EARS: Beamspace Communication Techniques and Architectures for Enabling Gigabit Mobile Wireless at Millimeter-Wave Frequencies

NSF EARS Workshop
October 7-8, 2013

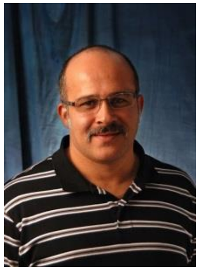
Akbar M. Sayeed

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

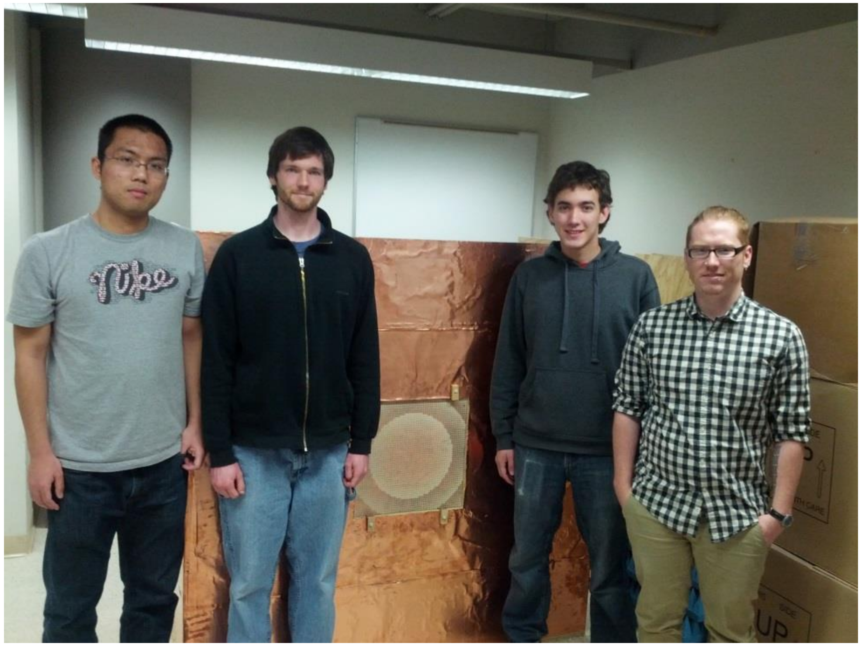
Supported by the NSF and the Wisconsin Alumni Research Foundation

Team

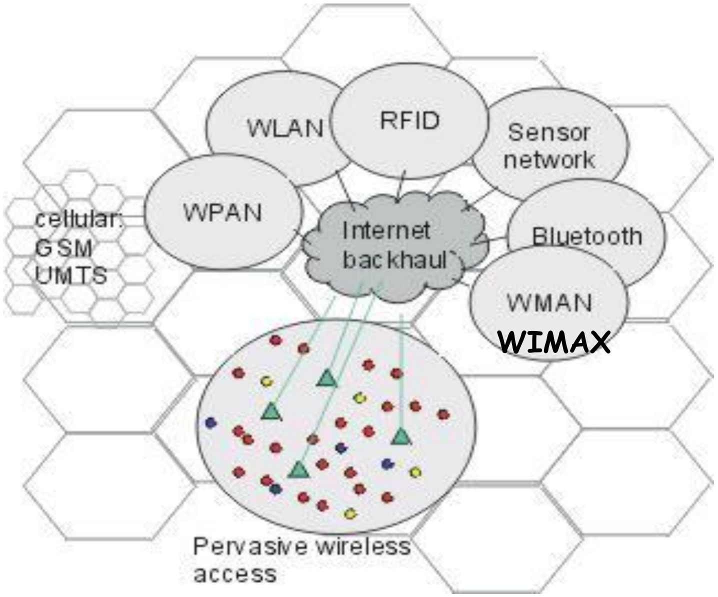
- Faculty:
  - Akbar Sayeed (PI)
  - Nader Behdad (co-PI)



- Students:
  - Hua Deng
  - Paul Thomas
  - David Virgilio (UG-REU)
  - John Brady



Explosive Growth in Wireless Traffic

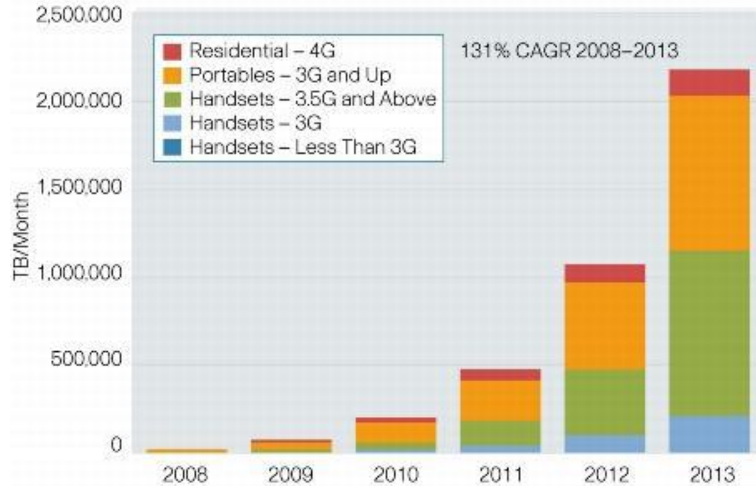


Source: www.nari.ee.ethz.ch

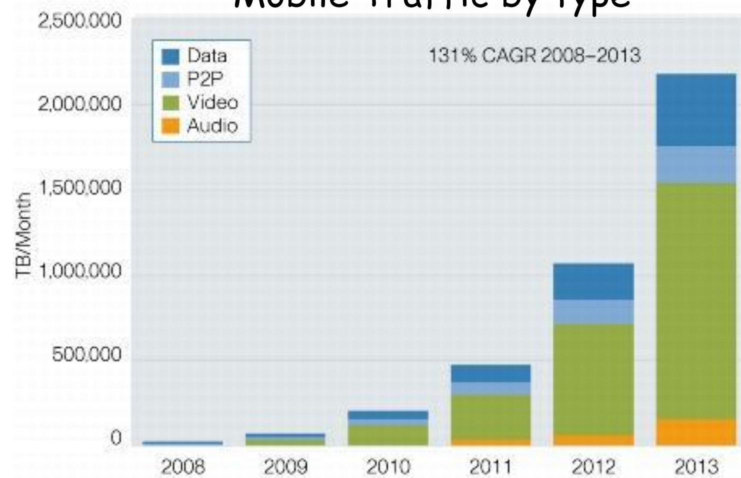
Heterogeneous devices and networks

Data-intensive apps Images/video

Mobile Traffic

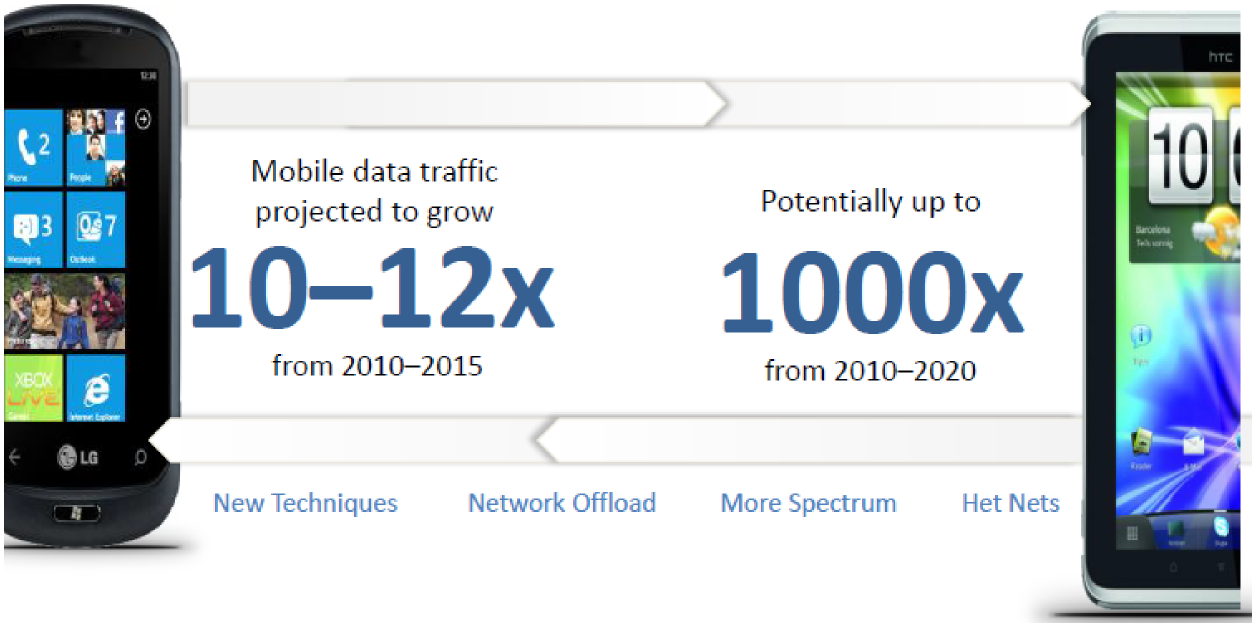


Mobile Traffic by type



Source: Cisco Visual Networking Index Oct. 2009

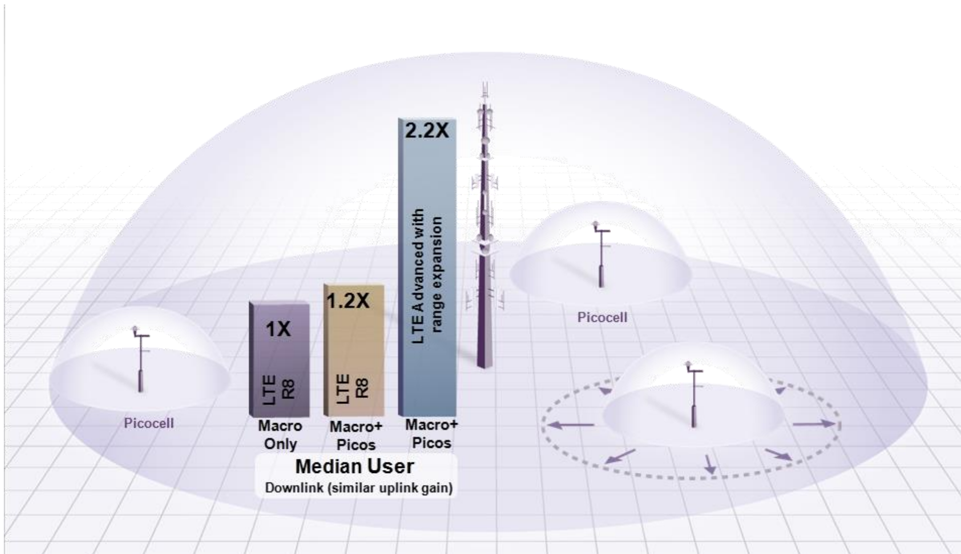
Wireless Data Challenge



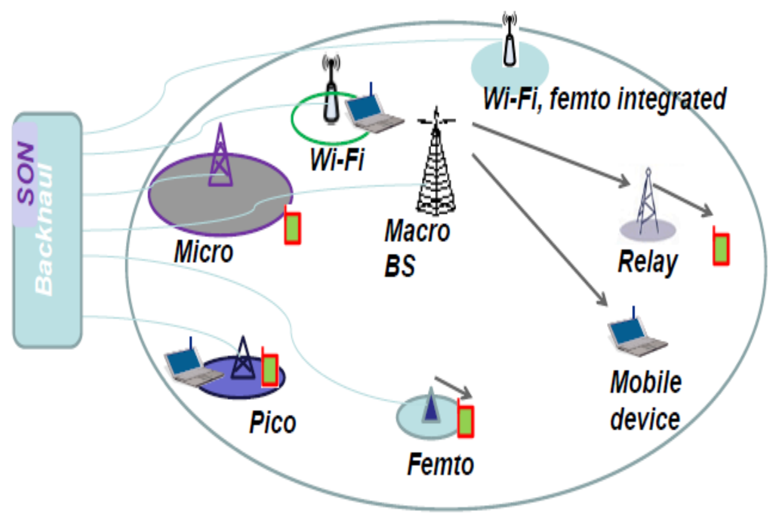
Courtesy: Dr. T. Kadous, Qualcomm

Current Industry Approach: Small Cells & Heterogeneous Networks

Key Idea:
Spatial reuse of precious spectrum



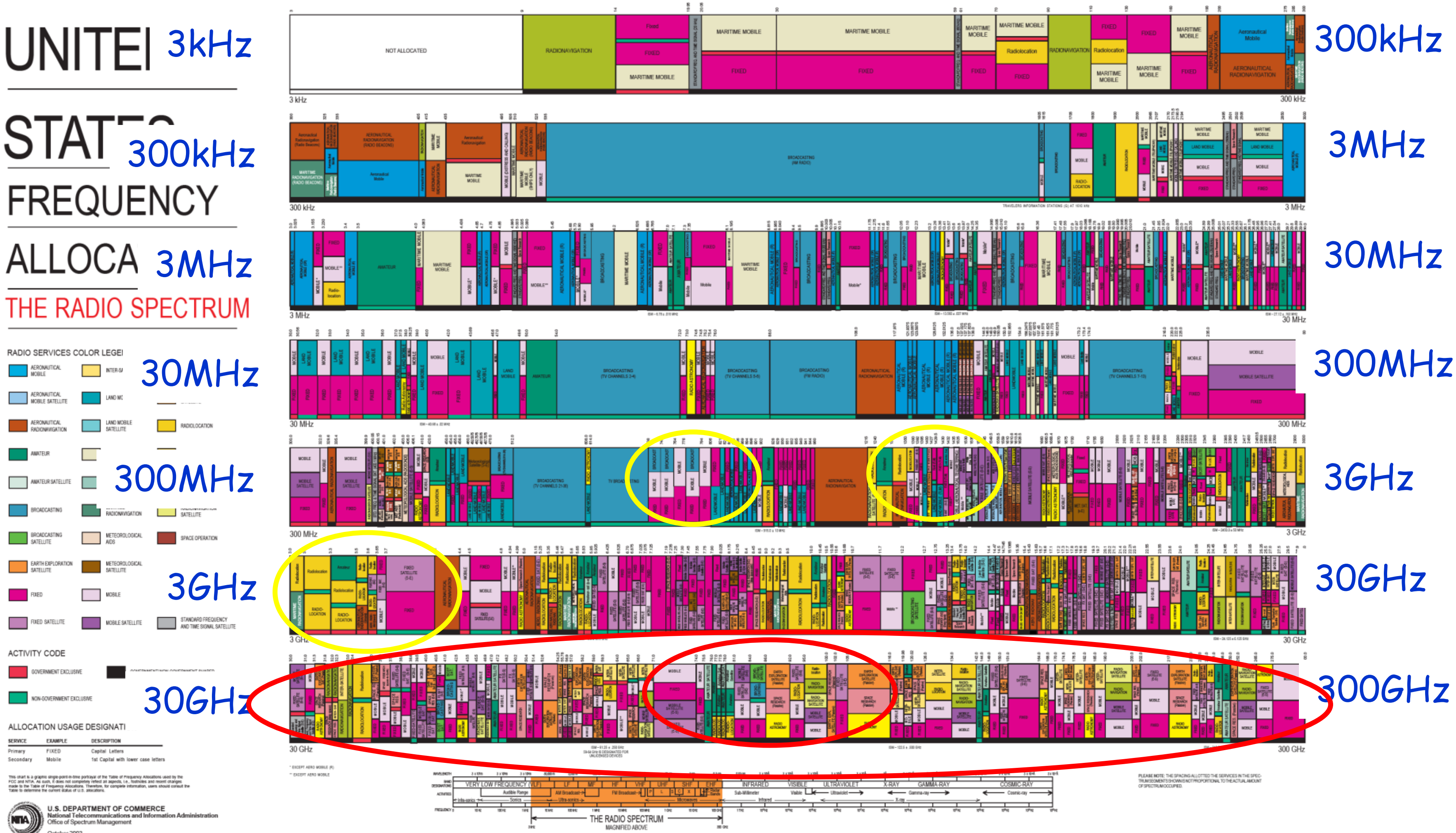
Courtesy: Dr. T. Kadous (Qualcomm)



Dr. J. Zhang (Samsung)

Some challenges: interference, backhaul

New Opportunity: mm-wave Band



Current cellular wireless: 300MHz-3GHz

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

Mm-wave Wireless: 30-300 GHz

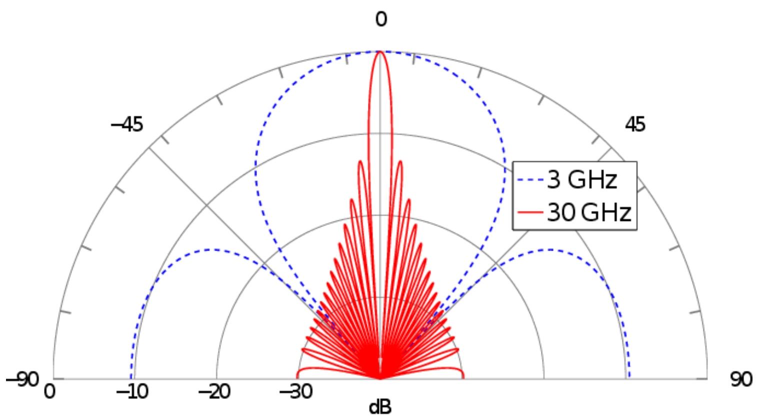
A unique opportunity for addressing the wireless data challenge

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

Compact high-dimensional multi-antenna arrays

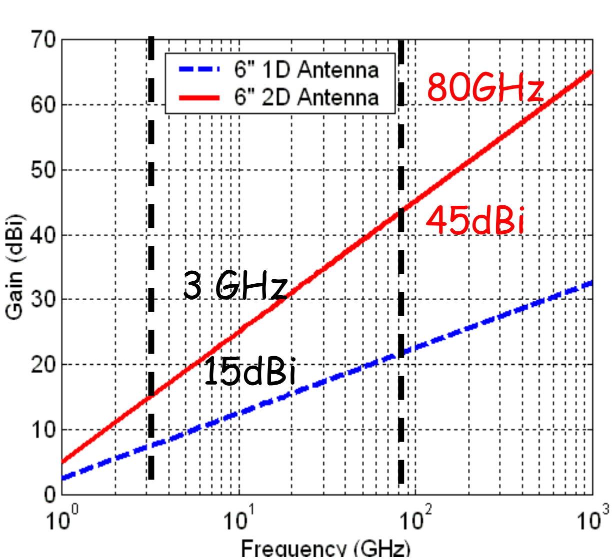
6″ antenna: 6400-element antenna array (80GHz)

Highly directive narrow beams
(low interference/higher security)



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

Large antenna gain



Key Challenges

Key Operational Functionality:

Electronic multi-beam steering & MIMO data multiplexing

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

Our Approach: Beamspace MIMO

Project Goal & Research Thrusts

Develop the Beamspace MIMO framework for realizing the full potential of mm-wave wireless (Gigabit mobile access)

- Antenna Array Architectures: Design, analysis and optimization for efficient access to beamspace
- Beamspace MIMO System Design: channel modeling & estimation, beamspace communication techniques
- Computational modeling and evaluation
- Prototype-based measurements & experimentation

Expected Outcomes

- Potentially transformative new technology
- Gigabit mobile wireless
- Technology transfer
- Unique platform for interdisciplinary training of students

Current & Emerging Applications

- Wireless backhaul; alternative to fiber
- Indoor wireless links (e.g., HDTV) IEEE 802.11ad, WiGig
- Smart basestations (point to multipoint operation)
- New cellular/mesh networks (data growth)

Gigabits/s speeds

Beamspace MIMO

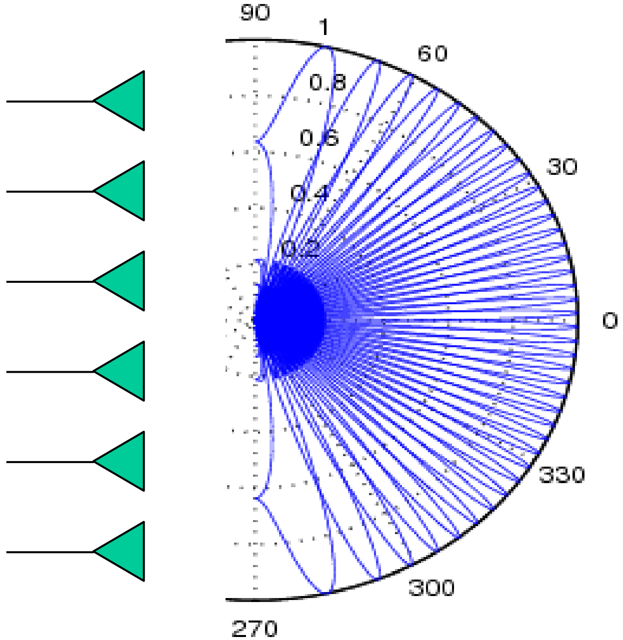
(AS '02, AS & NB '10)

Discrete Fourier Transform
(DFT)

Antenna space
multiplexing

Beamspace
multiplexing

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

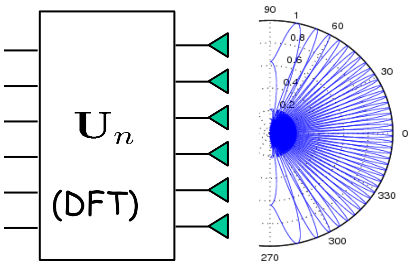


n orthogonal beams

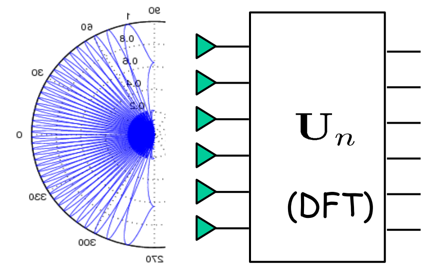
n dimensional signal space

Communication modes in optics (Gabor '61, Miller '00, Friberg '07)

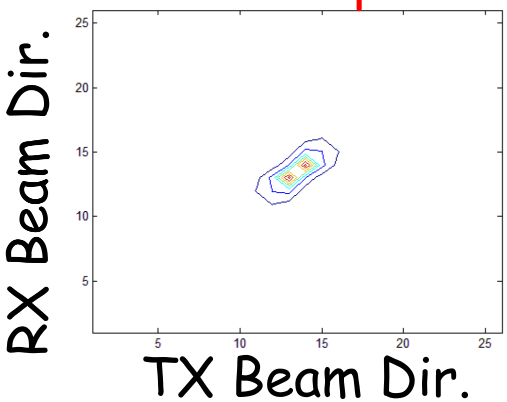
Channel Sparsity in Beamspace



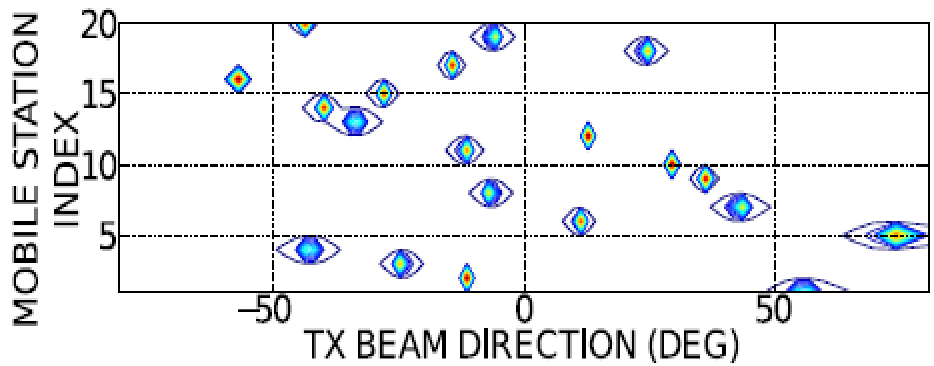
$$\mathbf{H}_b = \mathbf{U}_n^H \mathbf{H} \mathbf{U}_n$$



Point-to-point



Point-to-multipoint



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?

Hybrid Analog-Digital Transceiver Architecture

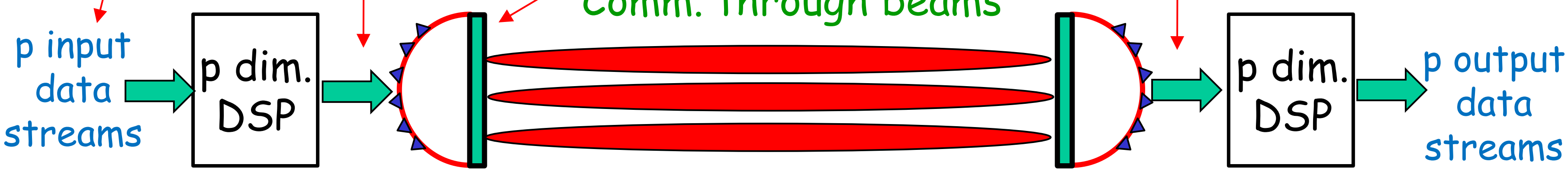
Digital modes:
p data streams

Analog modes:
n >> p (continuous aperture)

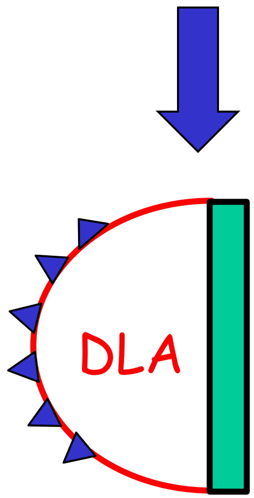
p dimensional D/A

p dimensional A/D

Comm. through beams



DLA focal surface



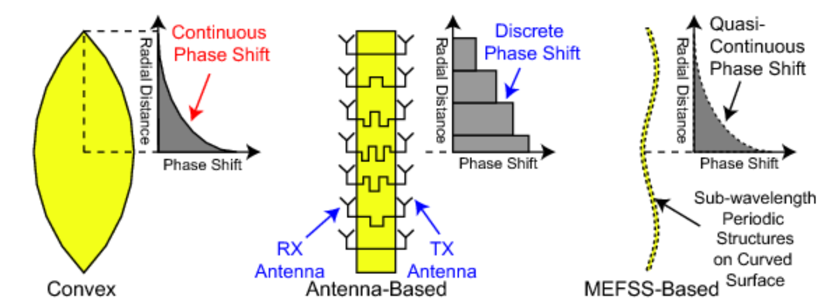
DLA Aperture (phase Profile)

Analog Fourier Transform

(Analog beamforming)

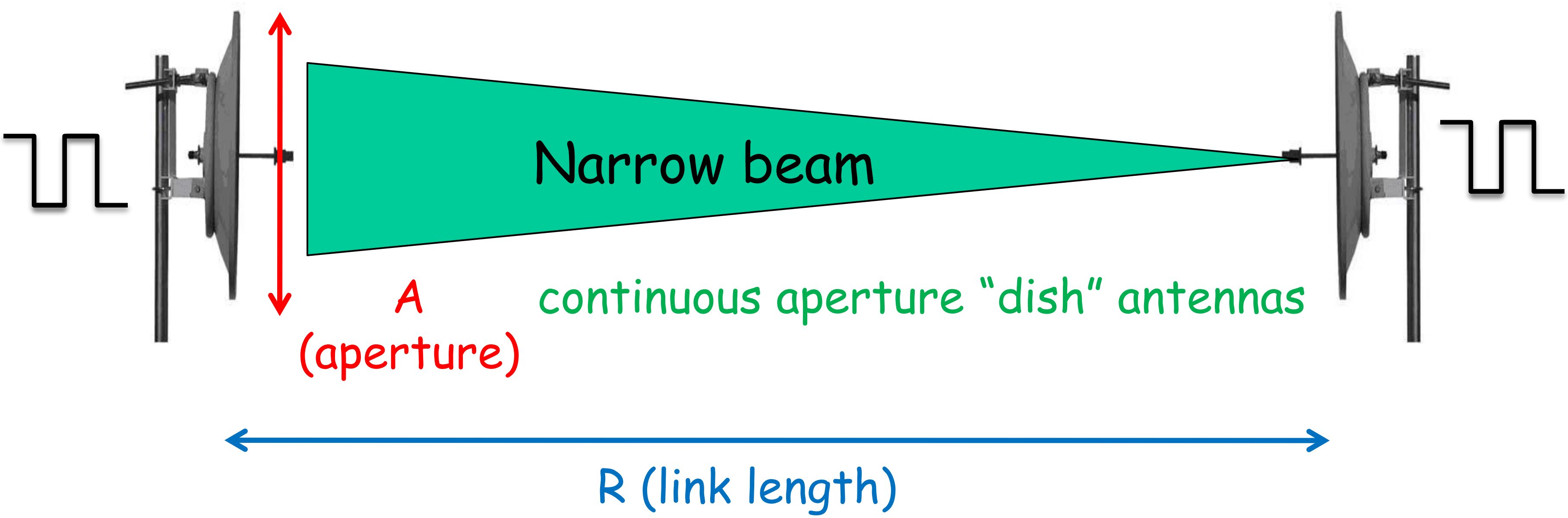
Analog Front-End: High-resolution Discrete Lens Array (DLA)

(Al-Joumayly and Behdad, 2010)



Convex Dielectric Lens (a) | Antenna-Based Discrete Lens Array (b) | MEFSS-Based Discrete Lens Array (c)

State-of-the-Art 1: DISH System



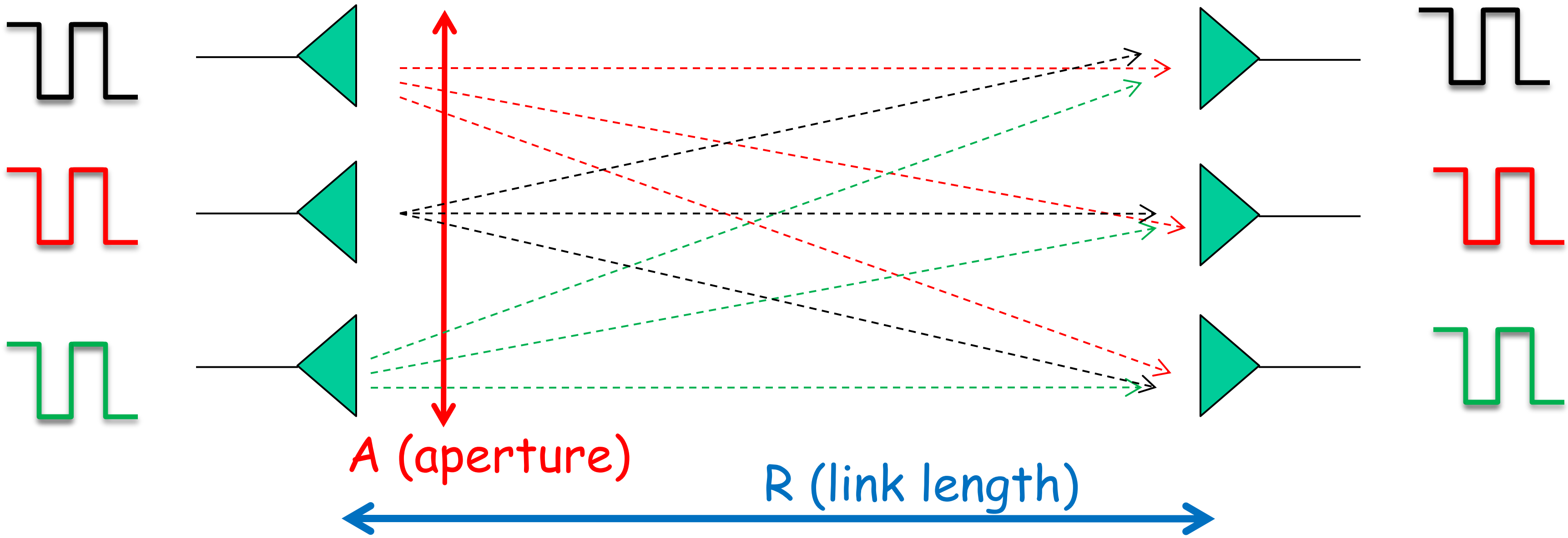
Pros: Large antenna gain (SNR gain) $G \propto \left(\frac{A}{\lambda}\right)^2$

Narrow beam (continuous aperture)

Cons: Single data stream

State-of-the-Art 2: MIMO System

Discrete Antenna Arrays (widely spaced)

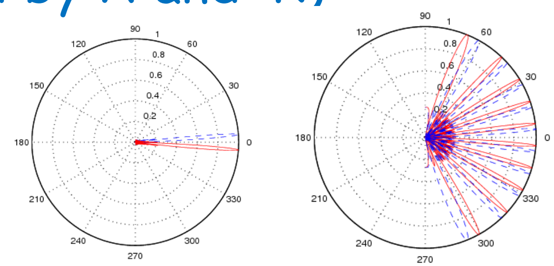


Pros: Multiplexing gain: Multiple (p) data streams

(p limited by A and R)

Cons: Reduced SNR gain

Grating lobes

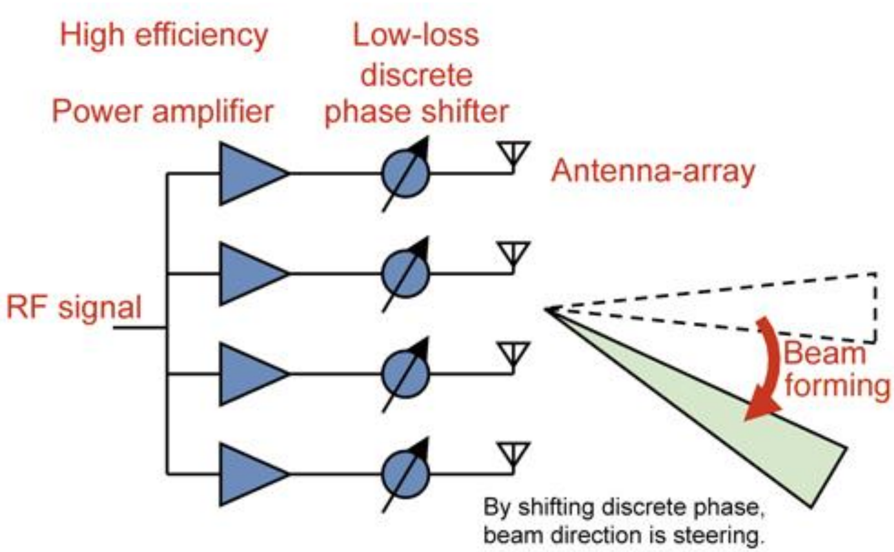


Madhow et. al. 06'

Bohagen et. al. 07'

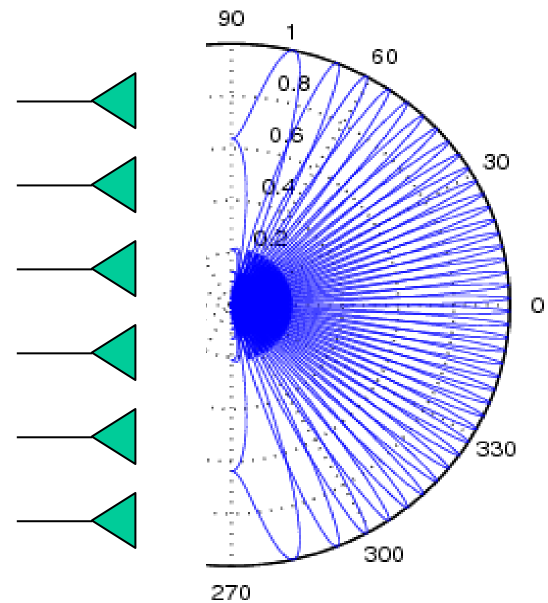
Chalmers

Phased Arrays & Beamspace MIMO



(Tohoku University)

Beam steering operation



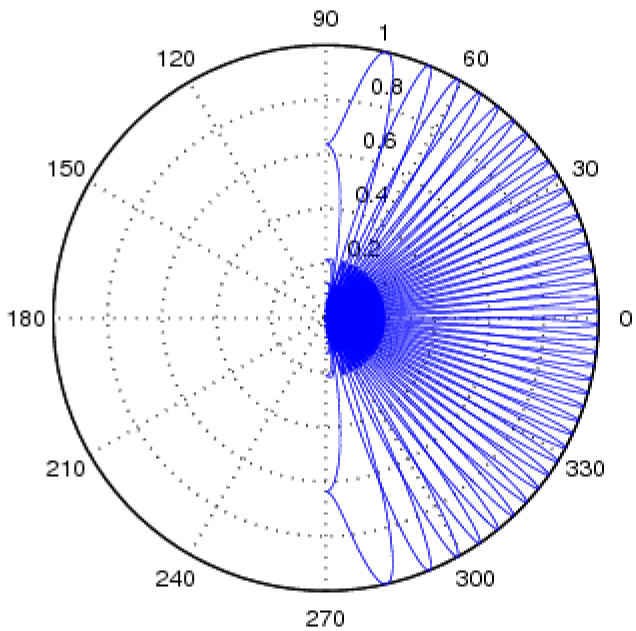
Multi-beam Operation

Key Operational Functionality:

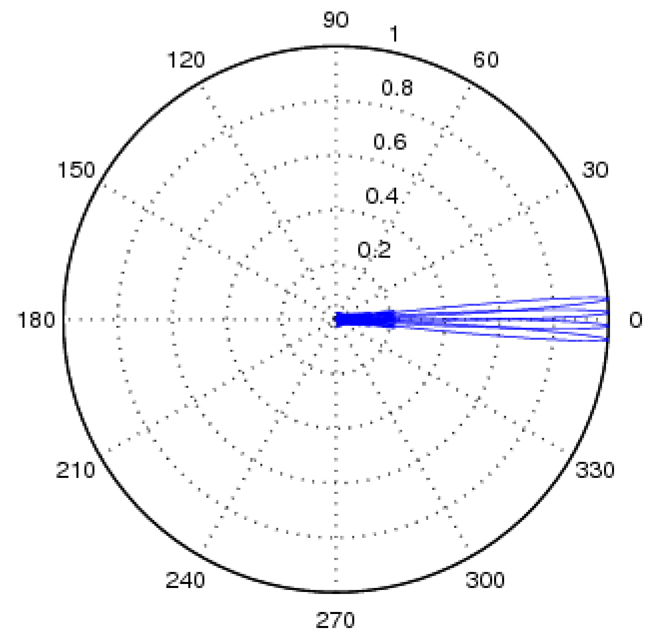
Electronic Multi-beam Steering and Data Multiplexing

LoS Channel: Coupled Orthogonal Beams

n = 40 orthogonal beams



$p_{max} = 4$ coupled beams



Finite Receiver Aperture

number of coupled beams:
(channel rank)

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

(Fresnel number)

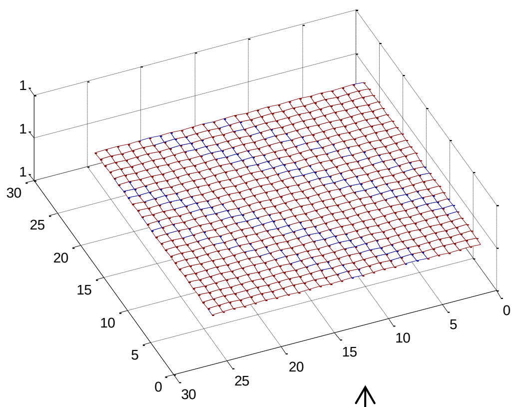
Spatial BW: $2\theta_{max} = \sin(\phi_{max}) \approx \frac{A}{2R}$

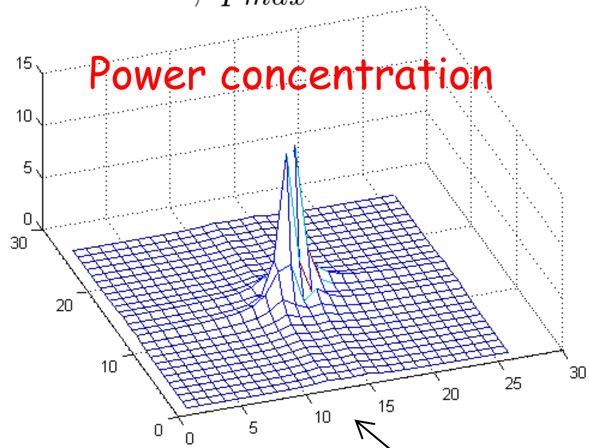
Spatial Res.: $\Delta\theta_o = \frac{1}{n} = \frac{\lambda_c}{2A}$

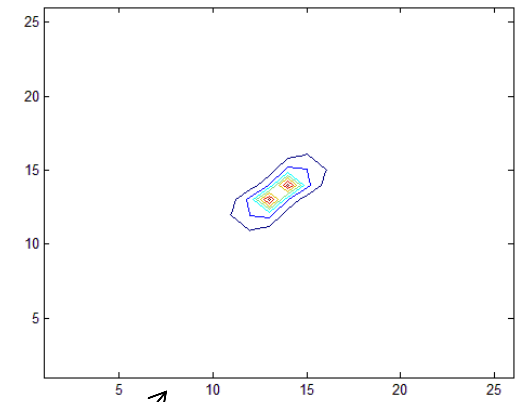
Near-Optimality of Beamspace Signaling

Coupled beams ~ channel eigenvectors

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







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

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

approx. eigenvectors (comm. subspace)

approx. diagonal (eigenvalues)

approx. eigenvectors (comm. subspace)

Capacity Comparison with State-of-the-Art

CAP-MIMO

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

MUX gain over DISH: p_{max}

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

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

DISH
no multiplexing gain
large SNR gain

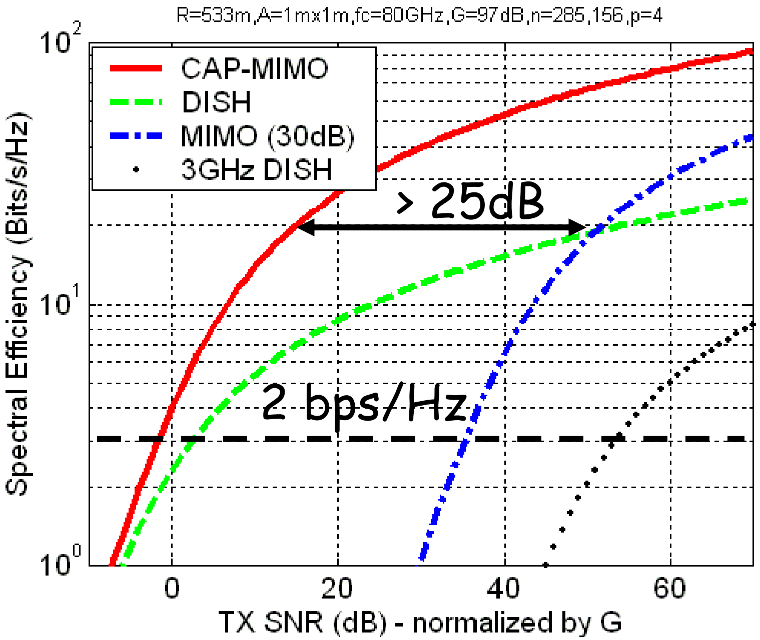
$$\boxed{C_{mimo}(\rho) = p_{max} \log(1 + \rho)}$$

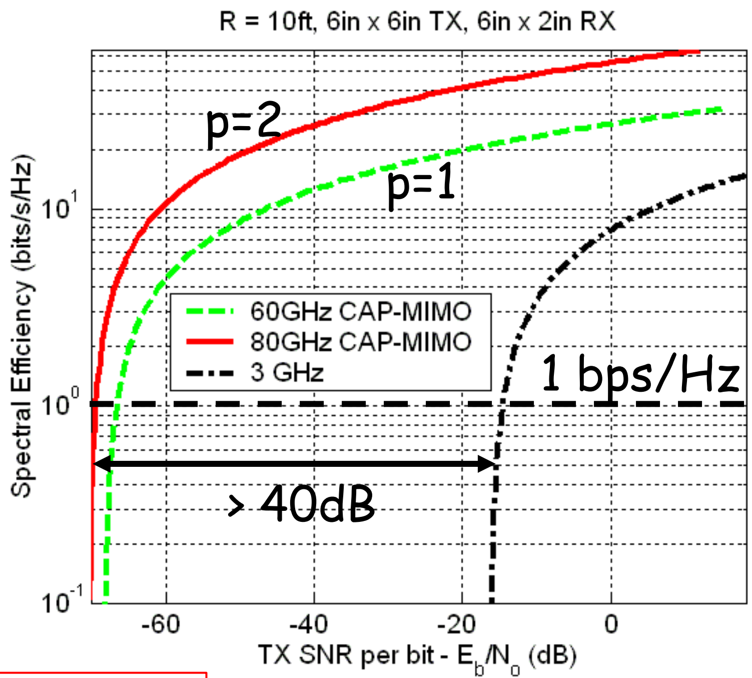
Conv. MIMO
maximum multiplexing gain
no/small SNR gain

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

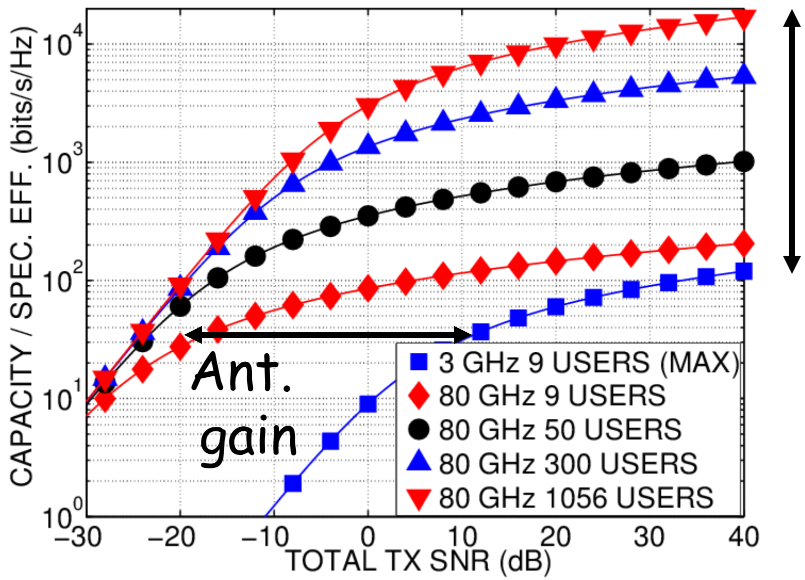
p: # data streams

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 Communication: Dense Spatial Multiplexing

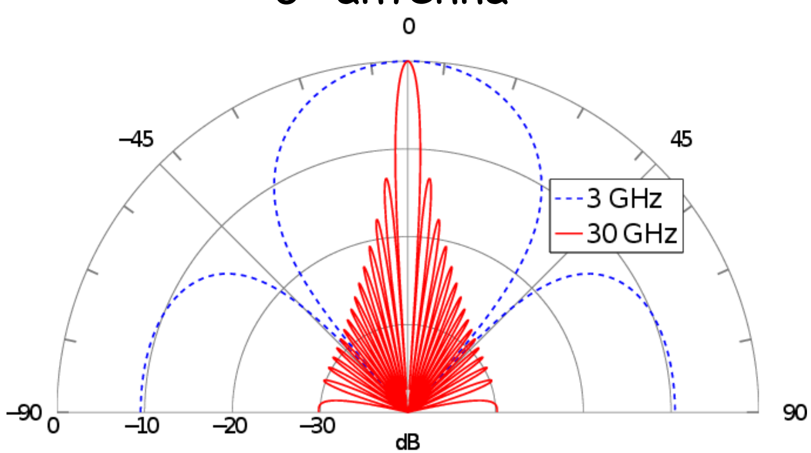


x100 increase in capacity due to beamspace multiplexing

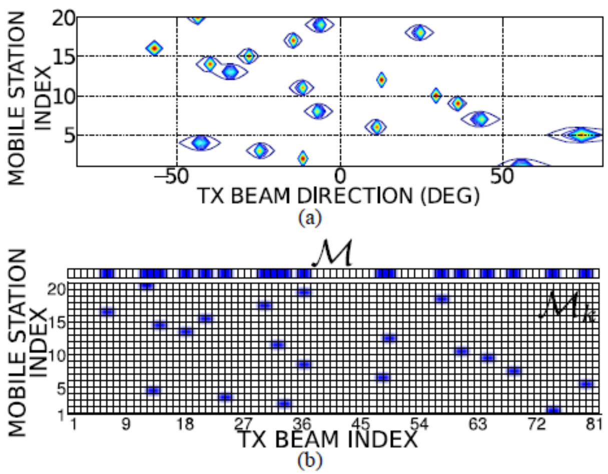
x10 increase in capacity due to extra bandwidth (~5GHz)

Potential throughput/cell:
500Gbps-50Tbps
(50Gbps/user)

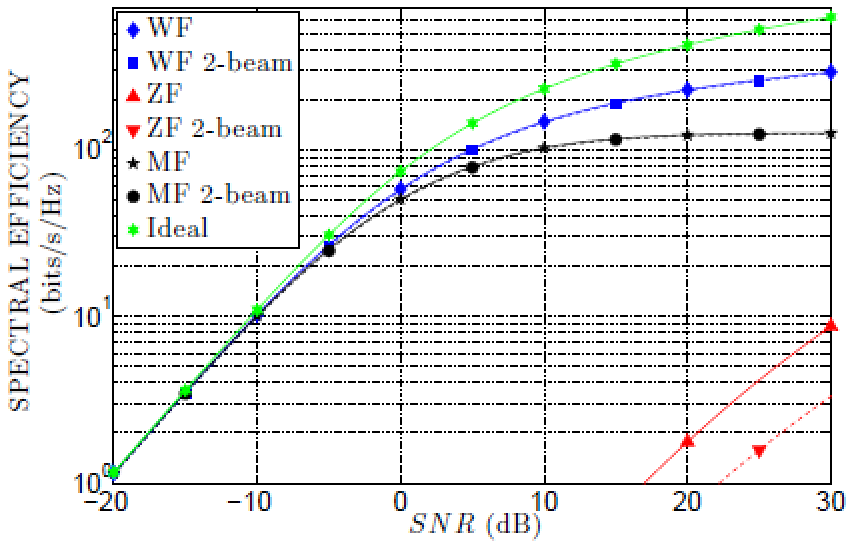
6" antenna

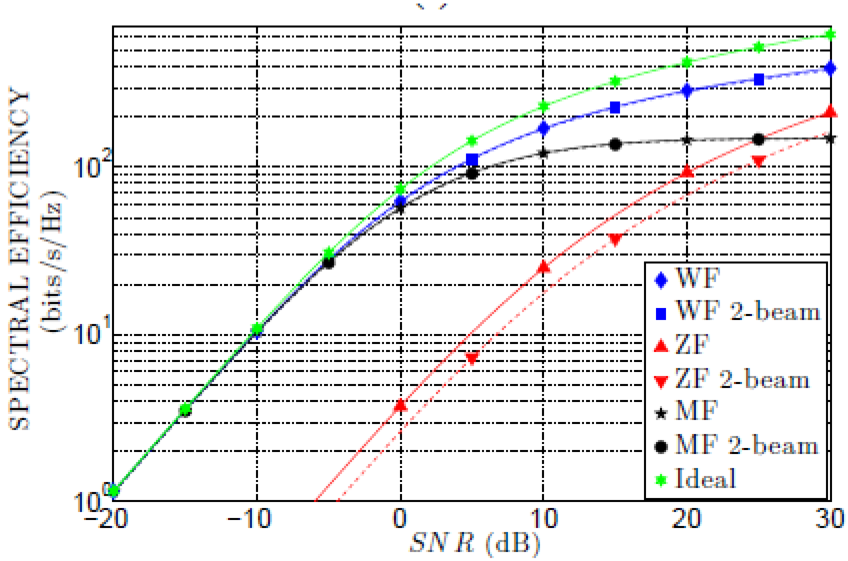


Beam selection



Approaching the Bound with Linear (Practical) 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

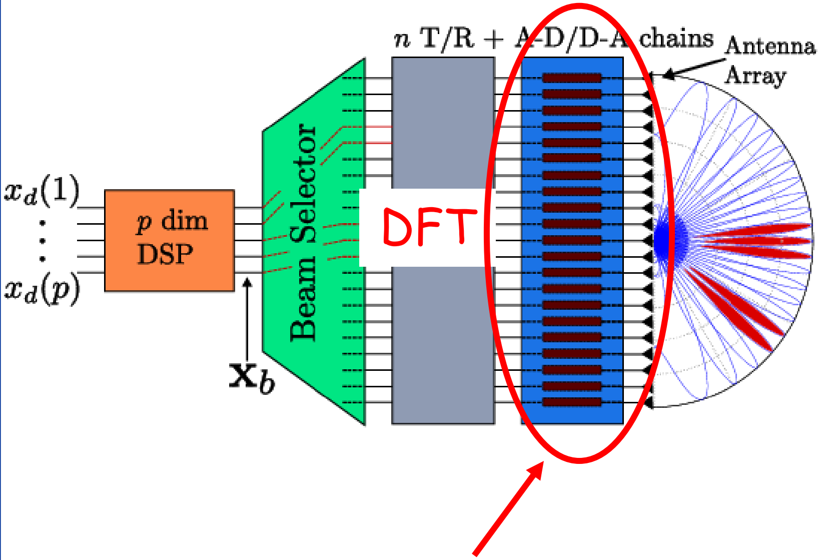
(AS & JB Globecom 2013)

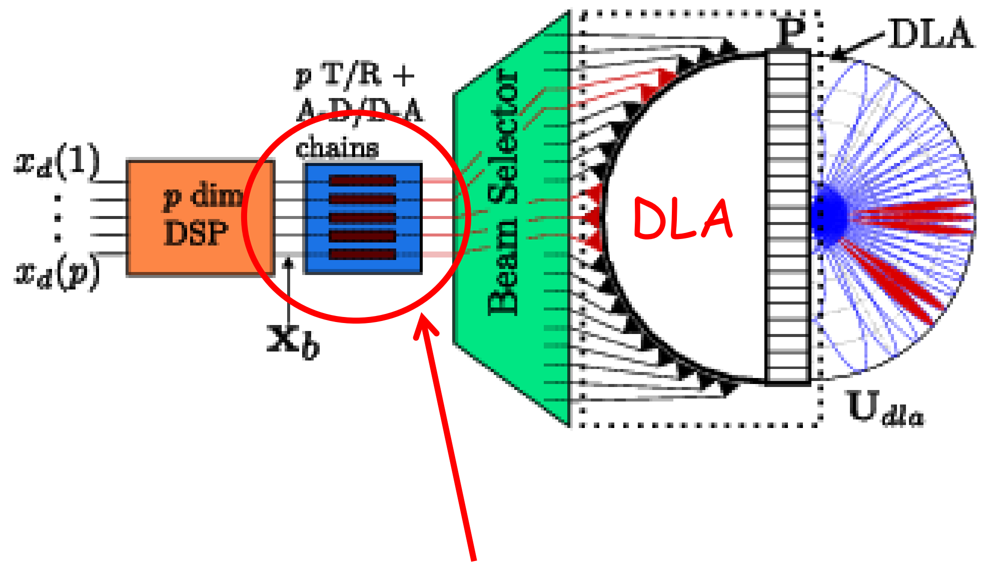
Spatial Analog-Digital Interface: Analog vs Digital Beamforming

Conventional MIMO:
Digital Beamforming

Beam Selection
p << n
active beams

CAP MIMO:
Analog Beamforming





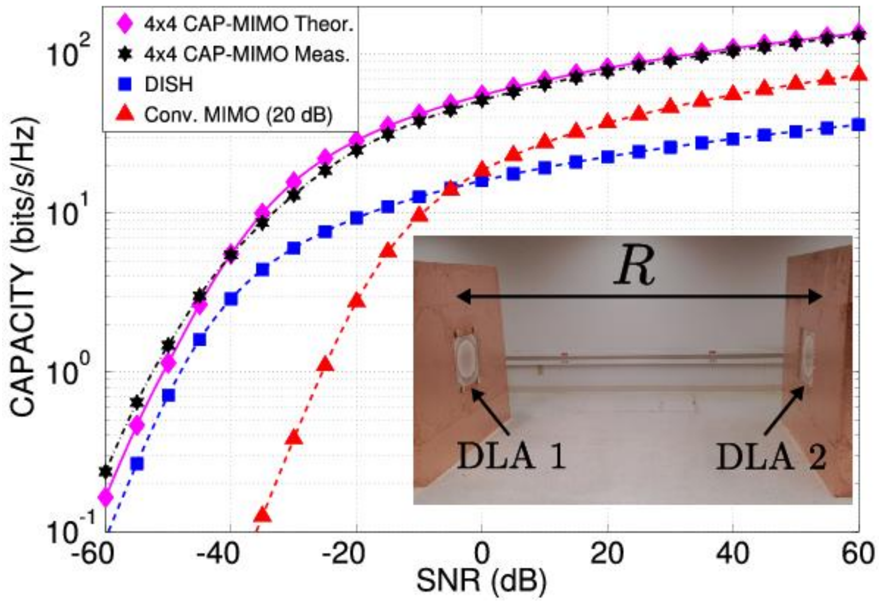
O(n) transceiver complexity

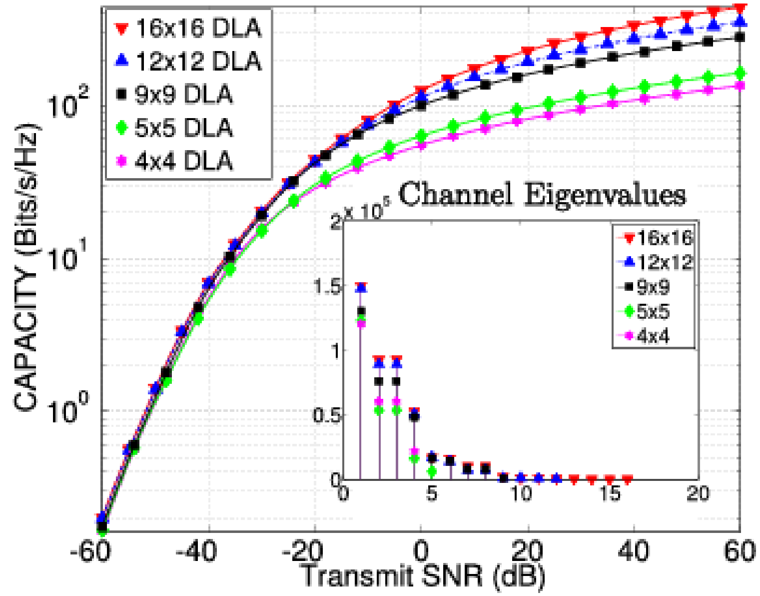
O(p) transceiver complexity

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

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

Initial Prototype Results (10 GHz)

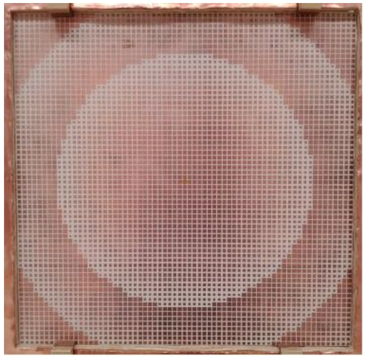




40cm x 40cm DLAs

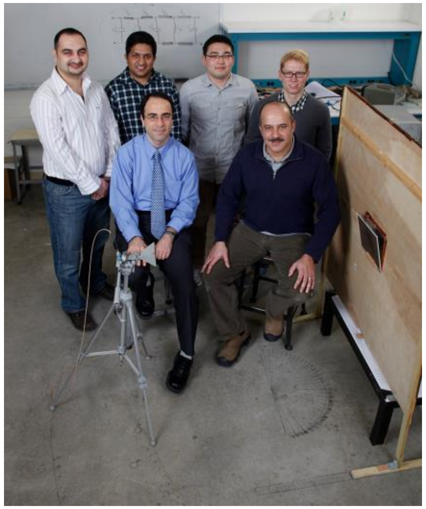
R = 10ft

n=676, p>=4



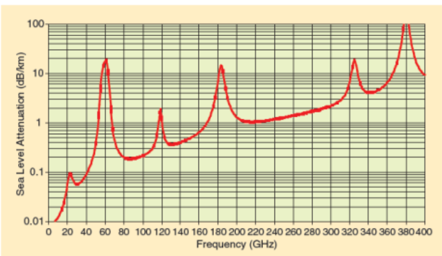
10-100 Gbps speeds (1 GHz BW)

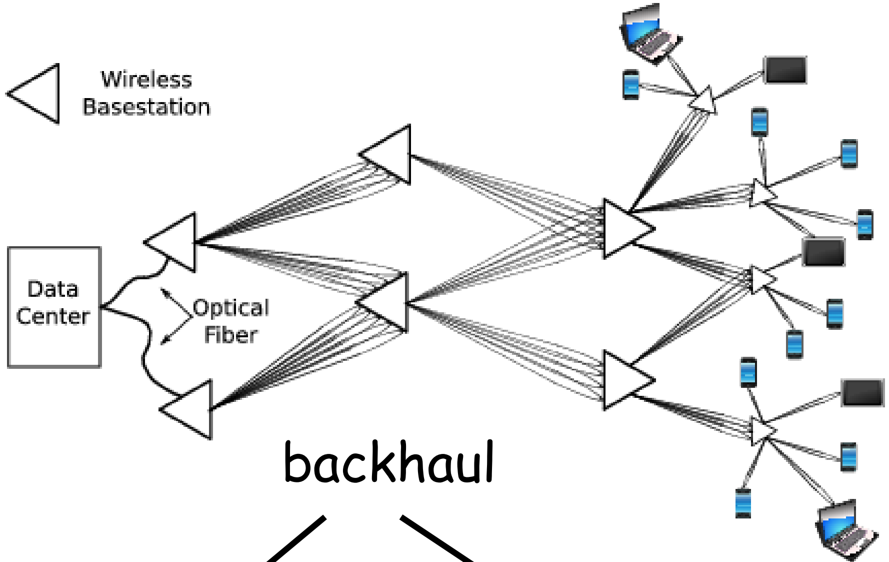
Capacity/SNR gains over DISH and conv. MIMO



Multi-scale mm-wave Networks

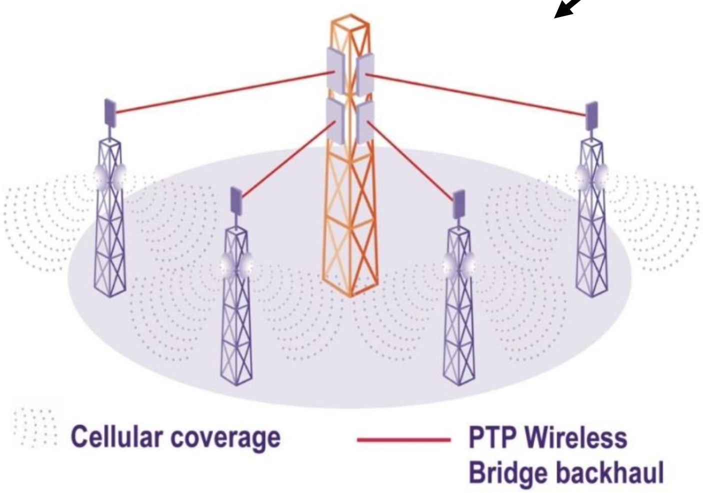
Availability:
Atmospheric absorption

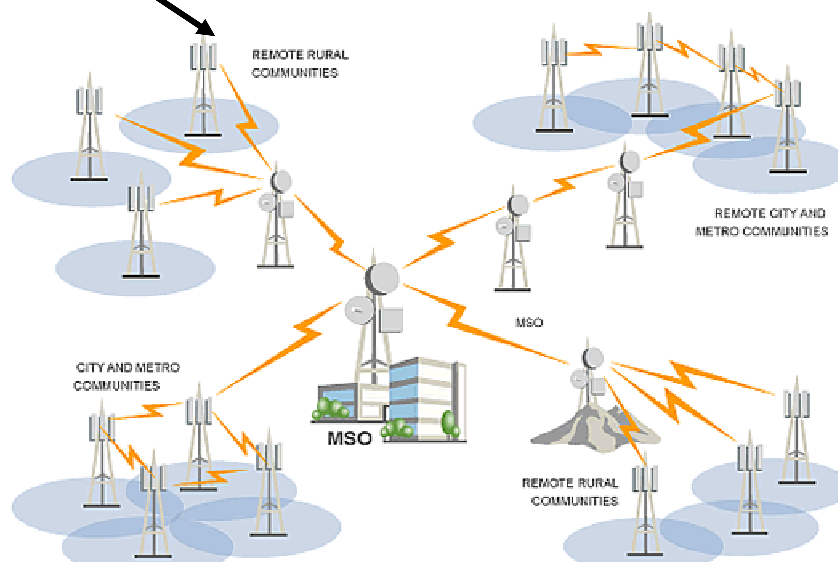




ideal "small cell" technology for multi-Gbps speeds

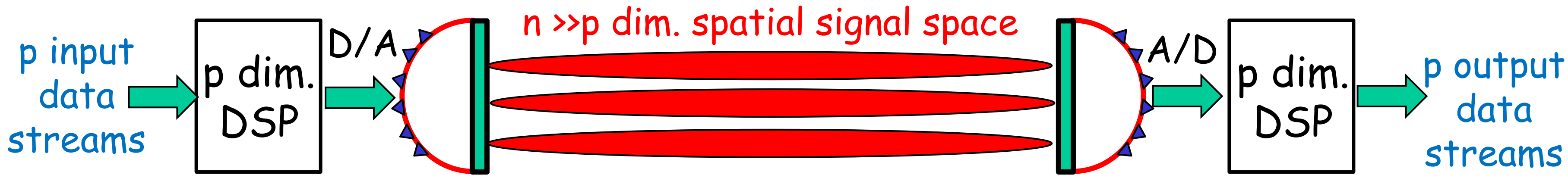
backhaul





(Source: 3G.co.uk)

Summary



- Optimal Beamspace MIMO Communication
- Lowest transceiver complexity: spatial A-D interface + DSP
- Compelling advantages over the state-of-the-art:
  - Capacity/SNR gains
  - Operational functionality (electronic multi-beam steering)
- Timely applications
  - Long-range wireless backhaul links (> 100 Gb/s)
  - High-rate short-range links (> 10 Gb/s)
  - Smart Basestations: High-Gain Dense Beamspace Multiplexing

Outlook

- Exciting but a lot still to be done!
  - Antenna array & feed optimization
  - Low-complexity transceiver design
  - Spatial analog-digital interface
- Prototyping & technology transfer
- Commercial mm-wave mobile broadband expected by 2020 (e.g., Samsung)
- Potentially new synergistic applications (optics, electro-optics, photonics)

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, to be presented at IEEE Globecom, Dec. 2013.