Beamforming on mobile devices: A first study

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Two invariants for wireless

- Spectrum is scarce
- Hardware is cheap and getting cheaper
Passive directional antennas

Findings: $\sim 3$ dB gain

- Multifold throughput increase at network edge
- $\sim 50\%$ TX power reduction at network center
Can we go beyond 3 dB?
Beamforming?

- Studied in the past for use on cellular base station, 802.11 access points, vehicles, and even wireless sensor nodes, e.g., MobiSteer (MobiSys’07), R2D2 (MobiSys’09), DIRC (SIGCOMM’09)
Beamforming primer
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Fixed transmission power
Beamforming primer

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Fixed transmission power
Is beamforming practical?

• Beamforming
  – Antenna array
  – Narrow beam
  – Power hungry

• Mobile devices
  – Small form factor
  – Rotate and move
  – Battery powered
Form factor?

Peak beamforming gain (dB)

Antenna spacing (wavelength)

0.3-0.4 \(\lambda\): 4.5-6 cm at 2 GHz
Form factor!

0.3-0.4 \( \lambda \) (4.5-6 cm at 2 GHz)
Rotation?
Rotation?

CSI estimation every 100 ms
Rotation!

CSI estimation every 10 ms
Power? (uplink only)

\[ P = P_{\text{shared}} + N \cdot P_{\text{Circuit}} + \frac{P_{\text{TX}}}{\eta} \]
Tradeoff No. 1

\[ P = P_{\text{shared}} + 1 \cdot P_{\text{Circuit}} + P_{TX} / \eta \]

Fixed receiver SNR
Tradeoff No. 1

\[ P = P_{\text{shared}} + 2 \cdot P_{\text{Circuit}} + \frac{P_{\text{TX}}}{\eta} \]

Fixed receiver SNR
Tradeoff No. 1

\[ P = P_{\text{shared}} + 3 \cdot P_{\text{Circuit}} + \frac{P_{\text{tx}}}{\eta} \]

Fixed receiver SNR
Tradeoff No. 1

\[ P = P_{\text{shared}} + 4 \cdot P_{\text{Circuit}} + \frac{p_{tx}}{\eta} \]
Tradeoff No. 1

- Optimal number of antennas for efficiency

\[ N_{opt} = a \cdot \sqrt{P_0 / P_{Circuit}} - b \cdot P_0 \]
Hardware is cheap & getting cheaper

\[ P = P_{\text{shared}} + N \cdot P_{\text{Circuit}} + \frac{P_{\text{TX}}}{\eta} \]

Sources: IEEE Int. Solid-State Circuits Conferences (ISSCC) and IEEE Journal of Solid-State Circuits (JSSC)
Power!

- Beamforming with state-of-the-art multi-RF chain realization is already more efficient!

- Tradeoff No. 1 is increasingly profitable!
Beyond a single link
What the carrier wants:
Use all your antennas!
What you want:

\[ N_{opt} = a \cdot \sqrt{P_O/P_{\text{Circuit}}} - b \cdot P_O \]
Tradeoff No. 2

- Network capacity vs. client efficiency
How can clients figure out its $N$ without talking to each other?
BeamAdapt

• Distributed algorithm to minimize TX power under uplink capacity constraints
  – No explicit inter-client cooperation
  – Iterative
  – Guaranteed to converge
  – Converge in a few iterations in practice
  – Converge to a good solution in practice

• Can be built on top of uplink power control in cellular networks
WARPLab-based prototype
Received SNR stable

Client Node 2

Link SNR constraint: 5 dB
Power close to optimal

Link SNR constraint: 5 dB
UMTS; Client movement: 0-70 mph; Client rotation: 0-120 °/s
Power reduced

![Diagram showing client power consumption for CBR traffic under different conditions. The x-axis represents the number of clients (N) with values 1, 2, 4, and 8, and the y-axis represents client power consumption (mW) ranging from 0 to 1000 mW. The graph compares power consumption between Beamforming/Omni and BeamAdapt.]
Network throughput maintained

![Network Throughput Graph](image)

- Beamforming/Omni
- BeamAdapt

Network Throughput (b/s)

CBR traffic
Conclusions

• Beamforming is feasible for mobile devices
  • Lower-power uplink for mobile devices

• Distributed optimization feasible
Looking forward

• Benefits of beamforming orthogonal to other spectrum efficiency technologies such as network MIMO

• Network capacity implications
Treating interference as noise

**Strong interference regime:**
Far from optimal from information theoretic perspective
Treating interference as noise

Weak interference regime:
Existing architecture yields close to optimal capacity
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