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

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Team

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Explosive Growth in Wireless Traffic

Heterogeneous devices and networks

Data-intensive apps

Images/video

Source: www.nari.ee.ethz.ch

Wireless Data Challenge

Mobile data traffic projected to grow
10–12x from 2010–2015

Potentially up to
1000x from 2010–2020

New Techniques  Network Offload  More Spectrum  Het Nets

Courtesy: Dr. T. Kadous, Qualcomm
Current Industry Approach: Small Cells & Heterogeneous Networks

Key Idea:
Spatial reuse of precious spectrum

Some challenges: interference, backhaul
New Opportunity: mm-wave Band

**UNITE** 3kHz

**STATE** 300kHz

**FREQUENCY**

**ALLOCA** 3MHz

THE RADIO SPECTRUM

300MHz

3GHz

30GHz

300GHz

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: Beam-space 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

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

n-dimensional signal space

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

Beamspace multiplexing

n orthogonal beams
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)

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

(Al-Joumayly and Behdad, 2010)

Analog Fourier Transform
(Analog beamforming)
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

(Bridgewave)
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

Key Operational Functionality:
Electronic Multi-beam Steering and Data Multiplexing
LoS Channel: Coupled Orthogonal Beams

number of coupled beams: $n = 40$ orthogonal beams

$P_{\text{max}} = 4$ coupled beams

Finite Receiver Aperture

(Fresnel number)

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

Spatial Res.: $\Delta\theta_{o} = \frac{1}{n} = \frac{\lambda_c}{2A}$
Near-Optimality of Beamspace Signaling

Coupled beams ~ channel eigenvectors

\[ H = U_n H_b U_n^H \quad \iff \quad H_b = U_n^H H U_n \]

\[ H = U_n H_b U_n^H \approx U_n (n \times p_{max}) H_b (p_{max} \times p_{max}) U_n^H (p_{max} \times n) \]

- approx. eigenvectors (comm. subspace)
- approx. diagonal (eigenvalues)
- approx. eigenvectors (comm. subspace)
Capacity Comparison with State-of-the-Art

**CAP-MIMO**

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

**MUX gain over DISH:**

\[ p_{\text{max}} \]

**SNR gain over MIMO:**

\[ G = \frac{n^2}{p_{\text{max}}^2} \]

**DISH**

no multiplexing gain  
large SNR gain

**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

Spectral efficiency (bits/s/Hz):

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

- \( n \): spatial dimension
- \( \rho \): SNR
- \( p \): # data streams

- 3GHz
  - \( n \sim 300,000 \)
  - \( G \sim 100\text{dB} \)
  - \( p = 4 \)

- 60GHz
  - \( n \sim 9, G \sim 15\text{dB} \)

- 80GHz
  - \( n \sim 3000, G \sim 66\text{dB} \)
  - \( n \sim 6000, G \sim 66\text{dB} \)
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)

Beam selection
Approaching the Bound with Linear (Practical) Precoding

\( K = \# \text{ users} \)

<table>
<thead>
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<th>( K )</th>
<th>( \Delta \theta_{\text{min}} )</th>
<th>Spectral Efficiency (bits/s/Hz)</th>
<th>Aggregate rate (Gbps)</th>
<th>Average per-user rate (Gbps)</th>
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<td>40</td>
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<td>( \Delta \theta_{\text{o}} / 4 )</td>
<td>283</td>
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</tbody>
</table>

(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

 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

(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


• G.-H Song, J. Brady, and A. Sayeed, *Beam space MIMO Transceivers for Low-Complexity and Near-Optimal Communication at mm-wave Frequencies*, ICASSP 2013