidth, Duplexing, Modulation, and Multiple Access.

The solutions to Items 30, 31, 32, 33 remain to be developed but we think while TDD is attractive from the viewpoint of downlink/uplink duality, due to sparse multipath FDD may also be possible. Bandwidth aggregation may also be feasible but available of contiguous frequencies would be useful initially. Similarly, we also think that the initial deployments will have the simplest functional modulation and coding schemes, in the spirit of being a truly disruptive technology. Any of the multiple access technologies could be used. However, the use of OFDM remains to be seen due to the large number of carriers. Single carrier options seem more attractive, especially due to limited frequency selectivity.

Millimeter-Wave MIMO Architectures for 5G Gigabit Wireless

GLOBECOM Workshop on
Emerging Technologies for 5G Wireless Cellular Networks
December 8, 2014

Akbar M. Sayeed
Wireless Communications and Sensing Laboratory
Electrical and Computer Engineering
University of Wisconsin-Madison
http://dune.ece.wisc.edu

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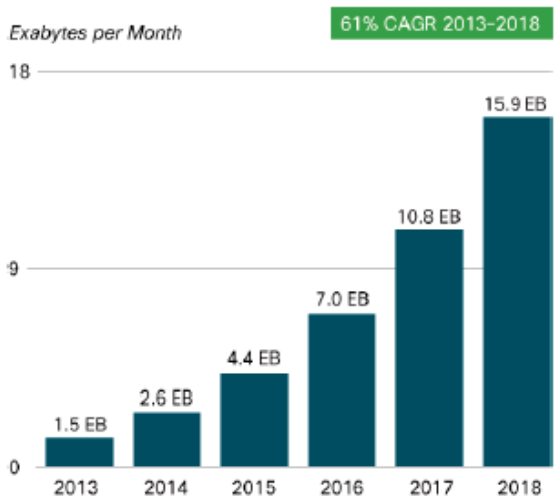
Explosive Growth in Wireless Traffic

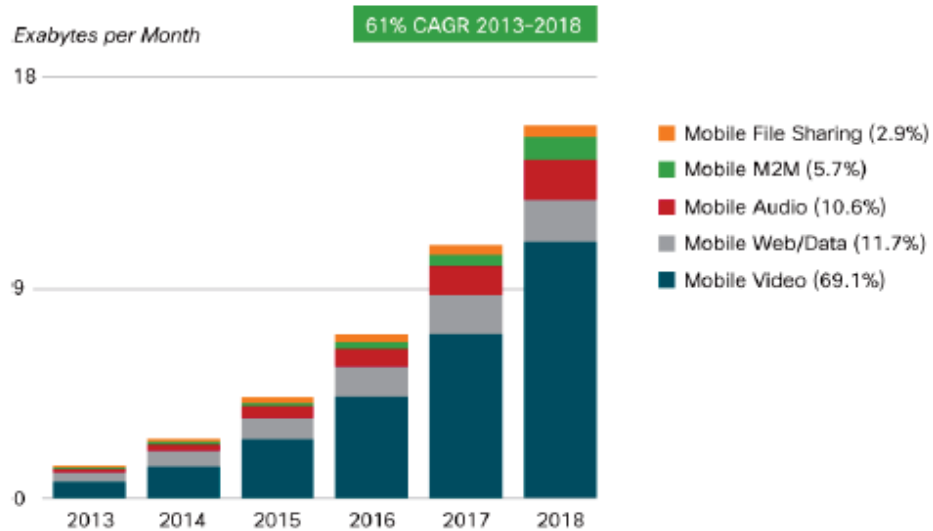
Figure 1. Cisco Forecasts 15.9 Exabytes per Month of Mobile Data Traffic by 2018



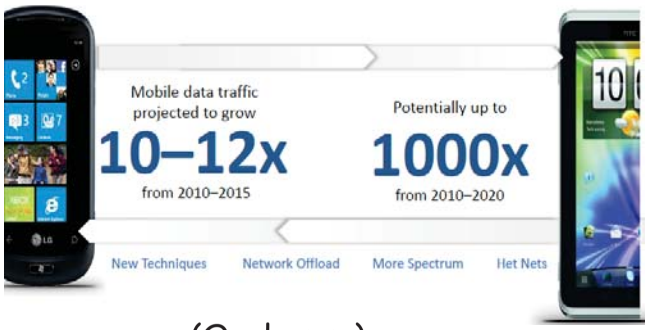
Source: Cisco VNI Mobile, 2014

(2014 Cisco visual networking index)

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



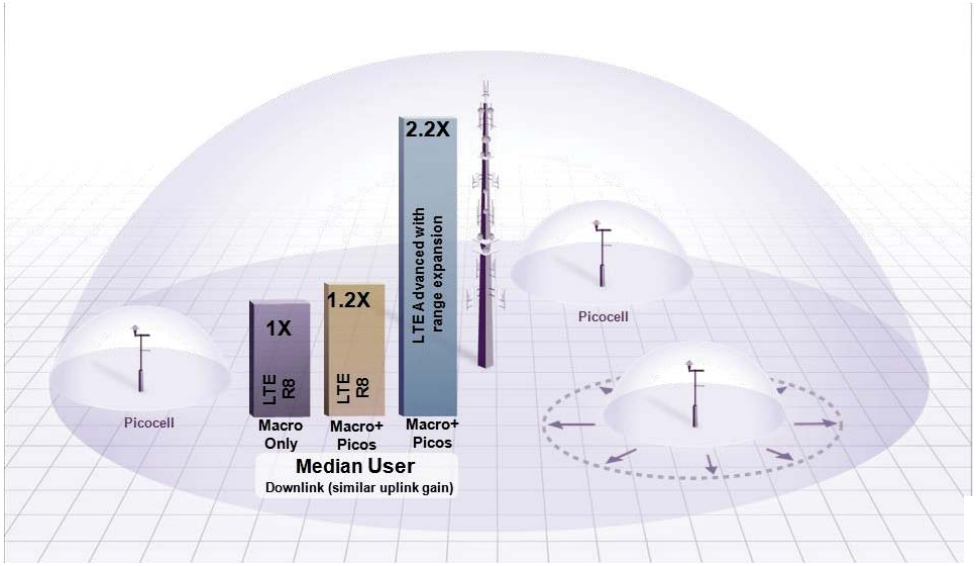
Figures in parentheses refer to traffic share in 2018.
Source: Cisco VNI Mobile, 2014



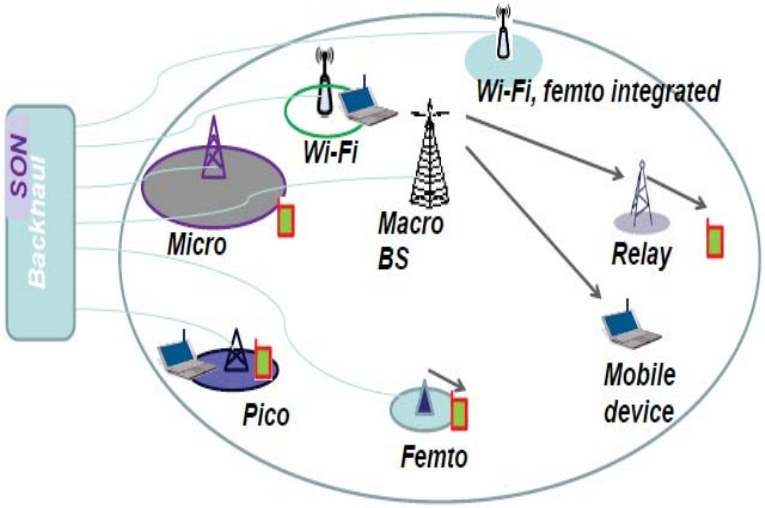
(Qualcomm)

Current Industry Approach: Small Cells & Heterogeneous Networks

Key Idea:
Denser spatial reuse
of limited spectrum



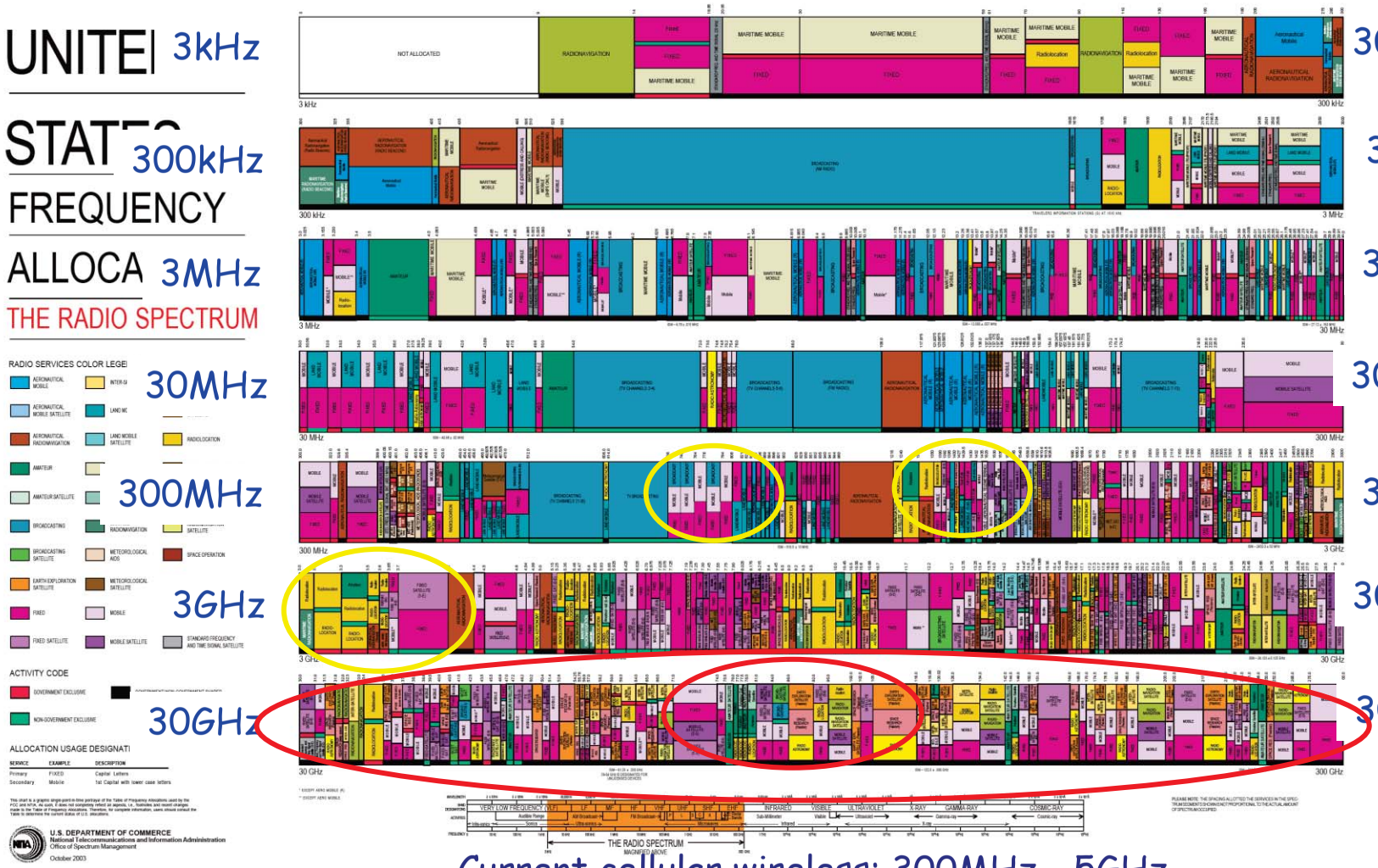
Courtesy: Dr. T. Kadous (Qualcomm)



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

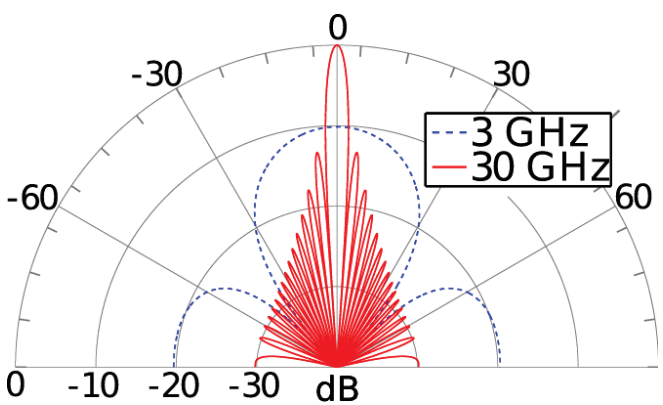
A unique opportunity for addressing the wireless data challenge

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

Compact high-dimensional multi-antenna arrays

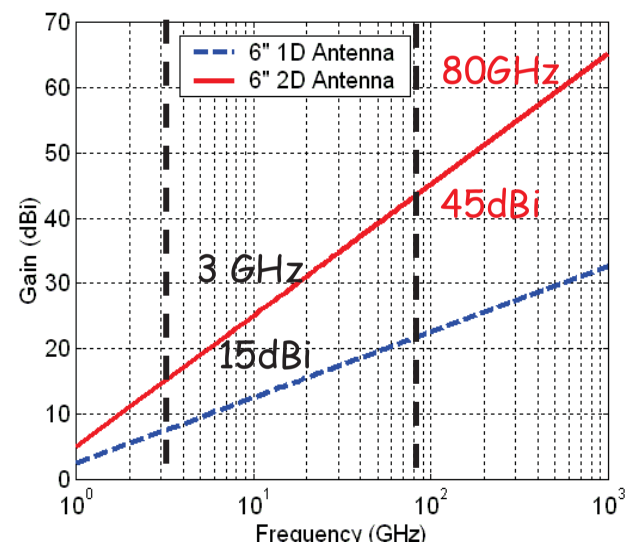
6" antenna: 6400-element antenna array (80GHz)

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)

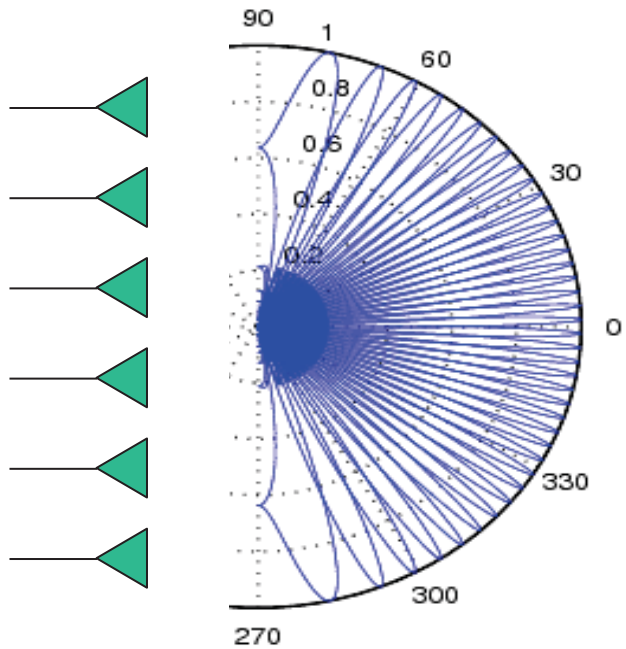
Beamspace MIMO

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

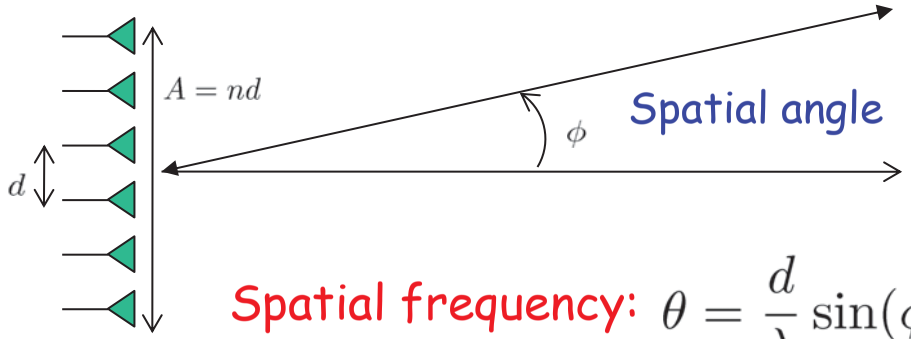
spatial channels

n dimensional signal space

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

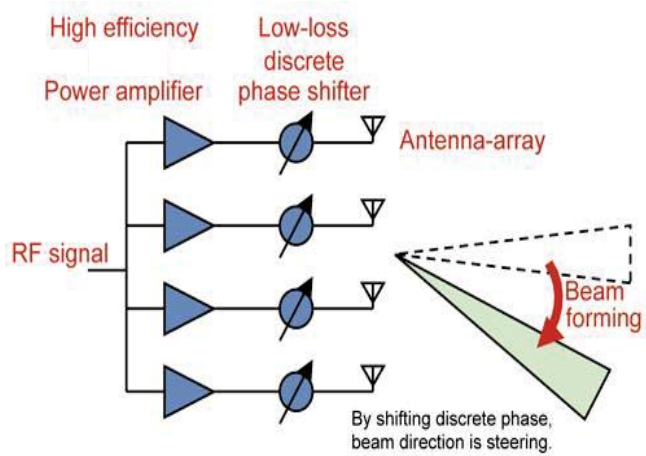
Related: communication modes in optics (Gabor '61, Miller '00, Friberg '07)

n-element Antenna (Phased) Array



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

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



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:

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

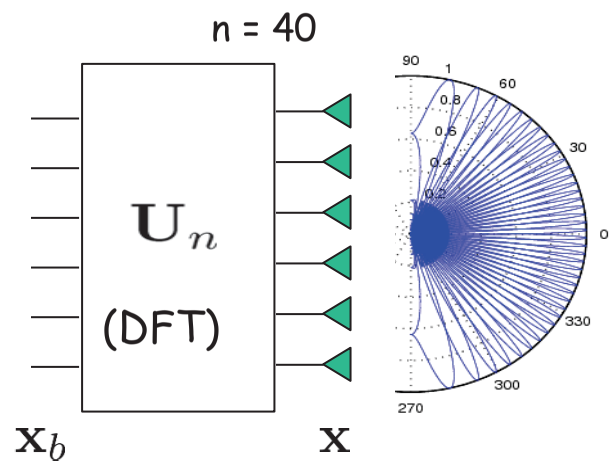
n orthogonal spatial beams

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

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)



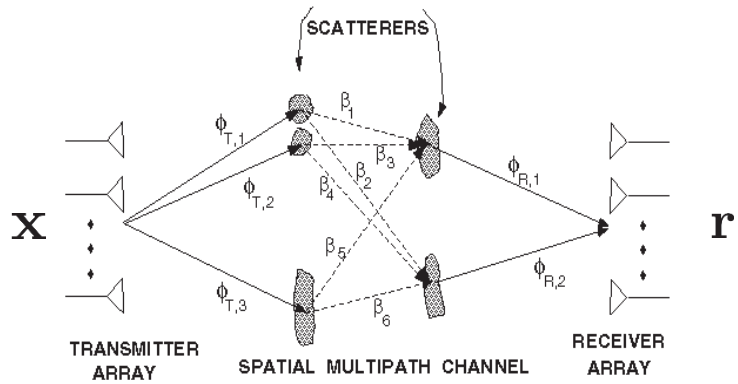
$$\mathbf{x}_b = \mathbf{U}_n^H \mathbf{x}$$
$$\mathbf{x} = \mathbf{U}_n \mathbf{x}_b$$

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

Unitary

Antenna vs Beamspace Representation

n x n
MIMO system

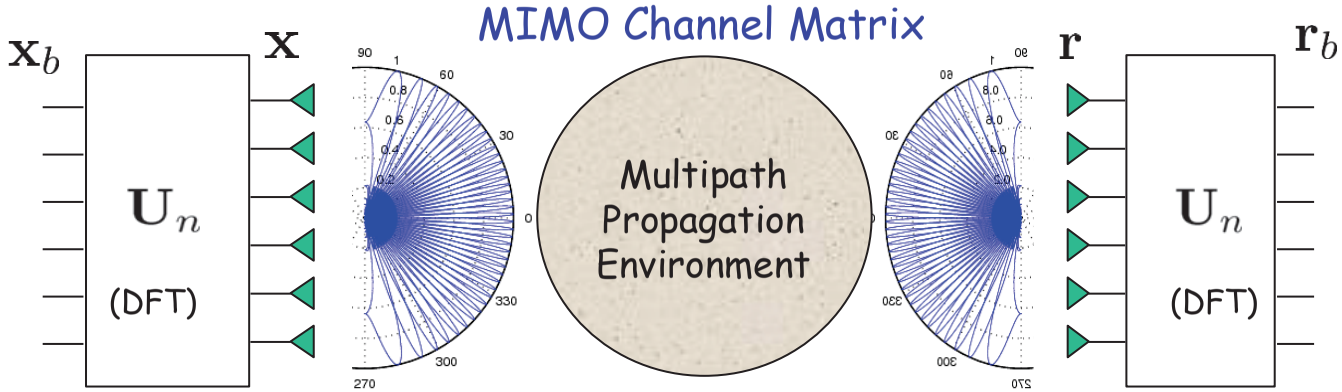


$$\text{Antenna domain: } \mathbf{r} = \mathbf{H}\mathbf{x} + \mathbf{w}$$

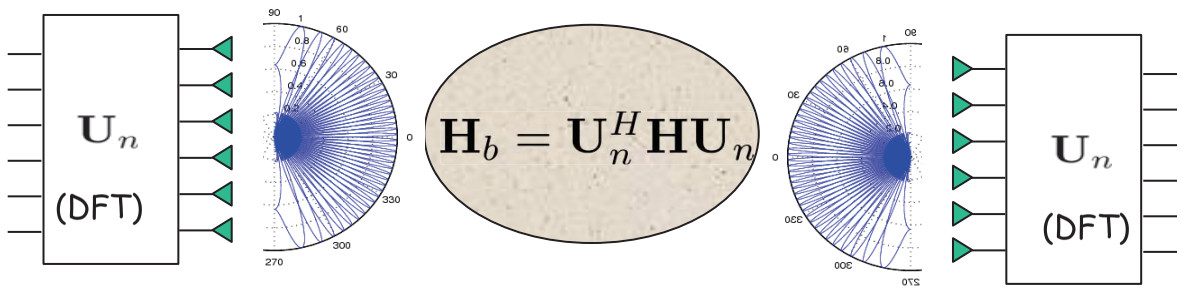
$$\text{Beam domain: } \mathbf{r}_b = \mathbf{H}_b\mathbf{x}_b + \mathbf{w}_b$$

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

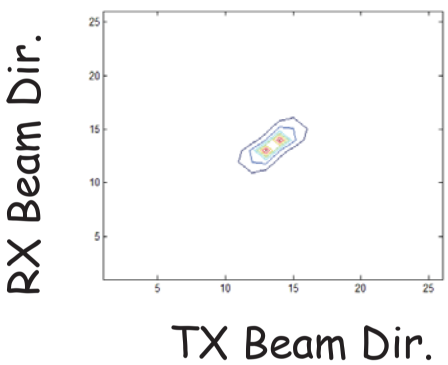
MIMO Channel Matrix



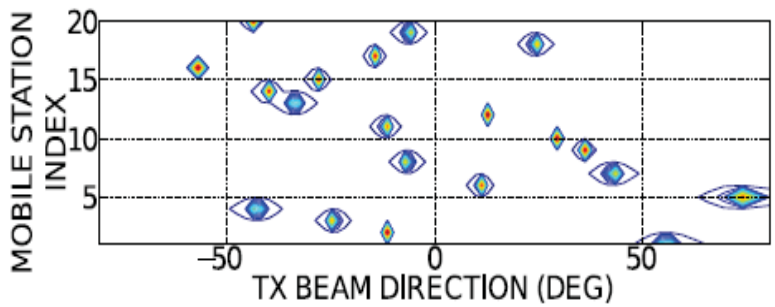
Key Characteristic at mmW: Beamspace Channel Sparsity



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

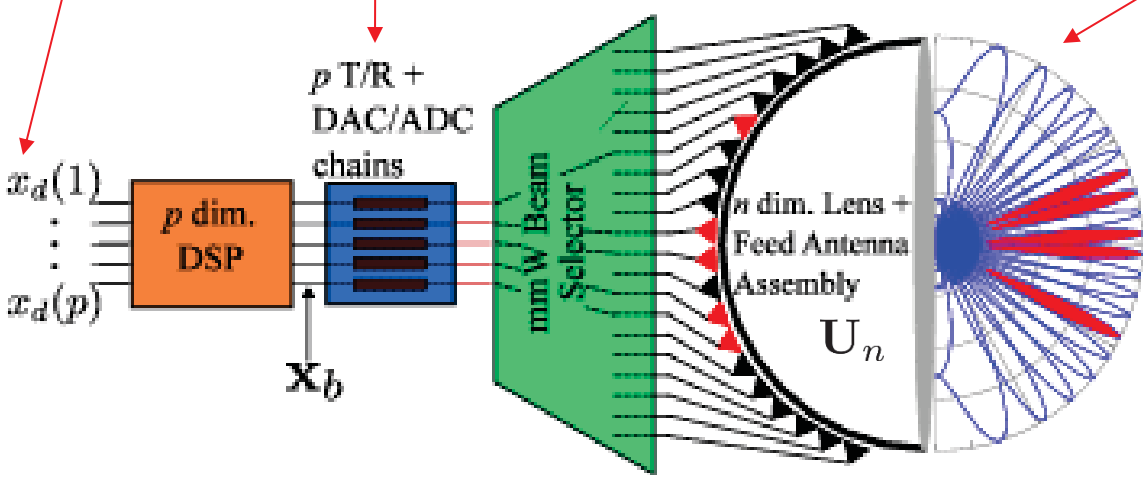
Practical Hybrid Analog-Digital Transceiver Architecture
for Beamspace MIMO (patented)

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

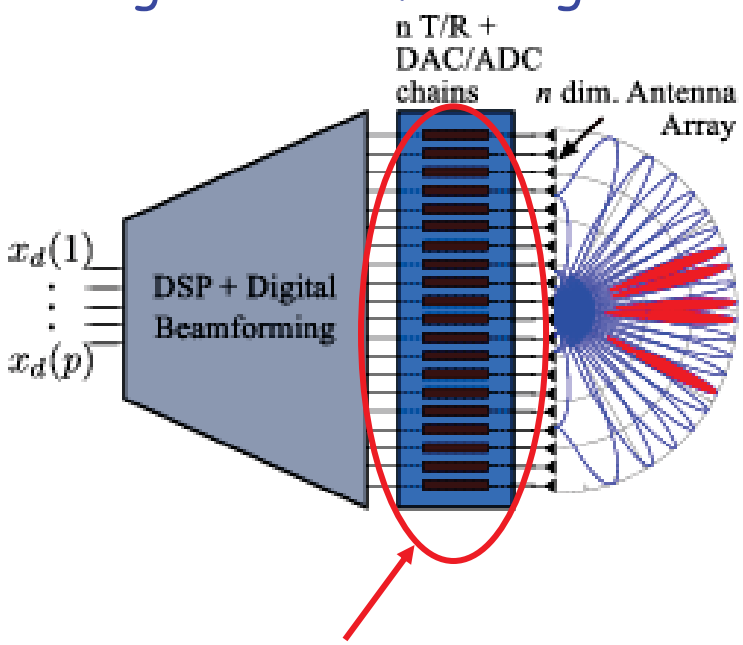
(AS & Behdad '10, '11; Brady, AS, Behdad, '12)

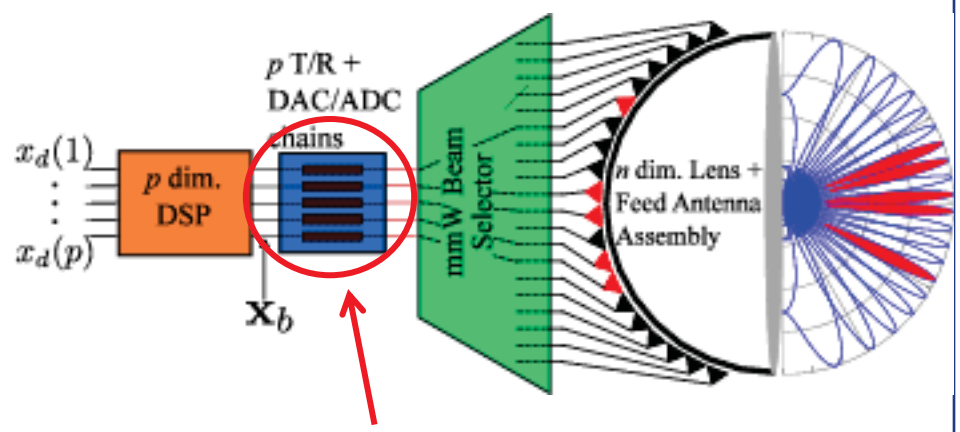
Spatial Analog-Digital Interface: Digital vs Analog Beamforming

Conventional MIMO:
Digital Beamforming

Beam Selection
p << n
active beams

CAP MIMO:
Analog Beamforming





O(n) transceiver complexity

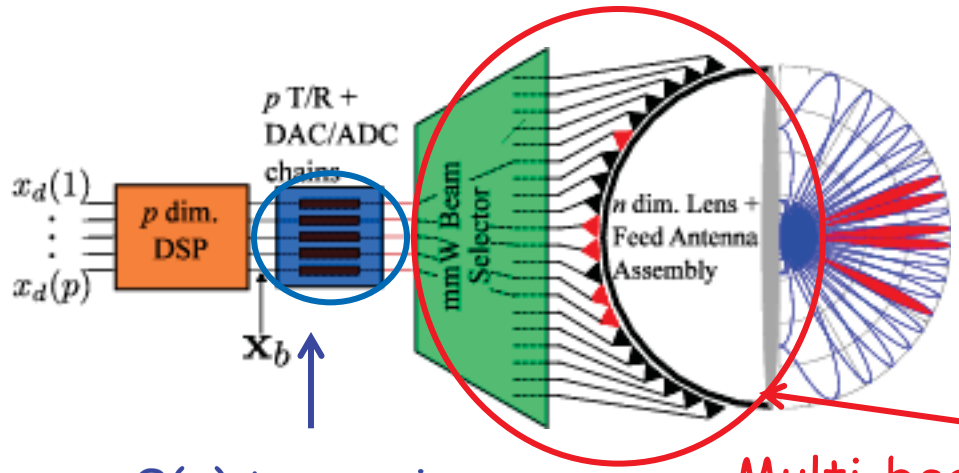
O(p) transceiver complexity

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:

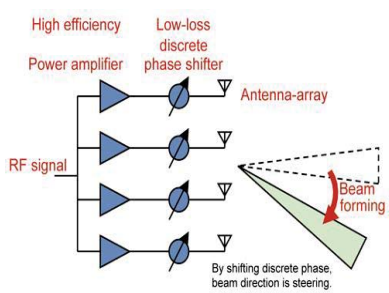


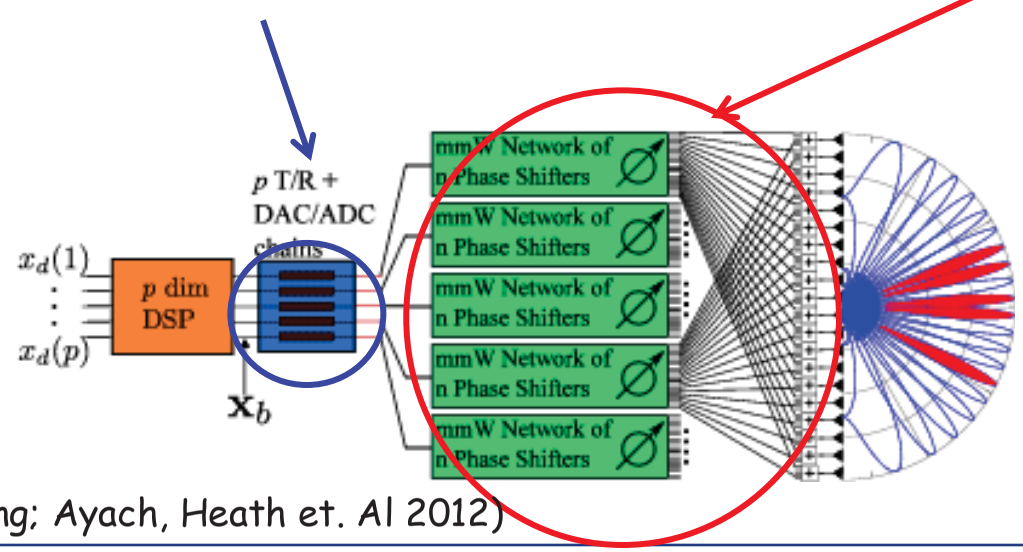
Lens
+
Beamspace Array
+
mmW Beam Selector Network

O(p) transceiver complexity

Multi-beam forming mechanism

Phased-Array Based Architecture:

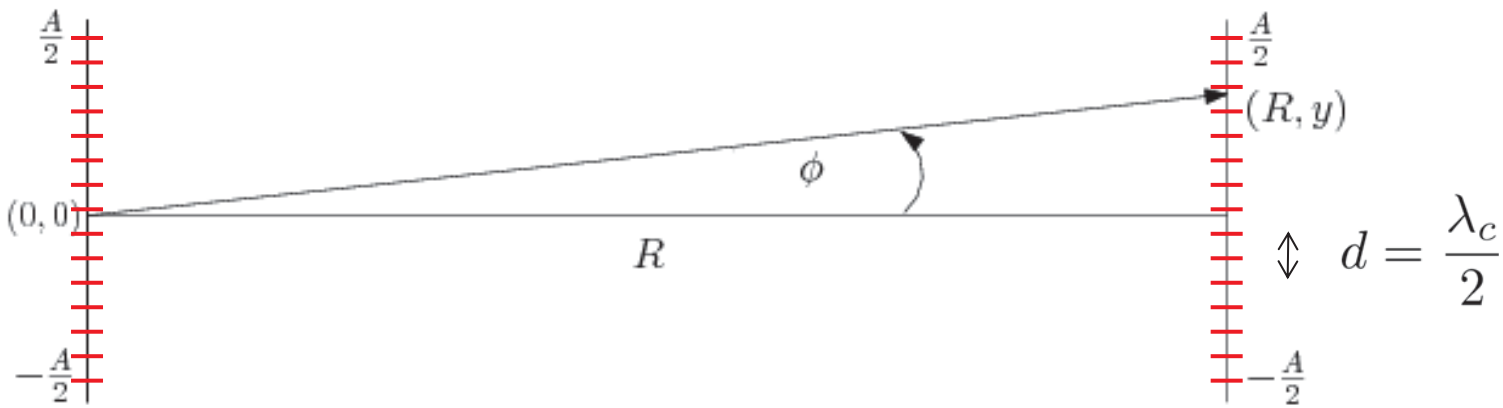




Phase Shifter Network (np)
+
Combiner Network

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

Case Study: Line-of-Sight Link



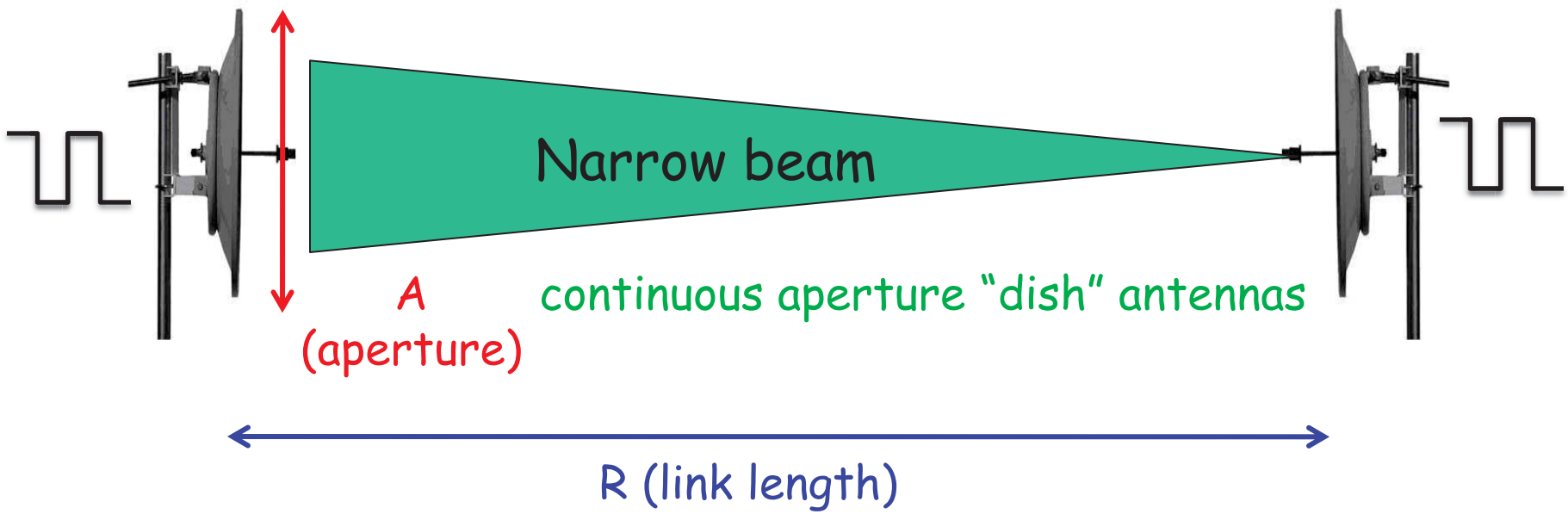
analog spatial modes: $n \approx \frac{A}{d} = \frac{2A}{\lambda_c}$ (~ antenna/array gain)

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



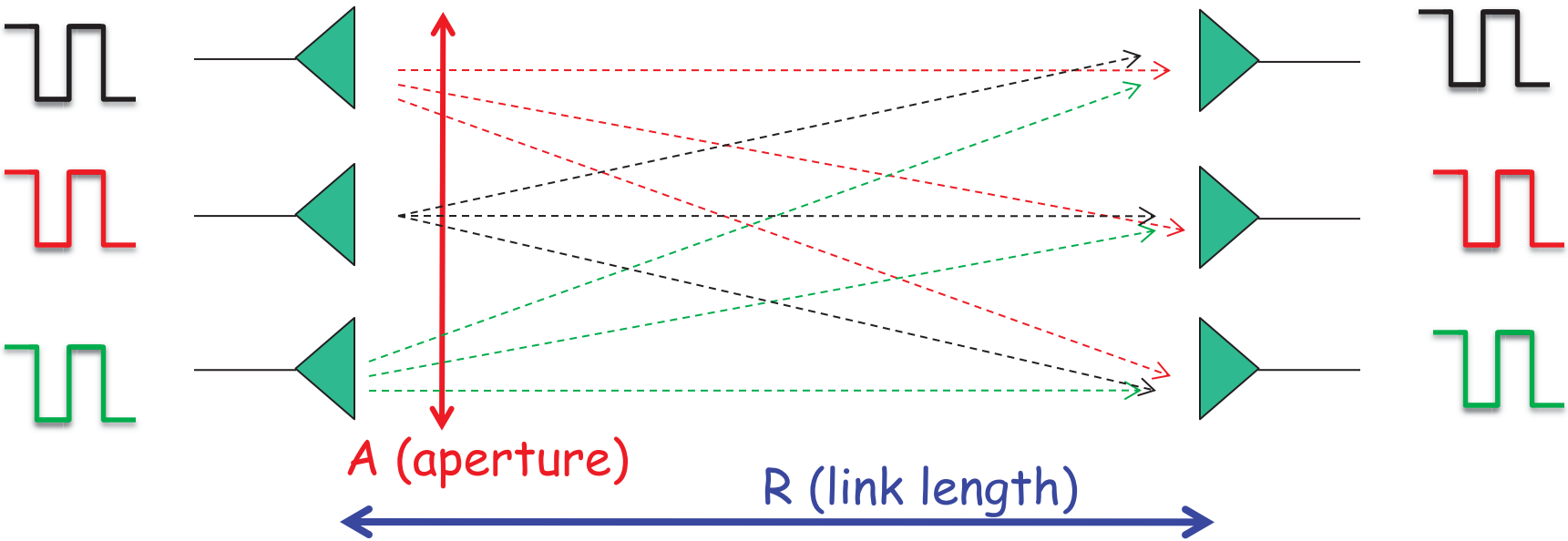
Pros: Large antenna gain (SNR gain) $G \propto \left(\frac{A}{\lambda}\right)^2$

Narrow beam (continuous aperture)

Cons: Single data stream

State-of-the-Art 2: MIMO System

Discrete Antenna Arrays (wide Rayleigh spacing)

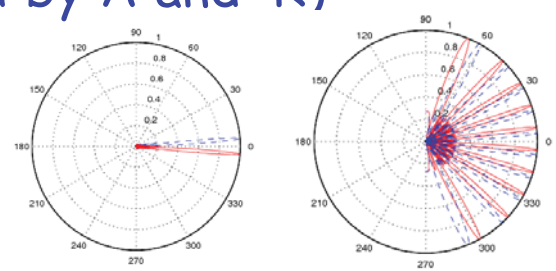


Pros: Multiplexing gain: Multiple (p) data streams

(p limited by A and R)

Cons: Reduced SNR gain

Grating lobes



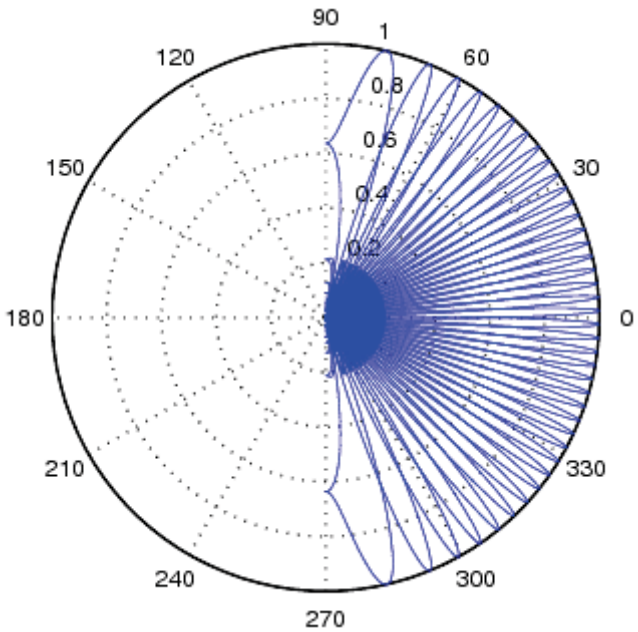
Madhow et. al. 06'

Bohagen et. al. 07'

Chalmers

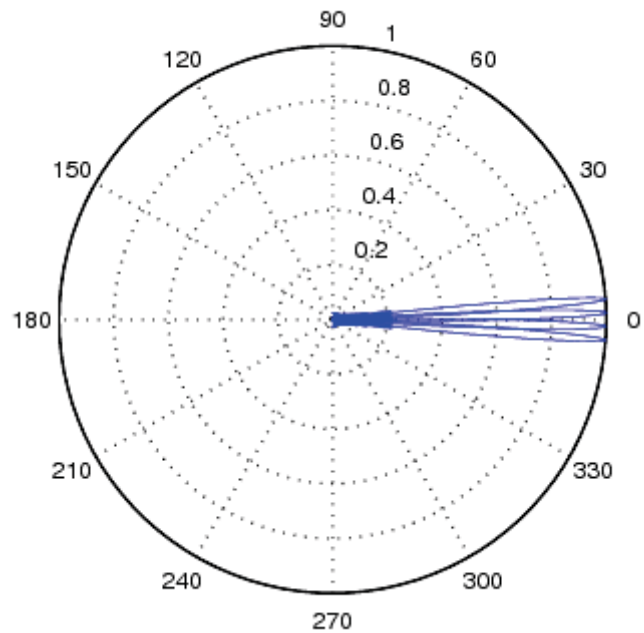
Beamspace MIMO: Coupled Orthogonal Beams

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

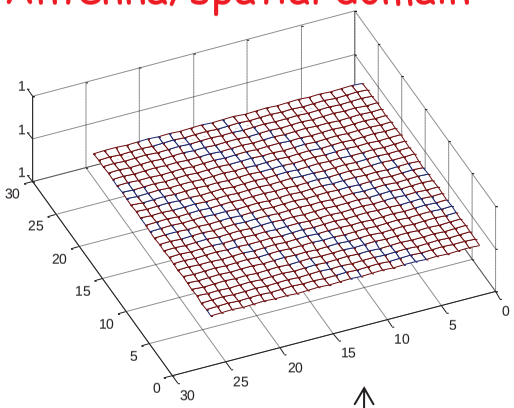
Spatial Res.: $\Delta\theta_o = \frac{1}{n} = \frac{\lambda_c}{2A}$

Near-Optimality of Beamspace MIMO

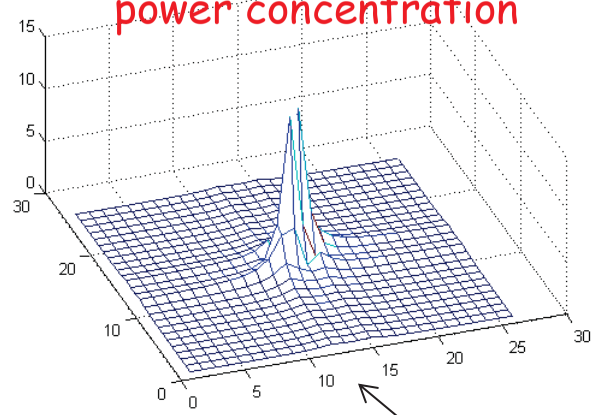
Coupled beams ~ channel eigenvectors

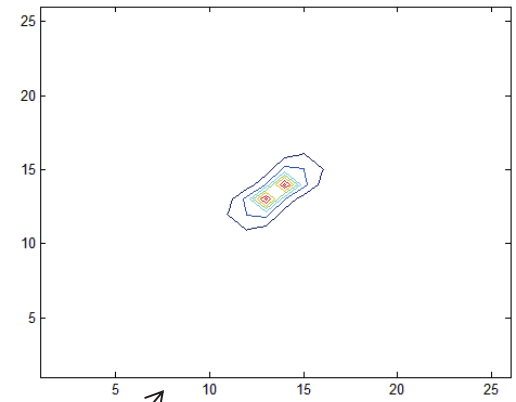
$n = 26;\ p_{max} = 2$

Antenna/spatial domain



Beamspace:
power concentration





$$\mathbf{H} = \mathbf{U}_n \mathbf{H}_b \mathbf{U}_n^H \quad \Longleftrightarrow \quad \mathbf{H}_b = \mathbf{U}_n^H \mathbf{H} \mathbf{U}_n$$

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

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

Subspace determination through beamspace thresholding!

Capacity Comparison with State of the Art

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: $G = \frac{n^2}{p_{max}^2}$

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

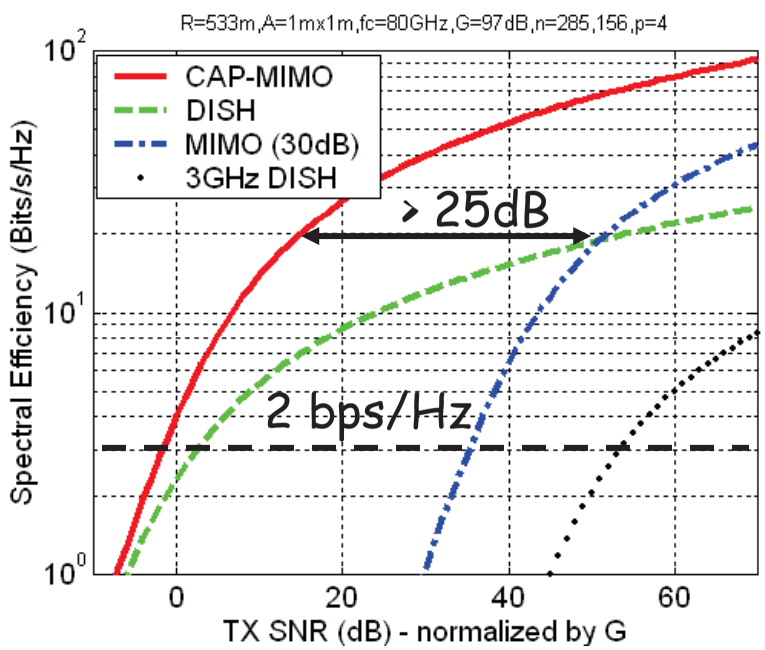
DISH
no multiplexing gain
Max. SNR gain

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

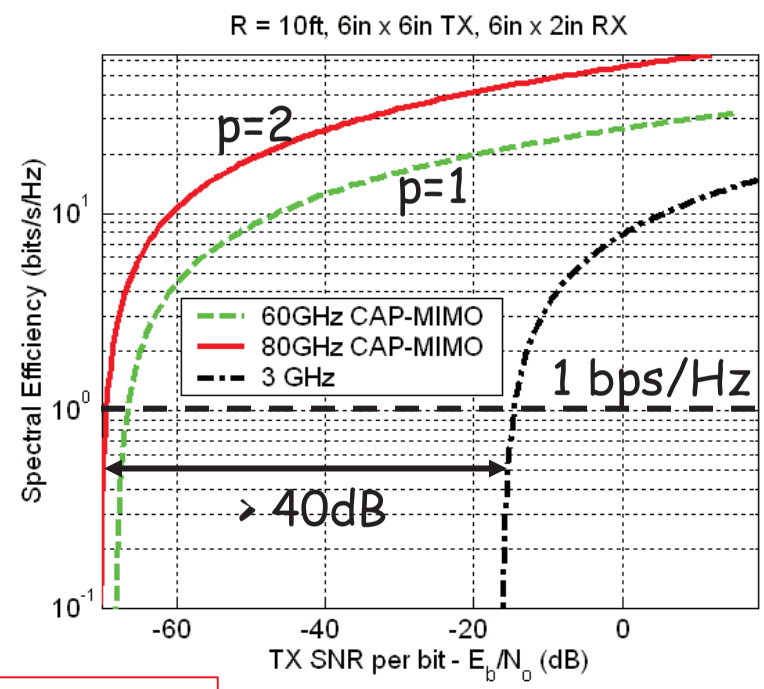
Conv. (widely spaced) MIMO
Max. multiplexing gain
small SNR gain

Potential Gains: Backhaul and Indoor Links

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

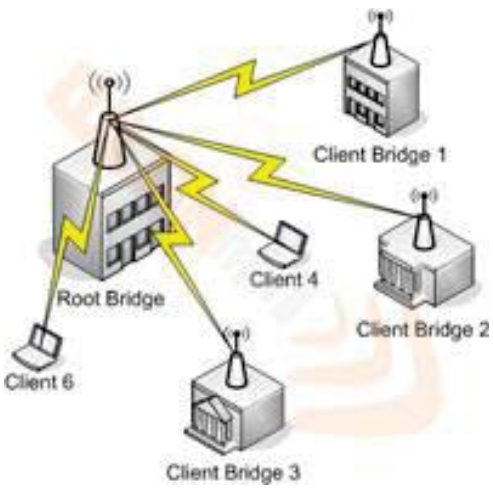
3GHz
$n \sim 9,\ G \sim 15\text{dB}$

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

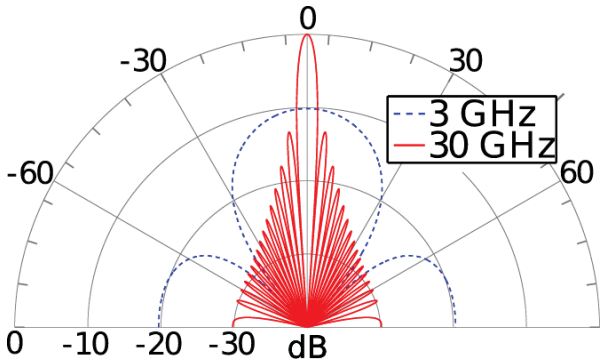
Beamspace precoding: $\mathbf{r} = \mathbf{H}_b^H \mathbf{G}_b \mathbf{s}_b + \mathbf{w}$

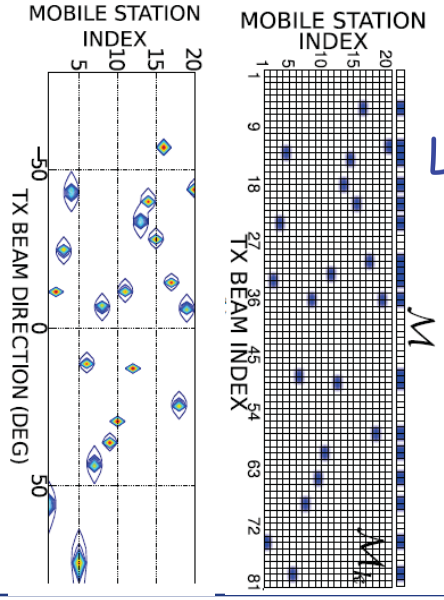
$$\mathbf{G}_b = \mathbf{U}_n^H \mathbf{G} = [\mathbf{g}_{b,1}, \mathbf{g}_{b,2}, \cdots, \mathbf{g}_{b,K}]$$

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

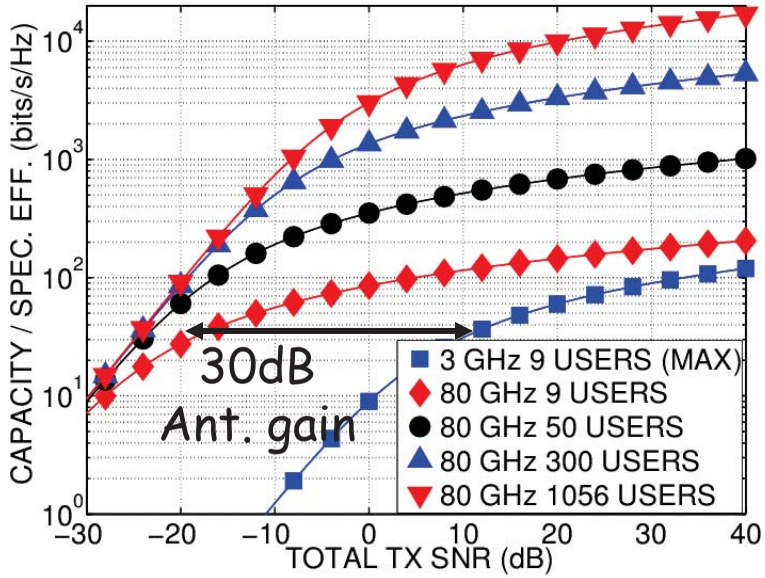
$$\mathbf{r} = \tilde{\mathbf{H}}_b^H \tilde{\mathbf{G}}_b \mathbf{s}_b + \mathbf{w}$$

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

Dense Beamspace Multiplexing

Key application: small-cell access points

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

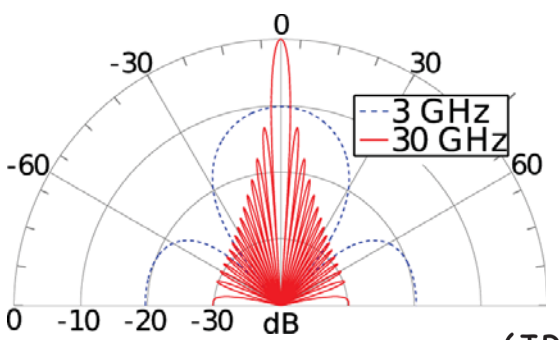


x 2-200 increase in capacity due to beamspace multiplexing

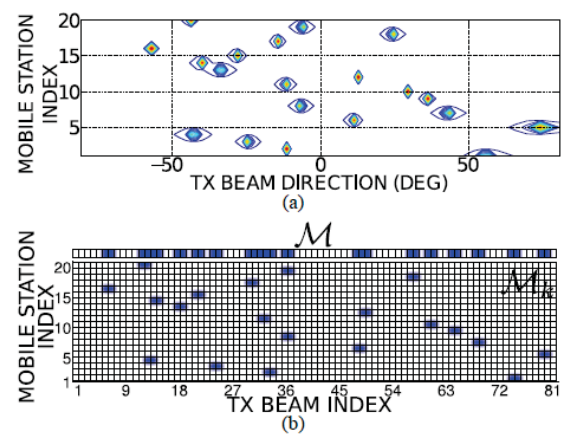
x 10-100 increase in capacity due to extra bandwidth (~1-10GHz vs 100MHz)

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

6" x 6" antenna

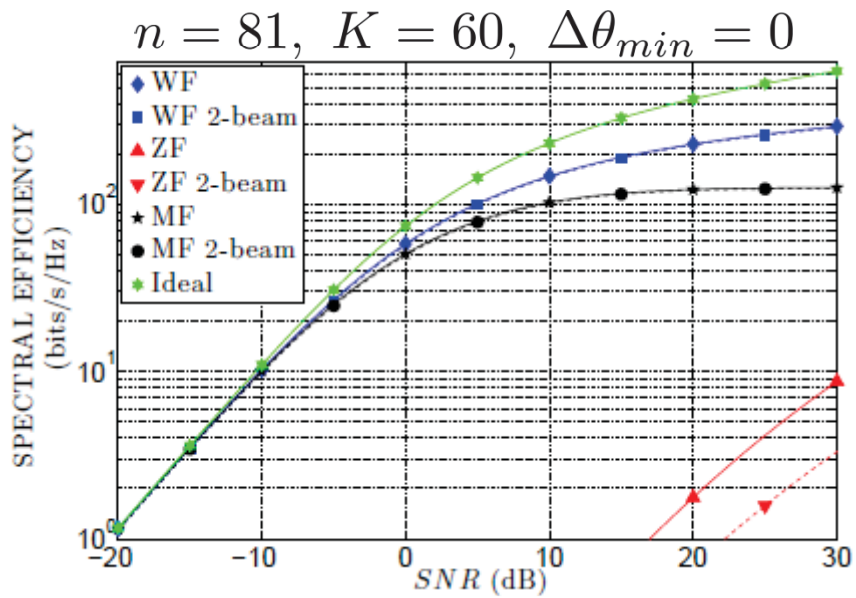


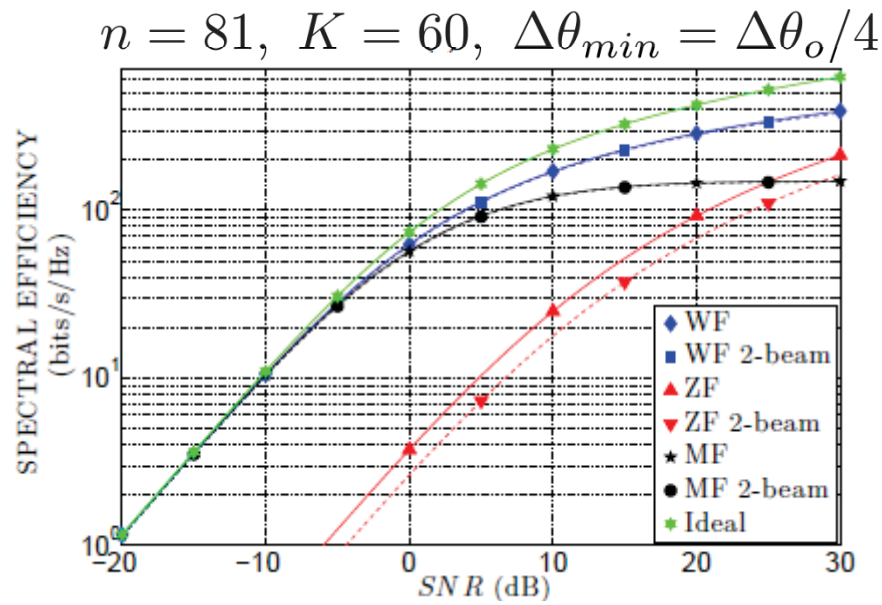
Beamspace channel sparsity



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

Performance with Linear Precoding

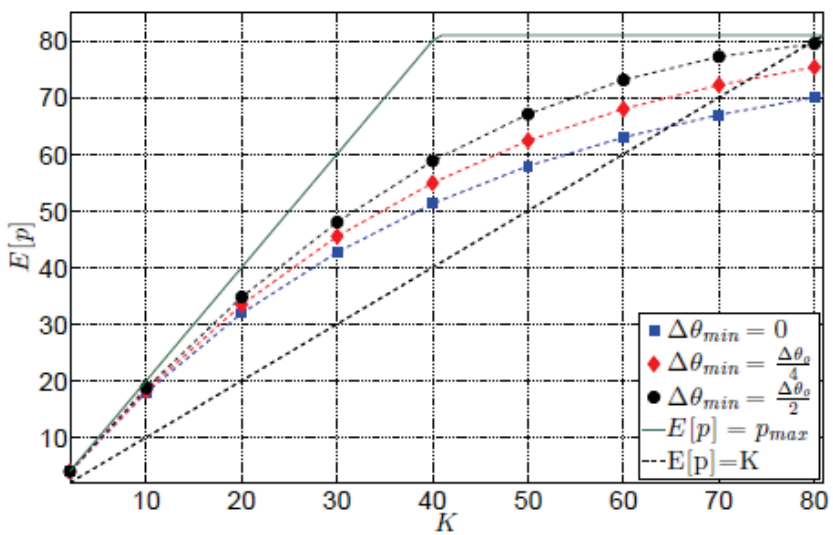




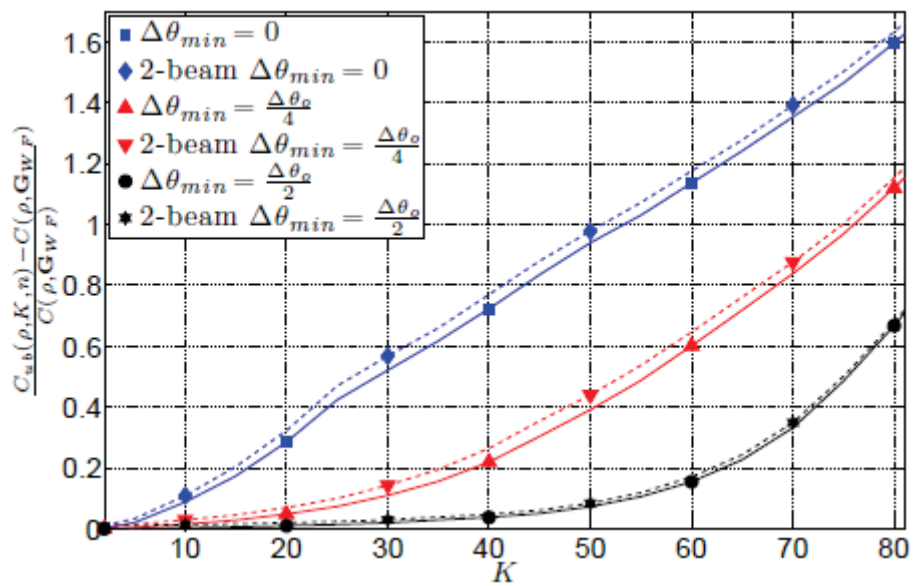
K = # users	Spectral Efficiency (bits/s/Hz)	Aggregate rate (Gbps)	Average per-user rate (Gbps)
$K = 20\ \Delta\theta_{min} = 0$	134	670	33.5
$K = 20\ \Delta\theta_{min} = \Delta\theta_o/4$	159	795	39.8
$K = 40\ \Delta\theta_{min} = 0$	192	960	24
$K = 40\ \Delta\theta_{min} = \Delta\theta_o/4$	243	1215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

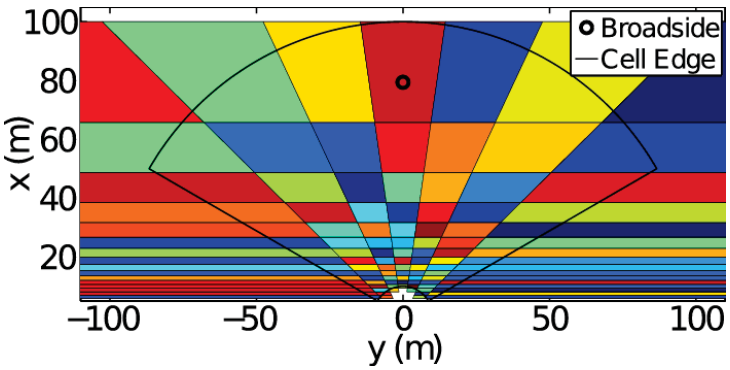
(JB & AS Globecom 2013)

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

Small-Cell Design: 2D Beam Footprints

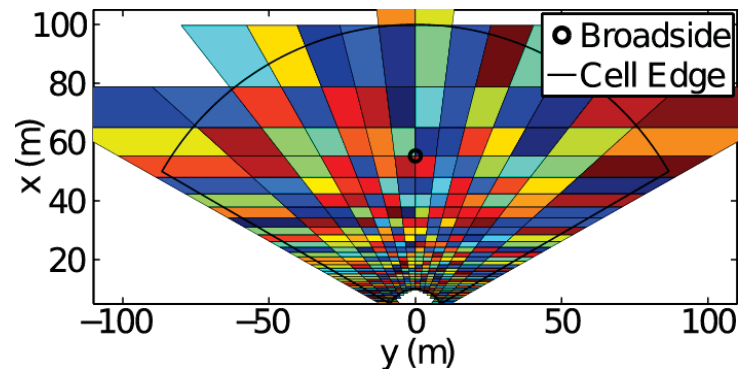
$p = K = 100$

0.45″ x 2.8″ antenna @ 80GHz



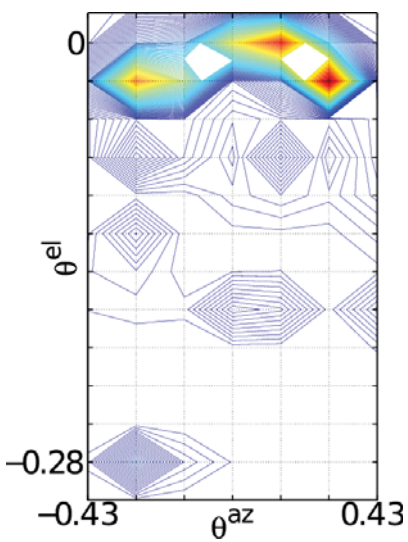
$p = 16K = 1600$

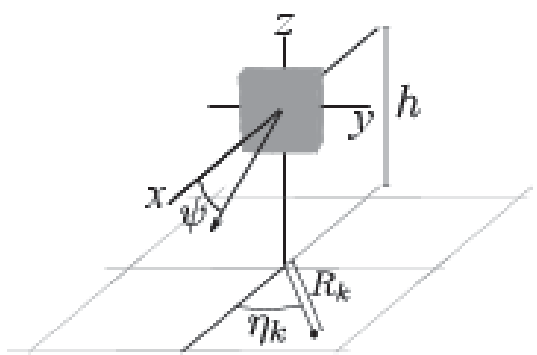
2.3″ x 12″ antenna @ 80GHz

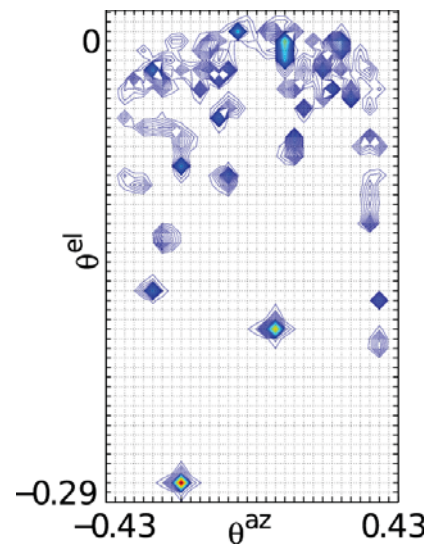


$n = 273: \ (n_{az}, n_{el}) = (7, 39)$

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

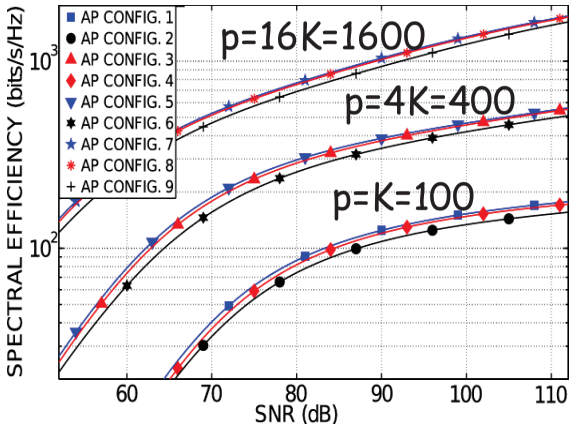


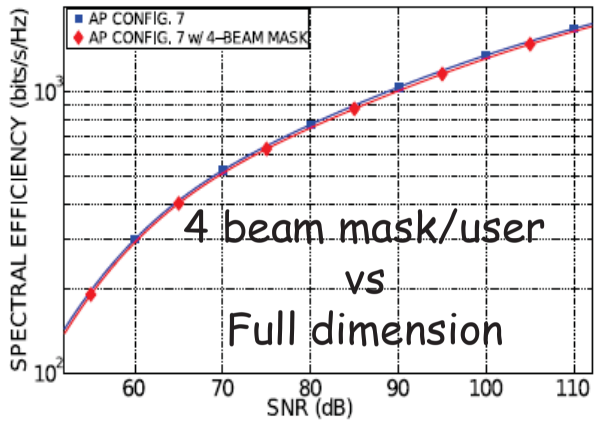




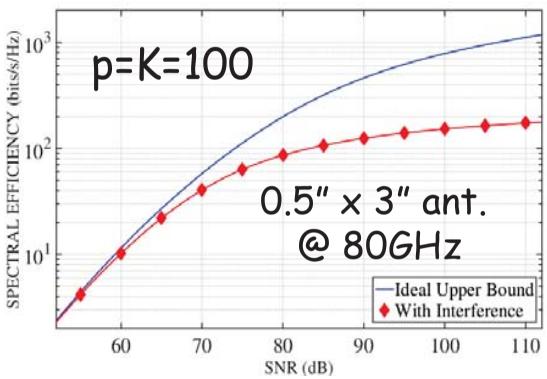
(JB & AS, SPAWC 2014)

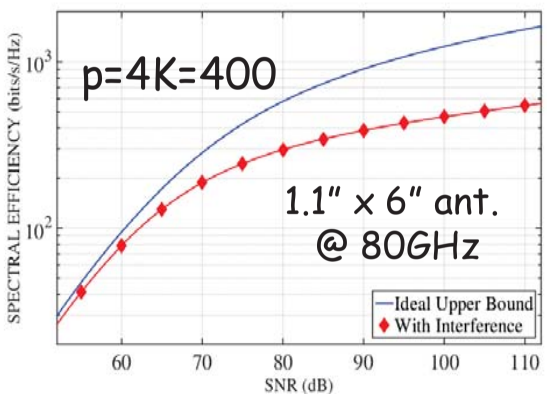
Performance of APs with 2D Arrays

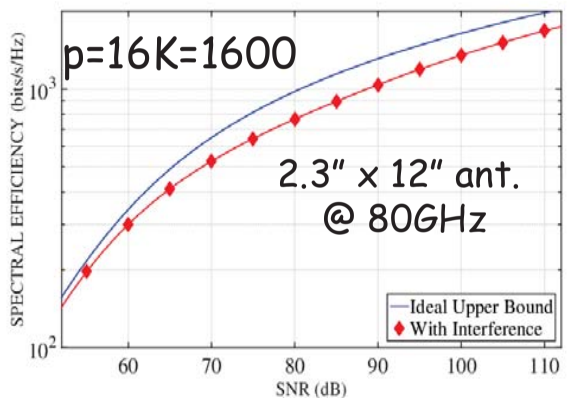




Upperbound vs MMSE precoder performance

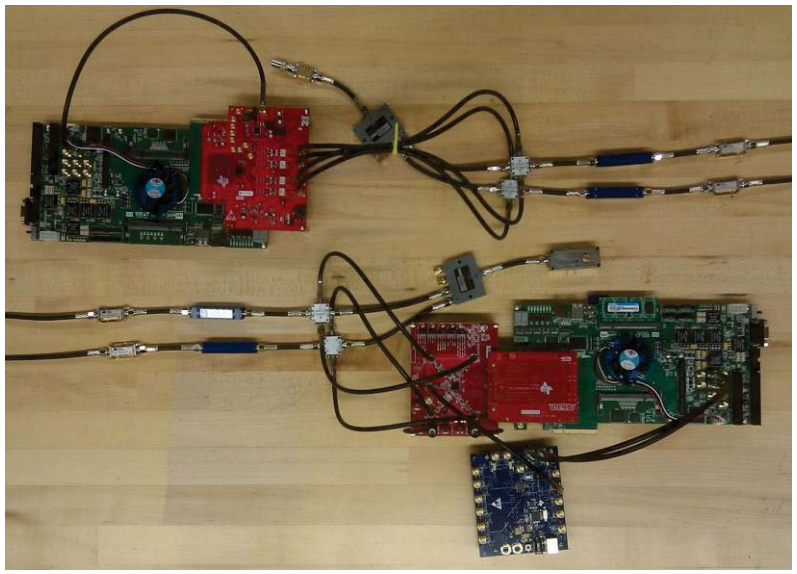


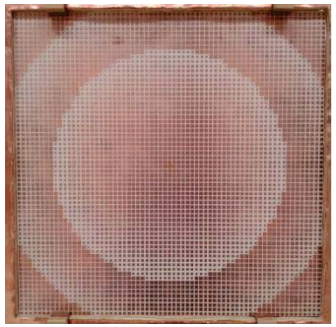




AP config.	$\psi(°)$	n_{az}	n_{el}	n	p	$\tilde{n}_{az}$	$\tilde{n}_{el}$	$\tilde{n}$	Array Size at 80 GHz
1	7.2	7	39	273	105	7	32	224	0.45"×2.81"
2	10.3	7	36	245	103	7	29	203	0.45"×2.58"
3	37	7	34	238	100	7	19	133	0.45"×2.44"
4	6.4	16	81	1296	408	15	66	990	1.11"×5.91"
5	10.3	16	76	1216	402	15	61	915	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"

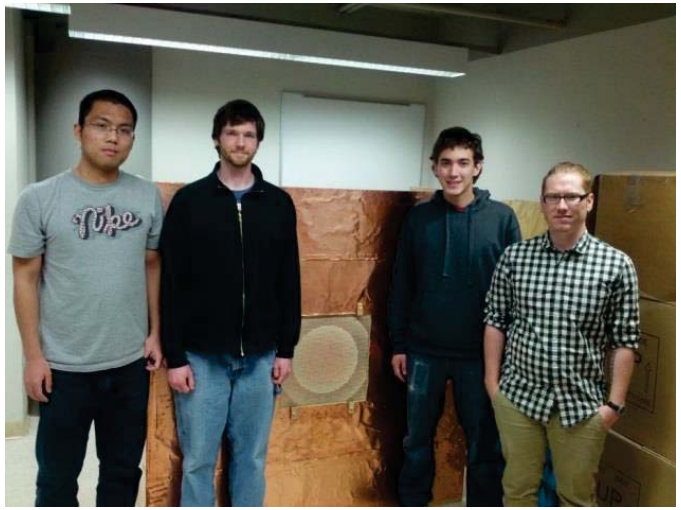
10GHz CAP-MIMO Prototype

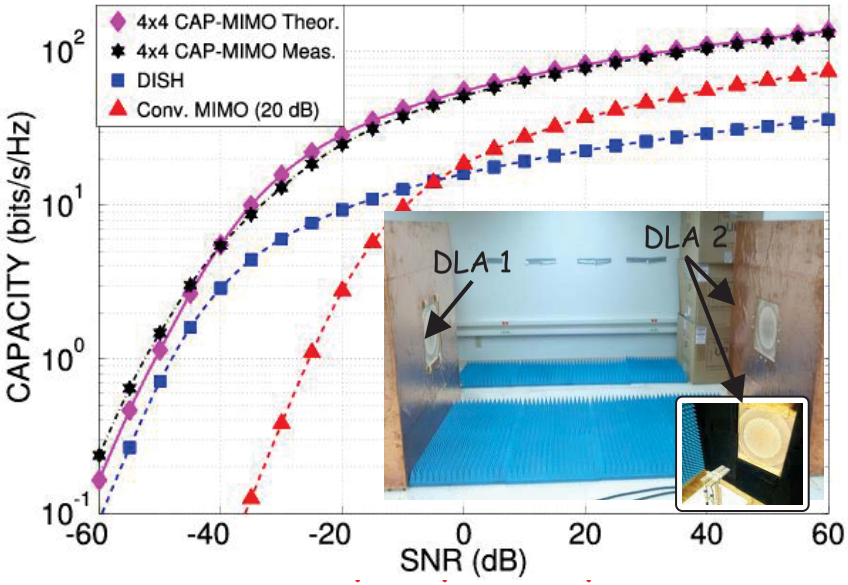




40cm x 40cm
DLA

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

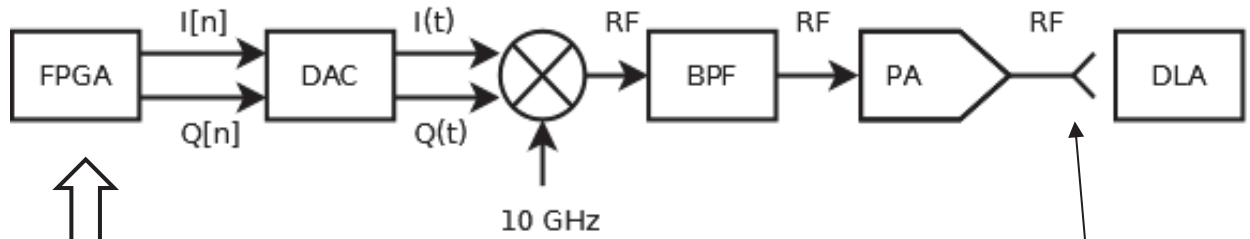




10 GHz prototype theoretical performance:
100 Gigabits/sec (1 GHz BW) at 20dB SNR
Compelling performance gains over state-of-the-art

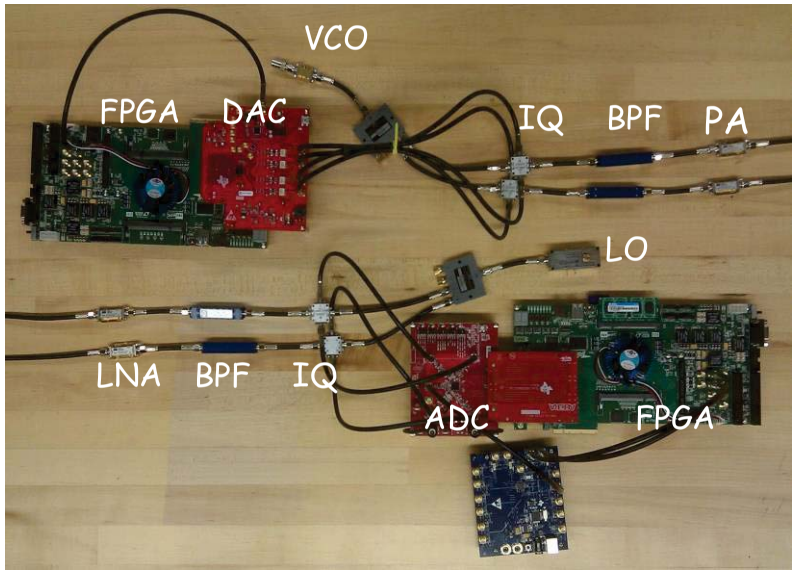
Prototype TX/RX Hardware

Transmitter:



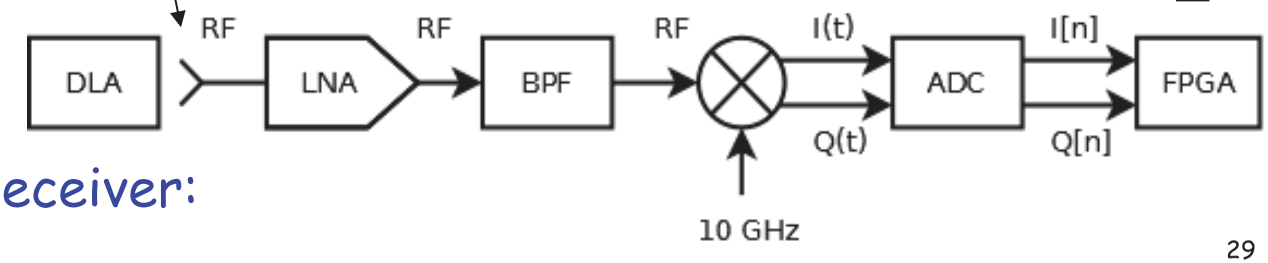
Prototype Specifications

- 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



To DLA

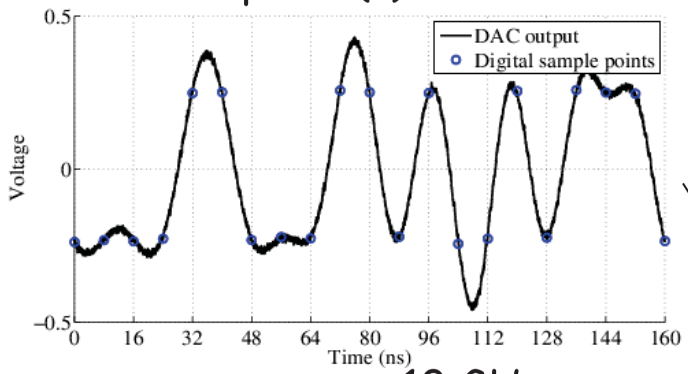
From DLA



Receiver:

Baseband to Passband

DAC output: I(t)

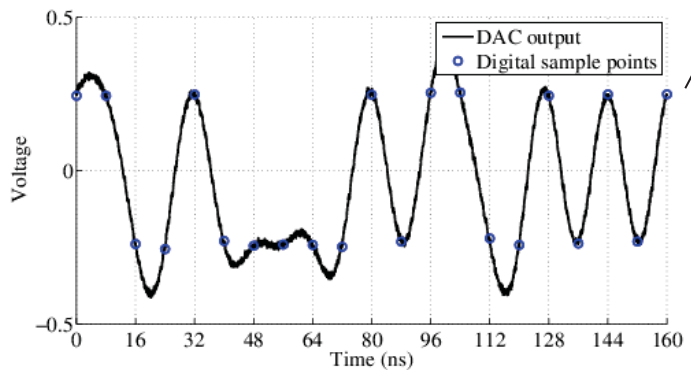


I(t)

10 GHz

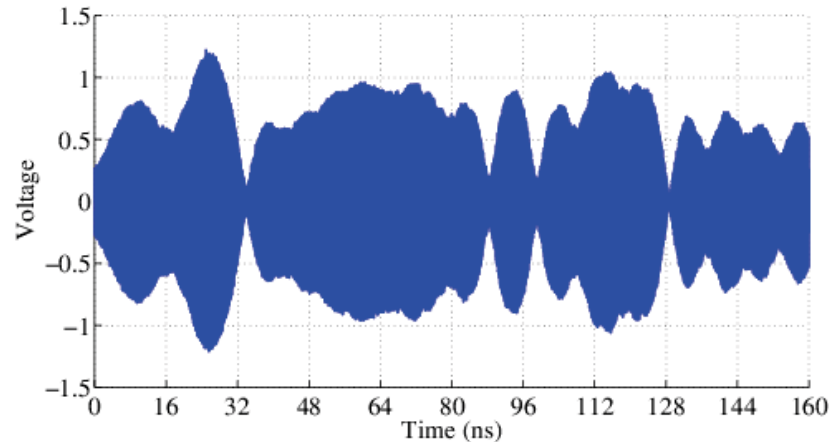
u(t)

DAC output: Q(t)

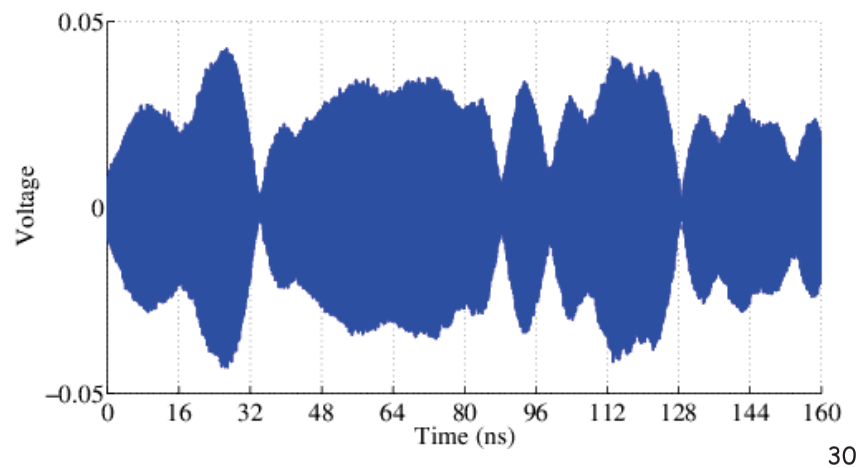


Q(t)

Passband: output of TX PA



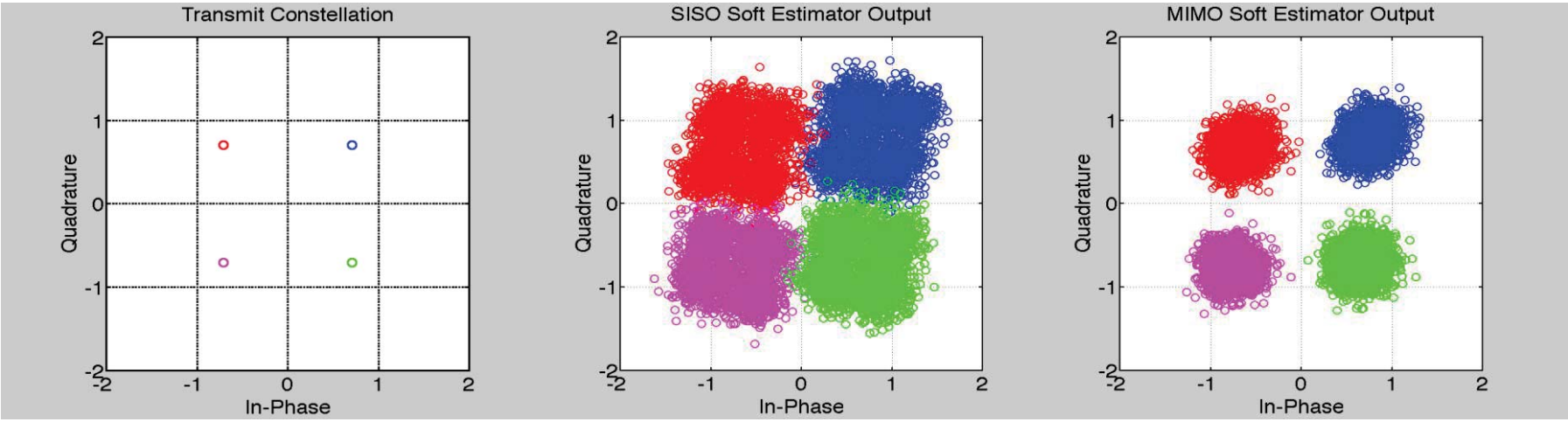
Passband: output of RX LNA



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

2x2 Spatial Multiplexing Test

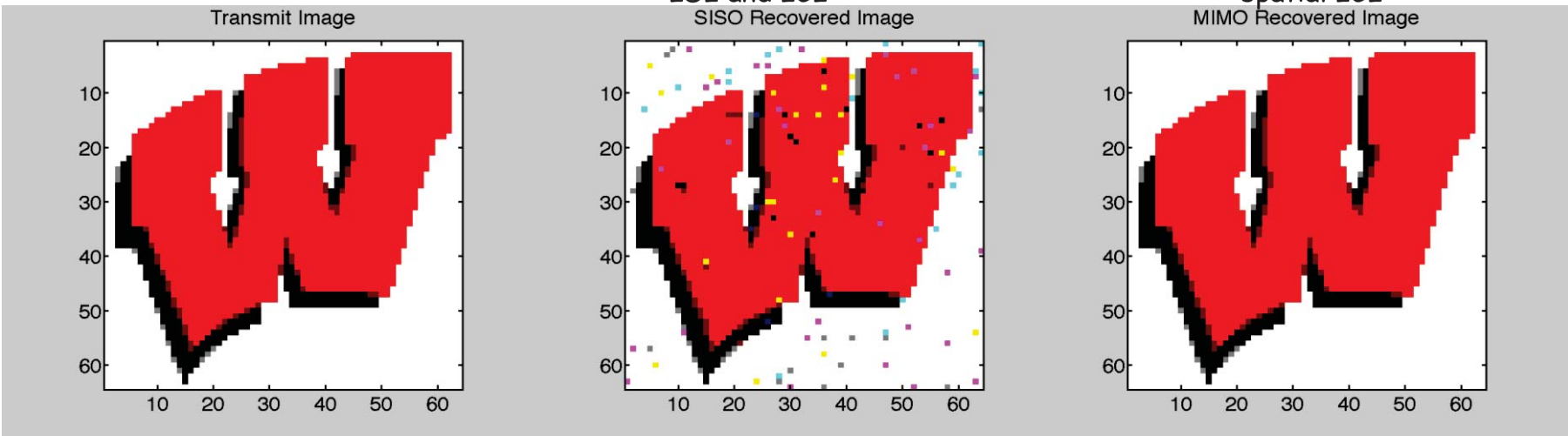
- 2 Spatial Channels
- Shared LO at TX and RX
- 500 Mbps data rate
- Separate TX and RX sample clocks



Transmitted 4-QAM Symbols

Channel 1 received symbols with ISI and ICI

After MMSE MIMO processing to suppress spatial ICI



16 kbit test image

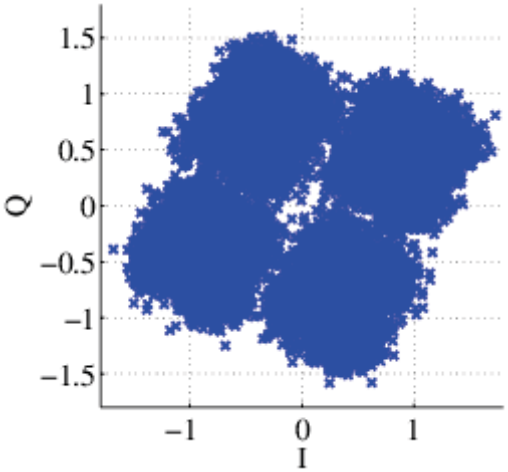
179 bit errors

0 bit errors

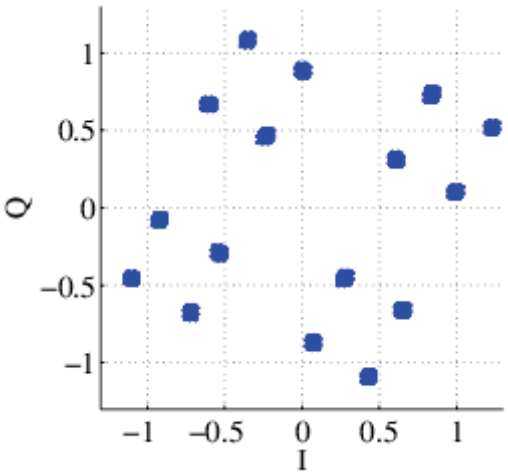
Received Symbols: ICI vs ISI

ISI + ICI

Without Guard Interval

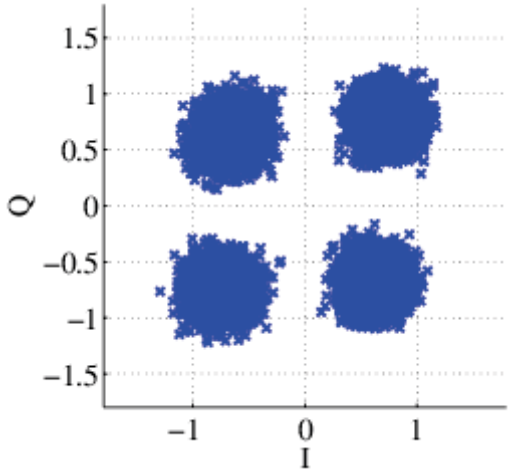


With Guard Interval (ICI only)

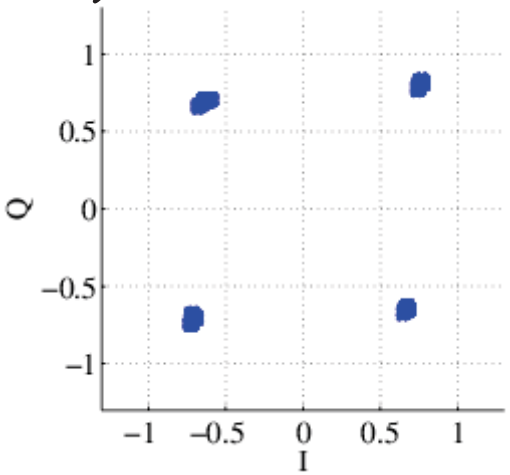


Suppressed ICI (MMSE Spatial Filter)

Without Guard Interval (ISI)

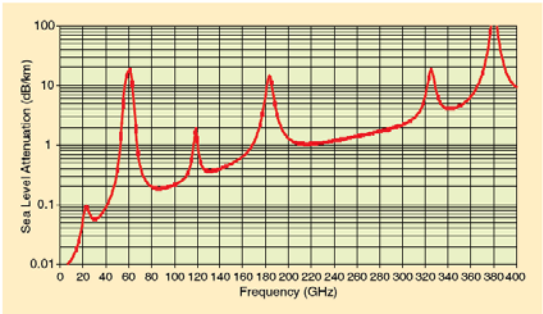


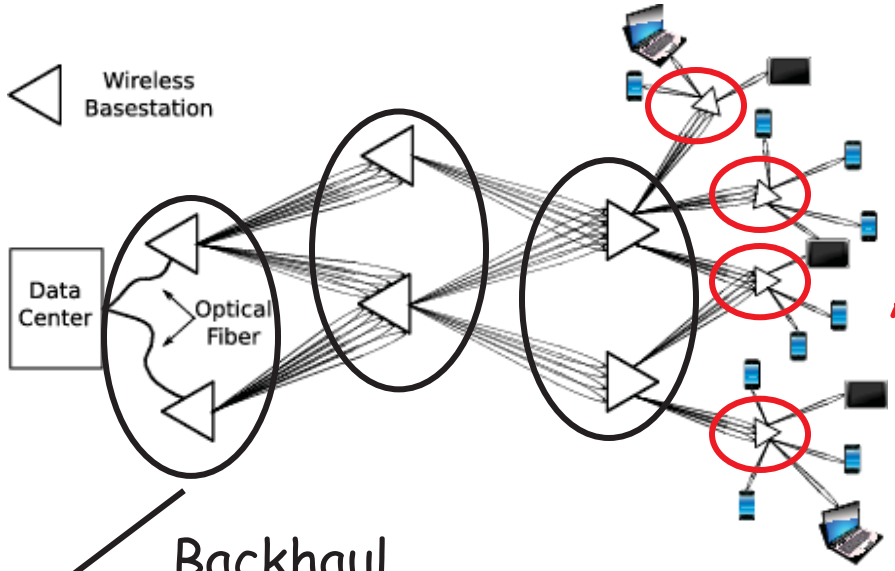
With Guard Interval (suppressed ISI & ICI)



Outlook: Multi-scale mmW MIMO Networks

Availability:
Atmospheric absorption

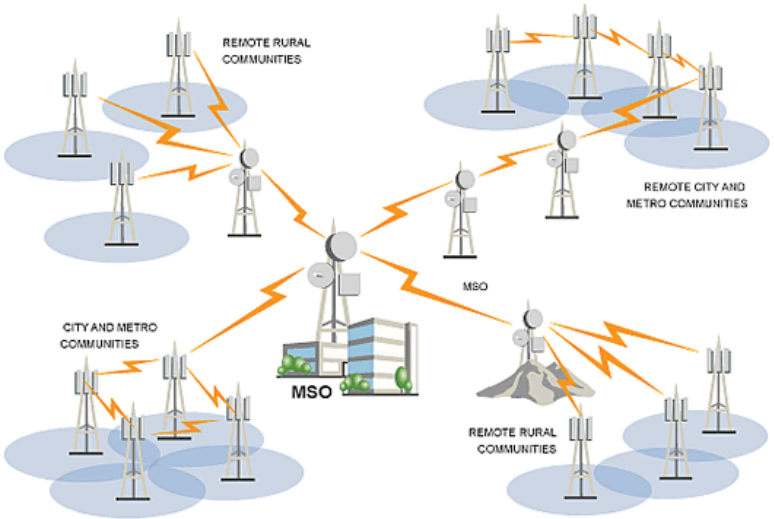




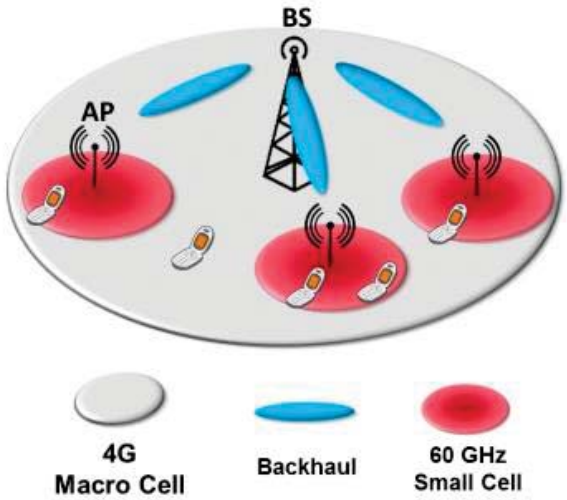
"small cell" Access Network

Multi-Gbps speeds

Backhaul network



(Source: 3G.co.uk)



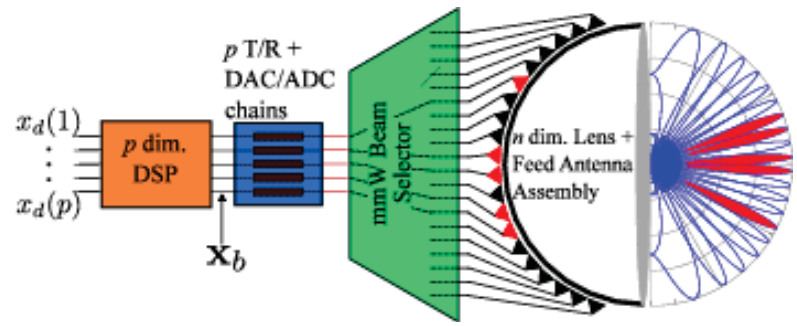
(siliconsemiconductor.net)

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!