Beamspace MIMO Architectures for Massive 2D Antenna Arrays

ICNC 2015 E-MIMO Workshop
International Workshop on Emerging MIMO Technologies with 2D Antenna Array for LTE Advanced and 5G

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Explosive Growth in Wireless Traffic

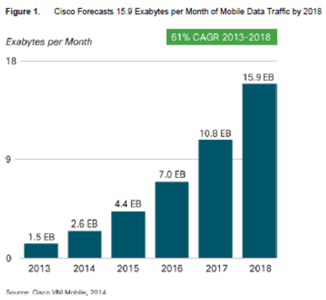


Figure 1. Cisco Forecasts 15.9 Exabytes per Month of Mobile Data Traffic by 2018

Source: Cisco VNI Mobile, 2014

(2014 Cisco visual networking index)

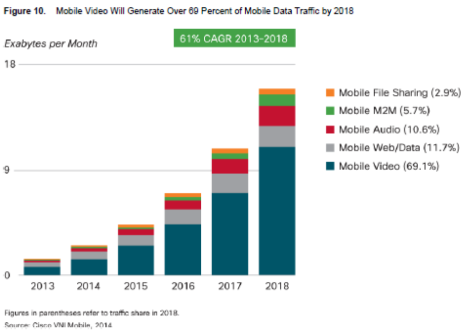
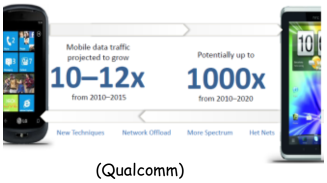


Figure 10. Mobile Video Will Generate Over 69 Percent of Mobile Data Traffic by 2018

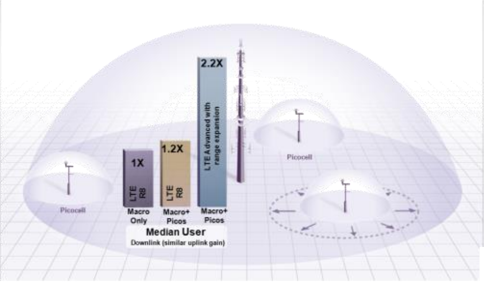
Figures in parentheses refer to traffic share in 2018.
Source: Cisco VNI Mobile, 2014



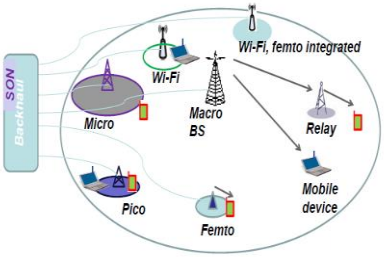
(Qualcomm)

Current Industry Approach: Small Cells & Heterogeneous Networks

Key Idea:
Denser spatial reuse
of limited spectrum



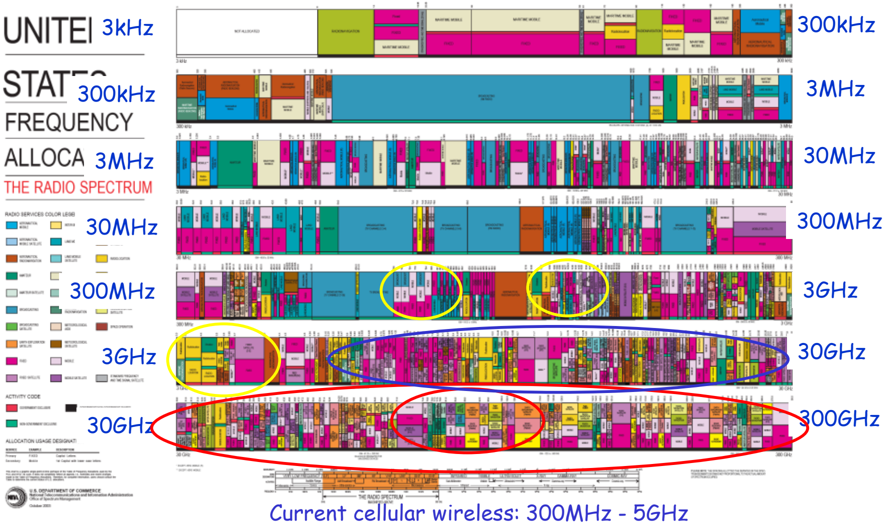
Courtesy: Dr. T. Kadous (Qualcomm)



Courtesy: Dr. J. Zhang (Samsung)

Some challenges: interference, backhaul

New Frequencies: mm-wave and cm-wave



Current cellular wireless: 300MHz - 5GHz

Mm-wave - Short range: 60GHz
Longer range: 30-40GHz, 70/80/90GHz

cm-wave: 6-30GHz

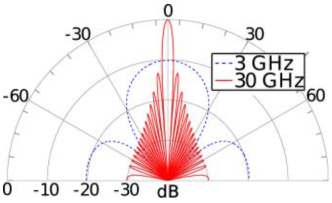
Mm-wave Wireless: 30-300 GHz

A unique opportunity for addressing the wireless data challenge

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

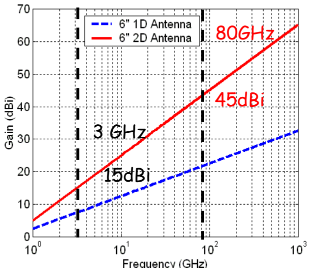
Compact high-dimensional (massive) multi-antenna arrays
6" x 6" antenna @ 80GHz: 6400-element antenna array

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&NB'10; JB,AS&NB '13)

Beamspace MIMO

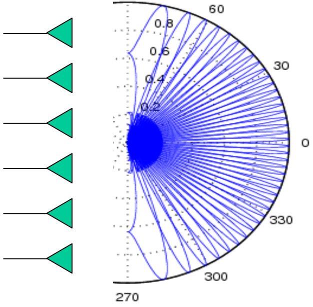
Multiplexing data into
multiple highly-directional (high-gain) beams

Antenna space multiplexing

Discrete Fourier Transform (DFT)

Beamspace multiplexing

n dimensional signal space



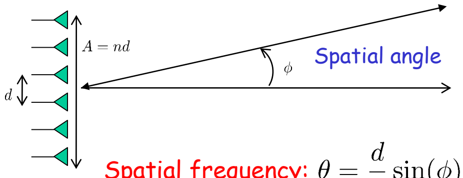
n-element array
($\frac{\lambda}{2}$ spacing)

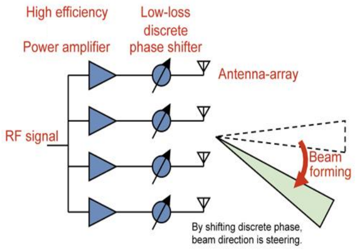
n orthogonal beams
↕
n spatial channels

(AS'02; AS&NB '10; JB,AS&NB '13)

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

n-element (Phased) Antenna Array





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

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

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:

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

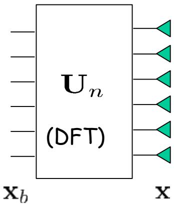
n orthogonal spatial beams

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

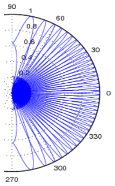
DFT spatial modulation matrix:

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

(n-dimensional orthogonal basis)



n = 40



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

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

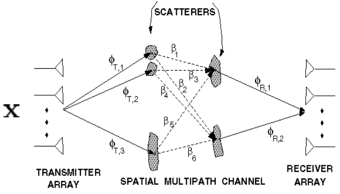
Unitary

Antenna vs Beamspace Representation

$n_R \times n_T$
MIMO system

TX

RX



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

(correlated)

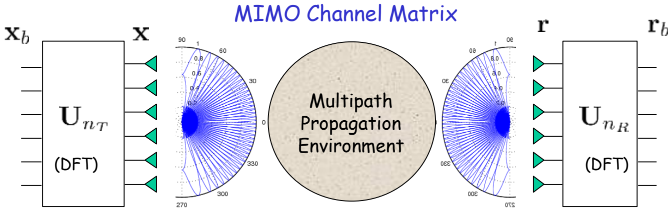
$$\boxed{\mathbf{H}_b = \mathbf{U}_{n_R}^H \mathbf{H} \mathbf{U}_{n_T}}$$

MIMO Channel Matrix

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

(decorrelated)

TX:
$\mathbf{x} = \mathbf{U}_{n_T} \mathbf{x}_b$



RX:
$\mathbf{r}_b = \mathbf{U}_{n_R}^H \mathbf{r}$

Multipath
channel:

$$\mathbf{H} = \sum_{\ell=1}^{N_p} \beta_\ell \mathbf{a}_{n_R}(\theta_{R,\ell}) \mathbf{a}_{n_T}^H(\theta_{T,\ell})$$

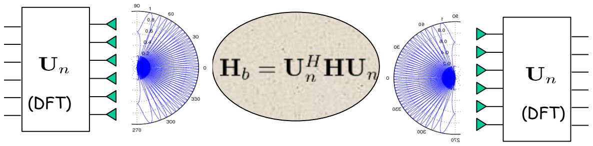
$$\mathbf{H}_b(i,m) = \sum_{\ell=1}^{N_p} \beta_\ell D_{n_R}\left(\theta_{R,\ell} - \frac{i}{n_R}\right) D_{n_T}\left(\theta_{T,\ell} - \frac{m}{n_T}\right) \qquad D_M(\theta) = \frac{\sin(\pi M \theta)}{\sin(\pi\theta)}$$

(AS'02)

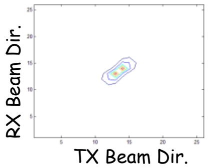
Massive MIMO Channel: Beamspace Sparsity

Massive Arrays (mmW)

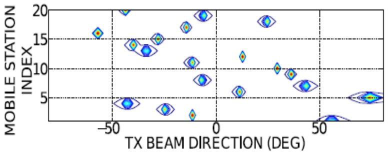
- Directional, quasi-optical
- Primarily line-of-sight
- Single-bounce multipath



Point-to-point
LoS Link



Point-to-multipoint
multiuser link



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?

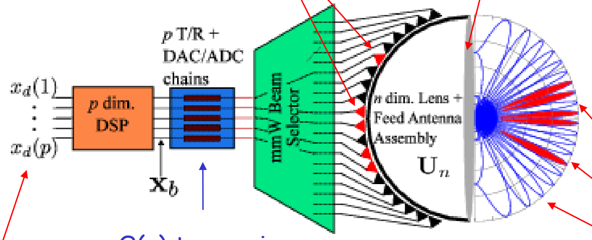
(AS&NB'10; Pi&Khan'11; Rappaport et. al,'13)

Continuous Aperture Phased (CAP) MIMO

Practical Hybrid Analog-Digital Beamspace MIMO Transceiver
(patented)

Focal surface feed antennas:
direct access to beamspace

Lens computes
analog spatial DFT



Data multiplexing
through
active beams

n analog
beams

p digital
data streams

O(p) transceiver
complexity

Beam Selection
p << n
active beams

Performance vs Complexity Optimization

(AS & NB'10, '11; JB, AS, NB, '13)

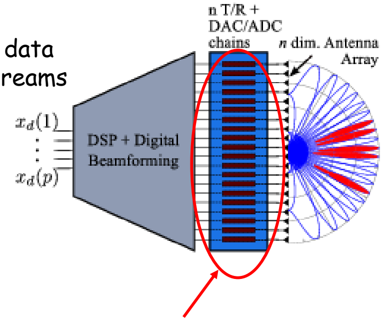
Digital vs Analog Beamforming:
Spatial Analog-Digital Interface

Conventional MIMO:
Digital Beamforming

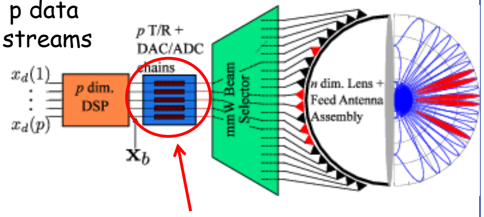
Beam Selection
p << n
active beams

CAP MIMO:
Analog Beamforming

p data
streams



p data
streams



O(n) transceiver complexity

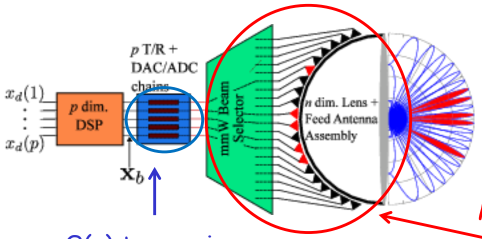
O(p) transceiver complexity

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

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

CAP-MIMO vs Phased-Array-Based Hybrid Architectures

CAP-MIMO:

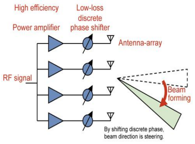


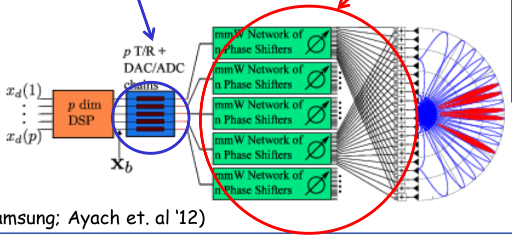
Lens
+
Beamspace Array
+
mmW Beam Selector Network

Multi-beam forming mechanism

O(p) transceiver complexity

Phased-Array-Based:
n phase shifters
per data stream



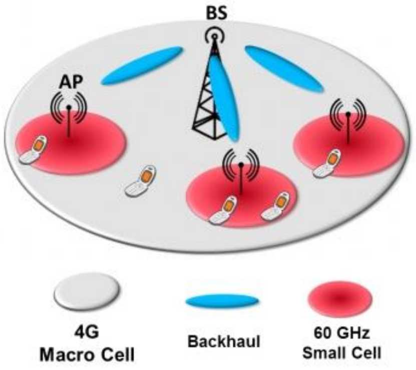


Phase Shifter Network (np)
+
Combiner Network

(e.g., Samsung; Ayach et. al '12)

Point-to-Multipoint Network Links

Fixed (backhaul) and dynamic (access) links



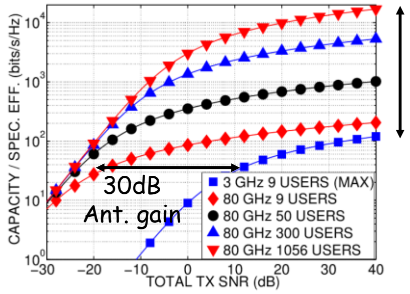
(siliconsemiconductor.net)

Electronic multi-beam steering and MIMO data multiplexing

Dense Beamspace Multiplexing

small-cell access points

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

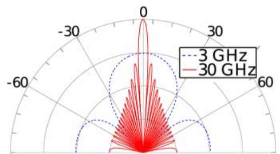


6" x 6" antenna

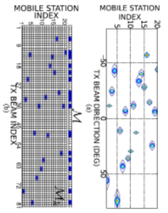
x 2-200 increase in capacity
due to beamspace multiplexing

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

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



Beamspace
channel sparsity



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

2D Arrays for Small-Cell AP

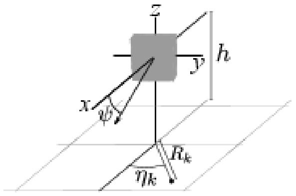
2D steering vector: $\mathbf{a}_n(\theta^{az}, \theta^{el}) = \mathbf{a}_{n_{az}}(\theta^{az}) \otimes \mathbf{a}_{n_{el}}(\theta^{el})$

Beamspace
Transformation
Matrix:

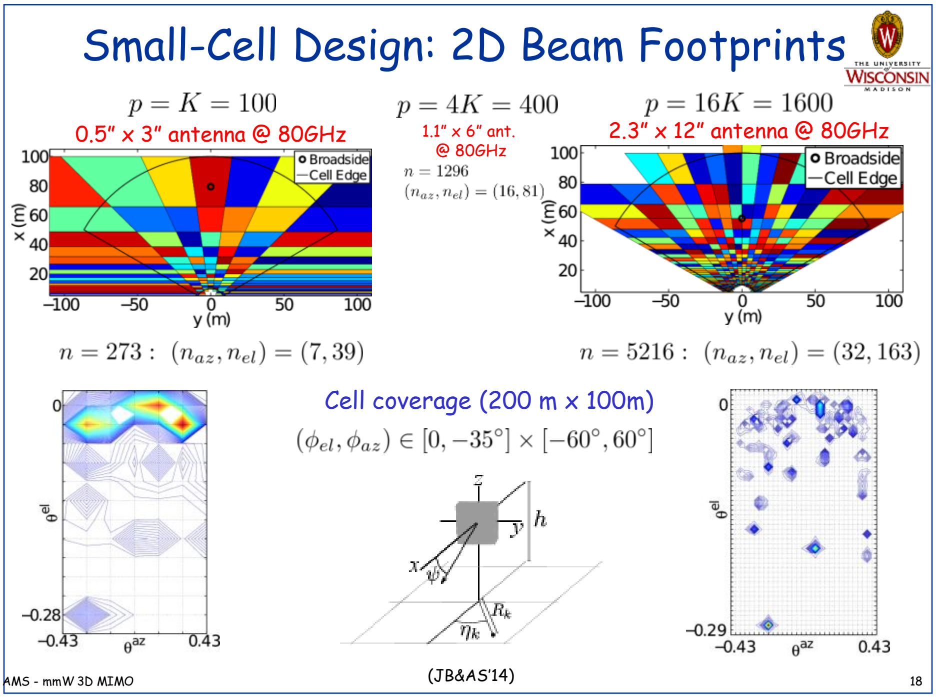
$$\mathbf{U}_n = \mathbf{U}_{n_{az}} \otimes \mathbf{U}_{n_{el}}$$

k-th user channel: $\mathbf{h}_k = \beta_{k,0}\mathbf{a}_n(\theta^{\mathrm{az}}_{k,0}, \theta^{\mathrm{el}}_{k,0}) + \sum_{i=1}^{N_p} \beta_{k,i}\mathbf{a}_n(\theta^{\mathrm{az}}_{k,i}, \theta^{\mathrm{el}}_{k,i})$

$$\theta_k^{\mathrm{az}} = \frac{1}{2}\frac{R_k \sin\eta_k}{\sqrt{(R_k\cos\eta_k\cos\psi + h\sin\psi)^2 + R_k^2\sin^2\eta_k}}$$
$$\theta_k^{\mathrm{el}} = \frac{1}{2}\frac{R_k\cos\eta_k\sin\psi - h\cos\psi}{\sqrt{R_k^2\cos\eta_k^2 + h^2}}\ .$$



(JB&AS'14)



Small-Cell Design: 2D Beam Footprints

$p = K = 100$

0.5" x 3" antenna @ 80GHz

$p = 4K = 400$

1.1" x 6" ant. @ 80GHz

$n = 1296$

$(n_{az}, n_{el}) = (16, 81)$

$p = 16K = 1600$

2.3" x 12" antenna @ 80GHz

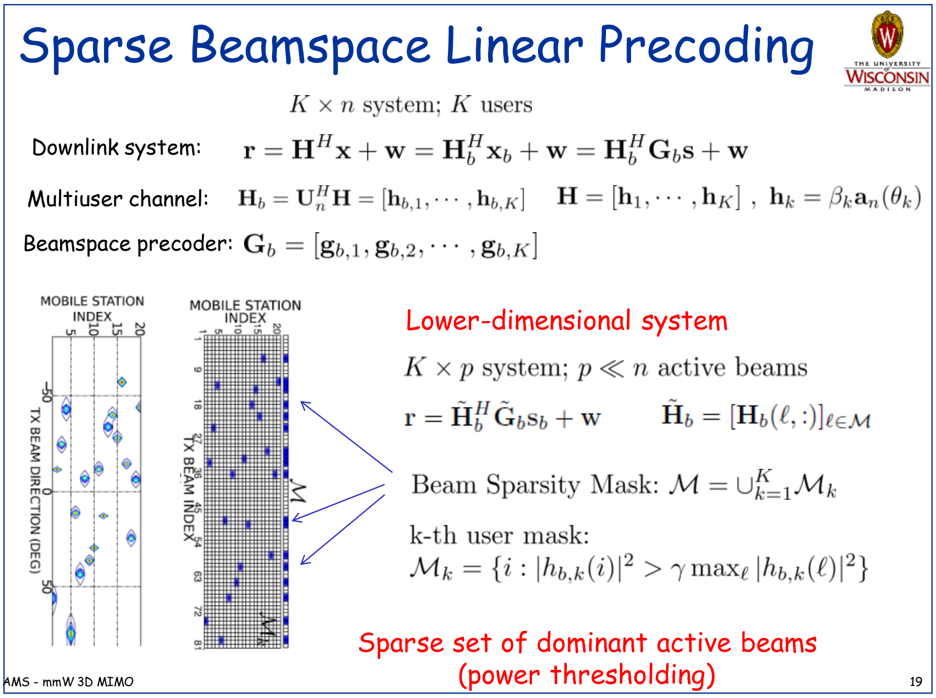
$n = 273 : \ (n_{az}, n_{el}) = (7, 39)$

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

Cell coverage (200 m x 100m)

$(\phi_{el}, \phi_{az}) \in [0, -35°] \times [-60°, 60°]$

(JB&AS'14)



Sparse Beamspace Linear Precoding

$K \times n$ system; K users

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

Multiuser channel: $\mathbf{H}_b = \mathbf{U}_n^H \mathbf{H} = [\mathbf{h}_{b,1}, \cdots, \mathbf{h}_{b,K}]$ $\quad \mathbf{H} = [\mathbf{h}_1, \cdots, \mathbf{h}_K]\ , \ \mathbf{h}_k = \beta_k \mathbf{a}_n(\theta_k)$

Beamspace precoder: $\mathbf{G}_b = [\mathbf{g}_{b,1}, \mathbf{g}_{b,2}, \cdots, \mathbf{g}_{b,K}]$

Lower-dimensional system

$K \times p$ system; $p \ll n$ active beams

$\mathbf{r} = \tilde{\mathbf{H}}_b^H \tilde{\mathbf{G}}_b \mathbf{s}_b + \mathbf{w} \qquad \tilde{\mathbf{H}}_b = [\mathbf{H}_b(\ell, :)]_{\ell \in \mathcal{M}}$

Beam Sparsity Mask: $\mathcal{M} = \cup_{k=1}^{K} \mathcal{M}_k$

k-th user mask:
$\mathcal{M}_k = \{i : |h_{b,k}(i)|^2 > \gamma \max_\ell |h_{b,k}(\ell)|^2\}$

Sparse set of dominant active beams
(power thresholding)

Sum Capacity: Sparse MMSE Precoding

Beamspace Downlink:

$$\mathbf{r} = \tilde{\mathbf{H}}_b^H \tilde{\mathbf{G}}_b \mathbf{s}_b + \mathbf{w} \qquad \tilde{\mathbf{x}}_b = \tilde{\mathbf{G}}_b \mathbf{s}_b = \sum_{i=1}^{K} \tilde{\mathbf{g}}_{b,i} s_{b,i}$$

MMSE Precoder:

$$\tilde{\mathbf{G}}_b = \alpha \mathbf{F} = \alpha[\mathbf{f}_1, \mathbf{f}_2, \cdots, \mathbf{f}_K] \ , \ \alpha = \sqrt{\frac{\rho}{\mathrm{tr}(\mathbf{F}\mathbf{\Lambda}_s\mathbf{F}^H)}}$$

$$\mathbf{F} = (\tilde{\mathbf{H}}_b \tilde{\mathbf{H}}_b^H + \zeta \mathbf{I})^{-1} \tilde{\mathbf{H}}_b \ , \ \zeta = \sigma^2 K / \rho$$

Capacity:

$$C(\rho) = E[C(\rho|\tilde{\mathbf{H}}_b)]$$

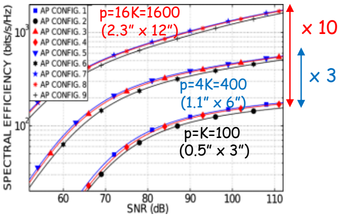
$$C(\rho|\tilde{\mathbf{H}}_b) = \sum^{K} \log_2(1 + \mathrm{SINR}_k(\rho|\mathbf{H})) \text{ bits/s/Hz}$$

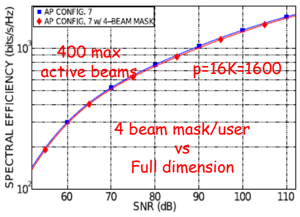
$$\mathrm{SINR}_k(\rho|\tilde{\mathbf{H}}_b) = \frac{\rho \frac{|\alpha|^2}{K} |\mathbf{h}_k^H \mathbf{f}_k|^2}{\rho \frac{|\alpha|^2}{K} \sum_{m \neq k} |\mathbf{h}_k^H \mathbf{f}_m|^2 + \sigma^2} \ .$$

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

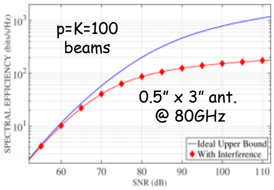
(MMSE precoder:
Joham, Utschick, & Nossek 2005)

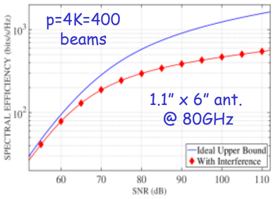
2D Array AP: Performance vs Complexity

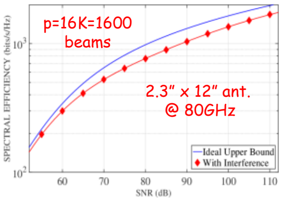




Upperbound vs MMSE precoder performance



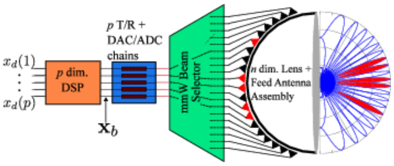


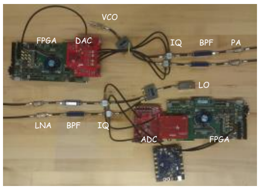


AP config.	$\psi(^\circ)$	n_{az}	n_{el}	n	p	$\tilde{n}_{az}$	$\tilde{n}_{el}$	$\tilde{n}$	Array Size at 80 GHz
1	7.2	7	39	273	105	7	32	224	0.45"×2.81"
2	10.3	7	36	245	103	7	29	203	0.45"×2.58"
3	37	7	34	238	100	7	19	133	0.45"×2.44"
4	6.4	16	81	1296	408	15	66	990	1.11"×5.91"
5	10.3	16	76	1216	402	15	61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

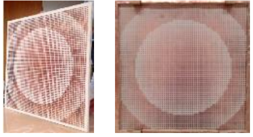
2-3 x times larger number of antennas in conventional arrays

10GHz CAP-MIMO Prototype

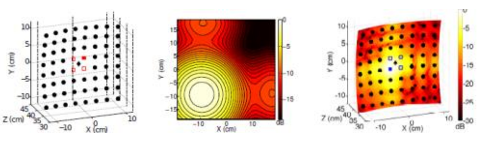


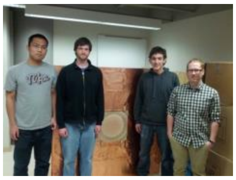


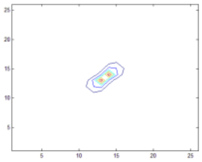
40cm x 40cm
Lens array

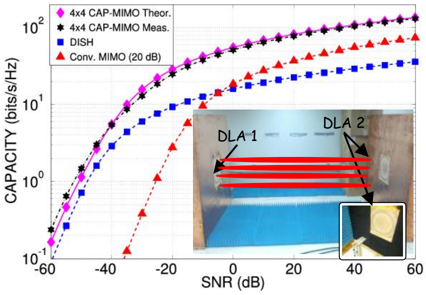


n=676, p=4 (channels), R=10ft







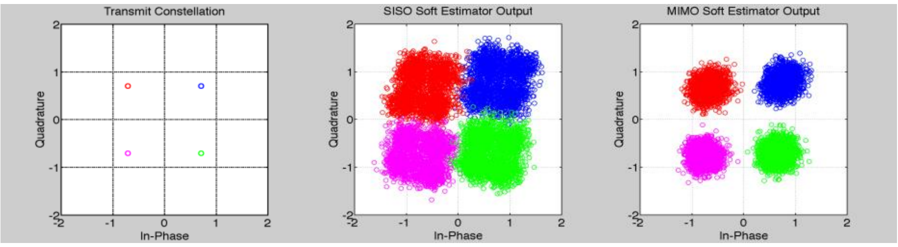


10 GHz LoS prototype theoretical performance:
100 Gigabits/sec (1 GHz BW) at 20dB SNR
Compelling gains over state-of-the-art

(JB,AS,NB '13; JB,PT,DV,AS '14)

Initial 2x2 Spatial Multiplexing Test

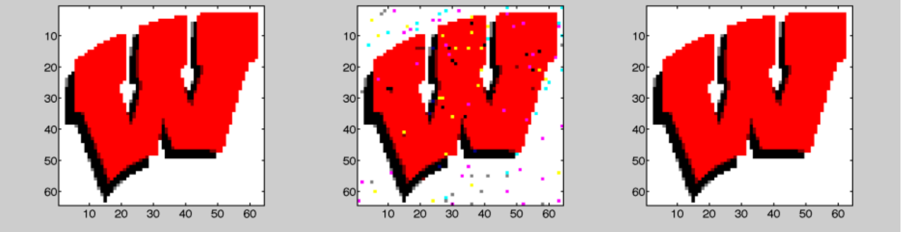
- 2 Spatial Channels
- Separate LO at TX and RX
- 500 Mbps data rate
- Separate TX and RX sample clocks



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

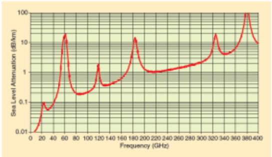
0 bit errors

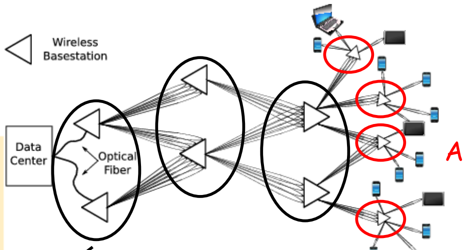
Ongoing Related Work

- Gen 2 prototype: 28 GHz, advanced functionality, higher BW
- Channel Measurements: truly massive and true beamspace
- Beam Selector Architecture; Channel Estimation & Discovery
- Spatial Analog-Digital Interface
  - High rates make DSP power hungry; more analog processing?
- Wideband High-Dimensional MIMO
  - Revisit “narrowband” model
  - OFDM, SC, SC-FDMA?

5G Use Cases of mmW MIMO Networks

Availability:
Atmospheric
absorption

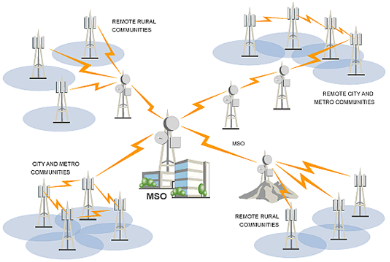




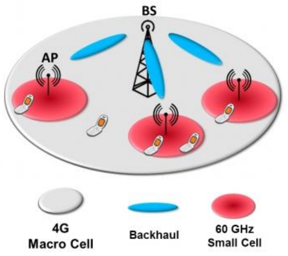
“small cell”
Access Network

Multi-Gbps
speeds

Backhaul
network



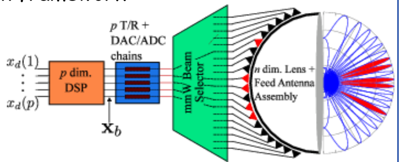
(Source: 3G.co.uk)



(siliconsemiconductor.net)

Conclusion

- Beamspace MIMO: Versatile theory & design framework
- CAP-MIMO: practical architecture
  - spatial A-D interface + DSP complexity



Performance-complexity optimization

- Compelling advantages over state-of-the-art
  - Capacity/SNR gains
  - Operational functionality
  - Electronic multi-beam steering & data multiplexing
- Timely applications (multi-Gigabits/s speeds)
  - Wireless backhaul networks; Indoor short-range links
  - Smart 5G Basestations: Dense Beamspace Multiplexing
- Prototyping: tech. demo + ch. meas. + industrial partnership

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Relevant Publications
(http://dune.ece.wisc.edu)

- A. Sayeed, Deconstructing Multi-antenna Fading Channels, IEEE Trans. Signal Proc., 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.
- J. Brady, P. Thomas, D. Virgilio, A. Sayeed, Beamspace MIMO Prototype for Low-Complexity Gigabit/s Wireless Communication, IEEE SPAWC, June 2014.
- A. Sayeed and T. Sivanadyan, Wireless Communication and Sensing in Multipath Environments Using Multiantenna Transceivers, Handbook on Array Processing and Sensor Networks, S. Haykin & K.J.R. Liu Eds, 2010.

Thank You!