EDI CON 2016 Electronic Design Innovation Conference

Simulation of Beamforming by Massive MIMO Antennas in Dense Urban Environments

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Introduction

- This paper presents innovative and optimized approach to channel modeling for *massive MIMO*, a key technology for 5G
- Our approach:
  - Extends 3D ray-tracing, and addresses shortfalls identified in literature
  - Significant optimizations allow simulations between each Transmit and Receive antenna in reasonable time (***<u>this is critical!</u>***)
- Study: uses to simulate beamforming with MRT and ZFBF
  - Calculate power, SINR, and interference
  - Predict impact of pilot contamination

Overall: provides new insight into the nature of beams in urban settings and demonstrates value of new MIMO simulation capability

Objectives of 5G

Key Objectives Move Toward Connected Information Society [1]

Challenges

- Massive Growth in Mobile Data Demand
- Massive Growth in Connected Devices
- Increasingly Diverse Use Cases & Requirements

Objectives

- 1000x Capacity
- 10-100x Devices (50-500B)
- 10-100x Data Rates (~10 Gbps)
- 5x Lower Latency
- 100x Energy Efficiency
- 10x Longer Battery Life for Low-power Devices

Potential Benefits of Massive MIMO[1]-[3]

- Increases capacity 10x via spatial multiplexing
- Improves radiated energy-efficiency 100x
  - Directs signal to user, reducing power & interference
- Can use inexpensive, low-power components
- Reduces latency, eliminates fading
- More robust to interference and jamming

Channel Modeling for 5G

- Organizations such as 3GPP and METIS have researched channel modeling requirements; METIS* requirements for 5G include [4]:
  - Very high bandwidths (hundreds of MHz)
  - Full three-dimensional & accurate polarization modeling
  - Massive MIMO: spherical waves and high spatial resolution
  - Extremely large array antennas
  - Spatial consistency as points move or are in close proximity
  - Wide range of propagation scenarios
  - Wide frequency range (<1GHz up to 86+ GHz)
  - Dual-mobility for D2D, M2M, V2V
  - Importance of diffuse vs. specular scattering at mm wave

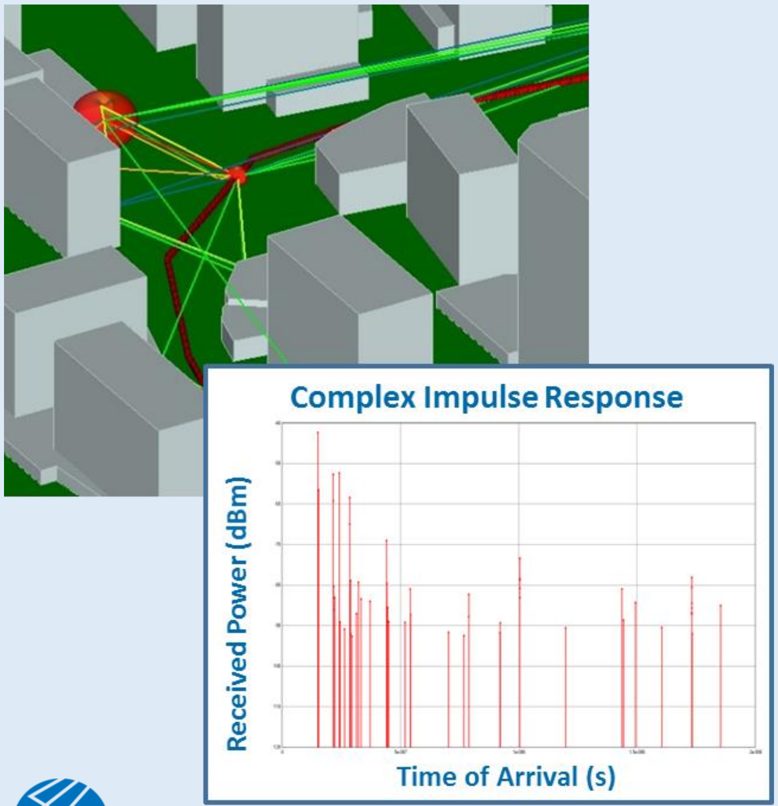
Our approach focuses on these MIMO-relevant requirements

* Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society

Simulating MIMO with 3D Ray-Tracing

- Use Wireless InSite® to simulate MIMO channels
- 3D ray-tracing provides data required by MIMO algorithms
  - Complex path gain
  - Full resolution of spherical & diffracted waves across array
  - 3D path data w/full time, angle & polarization information
  - Complete spatial consistency throughout complex scenes
- But: out-of-box, very complex for *traditional* ray-tracers

Propagation Paths for Channel between 1 Transmit/Receive MIMO Antenna Pair



wireless insite

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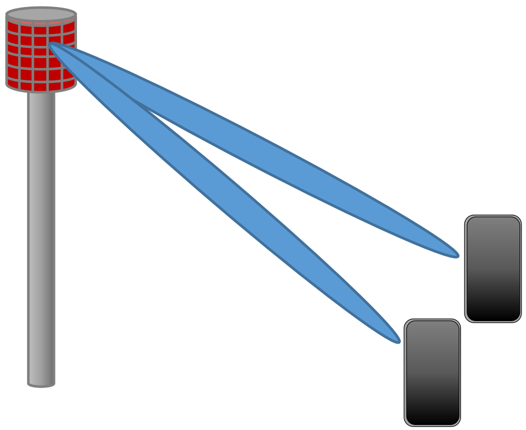
New Wireless InSite® MIMO Capability

- New capability offers innovative optimizations that made several parts of study possible
  - **Starting Point:** GPU-accelerated / multithreaded X3D ray model in Wireless InSite as starting point
  - **Optimizations:** Two key optimizations allow calculations within timeframes on same order as single-antenna simulations:
    - Adjacent Path Generation (APG): leverages path data for coarse points
    - MIMO exact path correction: finds precise paths to array elements
  - **Result:** precise path data between each Tx-Rx MIMO antenna pair while minimizing additional ray-tracing calculations
- These optimizations were critical for simulating a 128-element MIMO array

Beamforming: Spatial Multiplexing

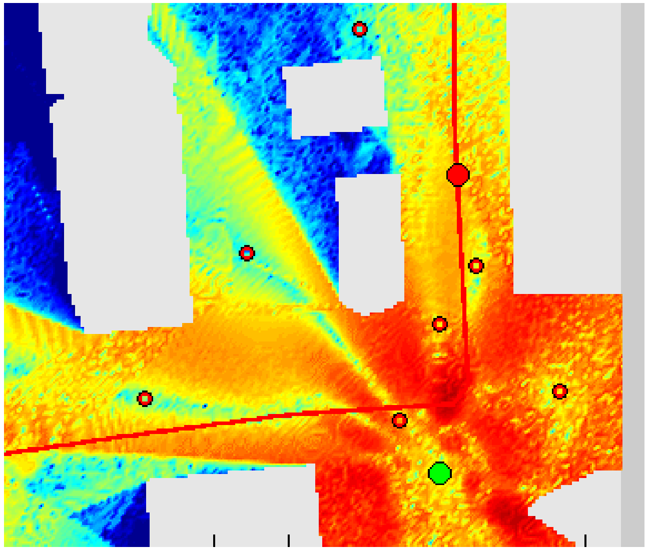
- Massive MIMO uses beamforming to send multiple data streams
  - Uses pilot signals to characterize channel
  - Different signals to different users in cell over same frequency
  - Sharing frequency increases capacity & data rate

How it's Often Conceptualized



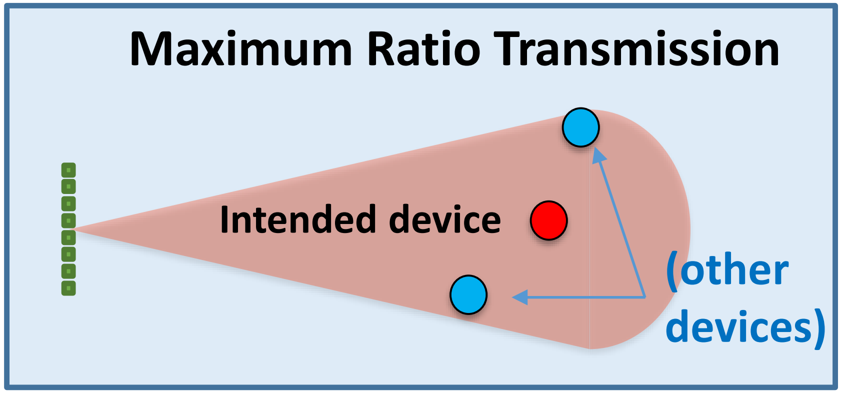
How it may actually look in an urban scene (example: zero forcing technique)

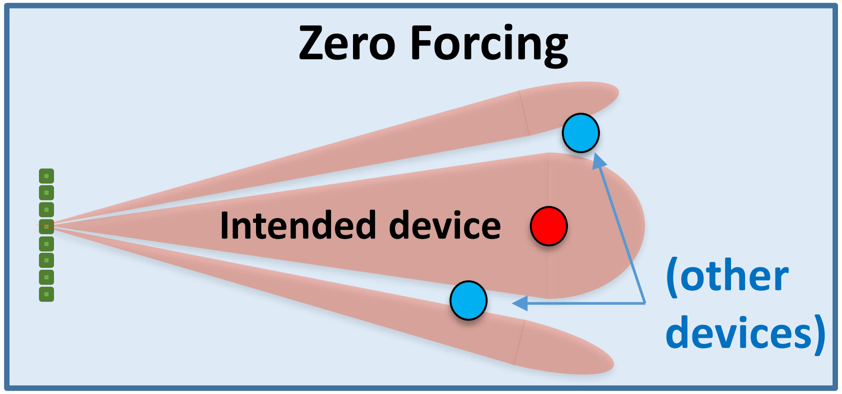
Image demonstrates concept of optimizing for one user (●) while minimizing interference to others (○)



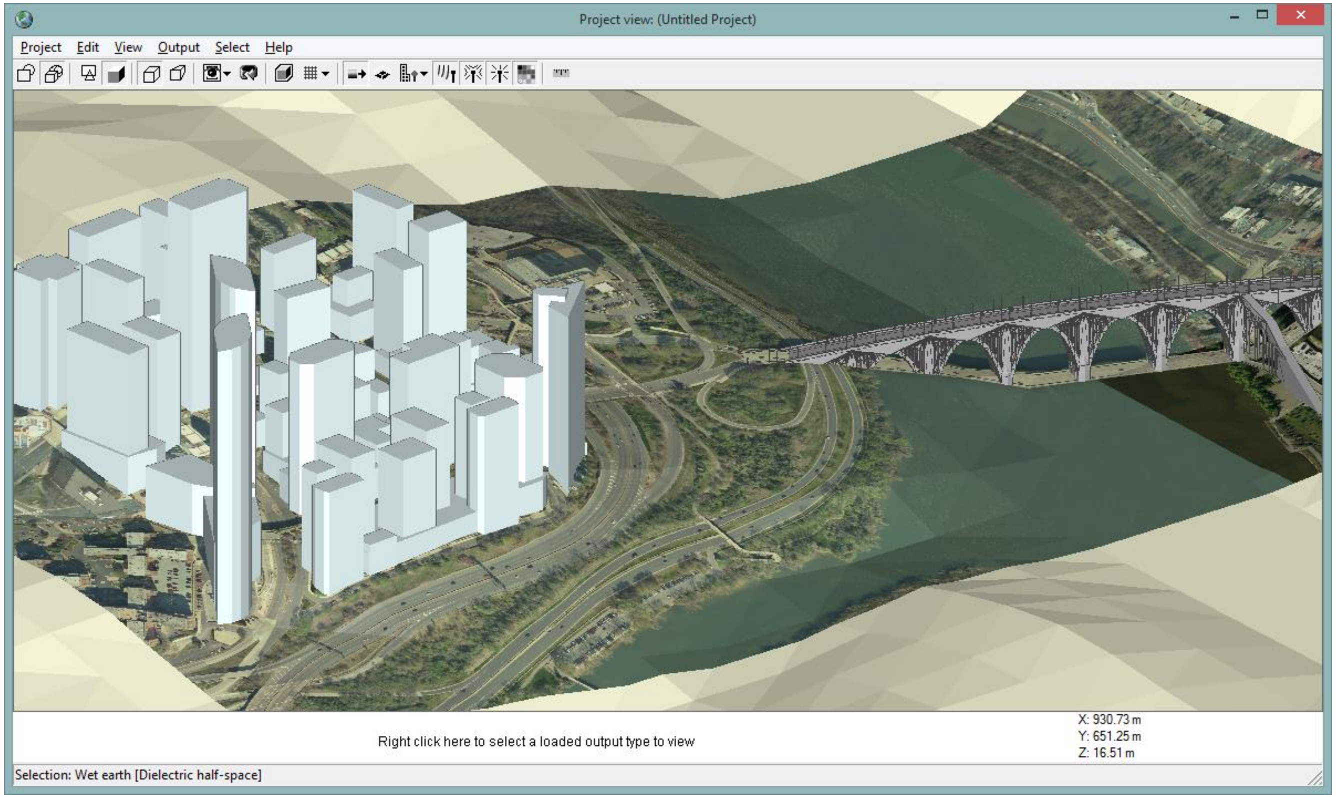
Beamforming Techniques in this Study

- Investigated two techniques:
  1) Max. Ratio Transmission (MRT)
     Sets beamforming weights for device to maximize sum of channel gains
  2) Zero Forcing (ZF)
     Sets beamforming weights to minimize interference to all other users in cell, placing them within local nulls
- Post-processed Results
  - Developed tools to extract simulation results and calculate beamforming weights
  - Used Matlab scripts provided by authors of [5] to calculate MRT and ZF weighting vectors



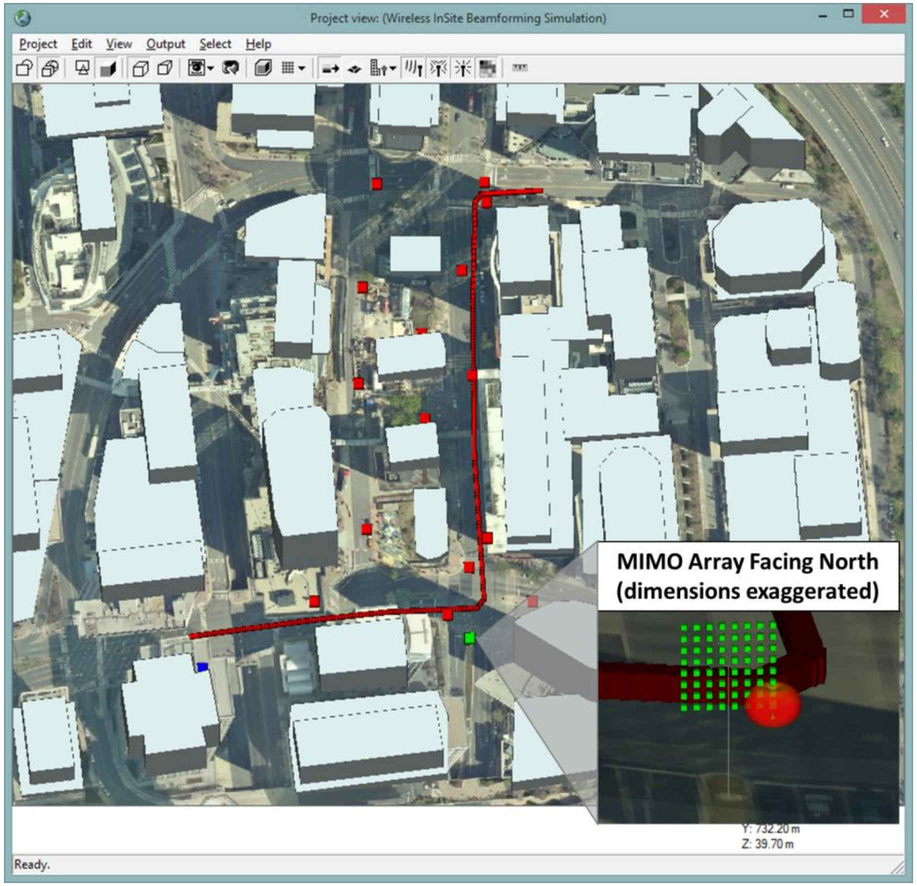


MIMO Simulation Scenario: Urban Small Cell in Rosslyn, Virginia



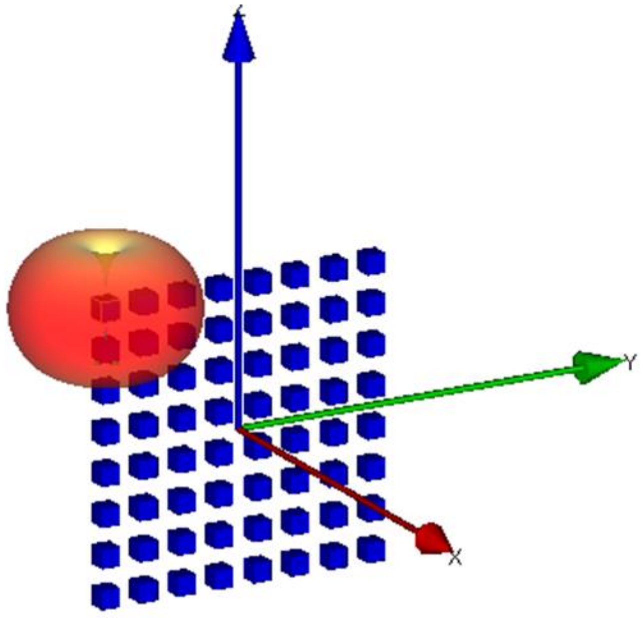
Scenario: Urban Small Cell

- Site: Rosslyn, Virginia
- MIMO Base Station
  - Massive MIMO atop pole in median (10m)
- 16 Mobile Devices (red)
  - 15 stationary
  - 1 moving along route
- 17th device in neighboring cell (blue)

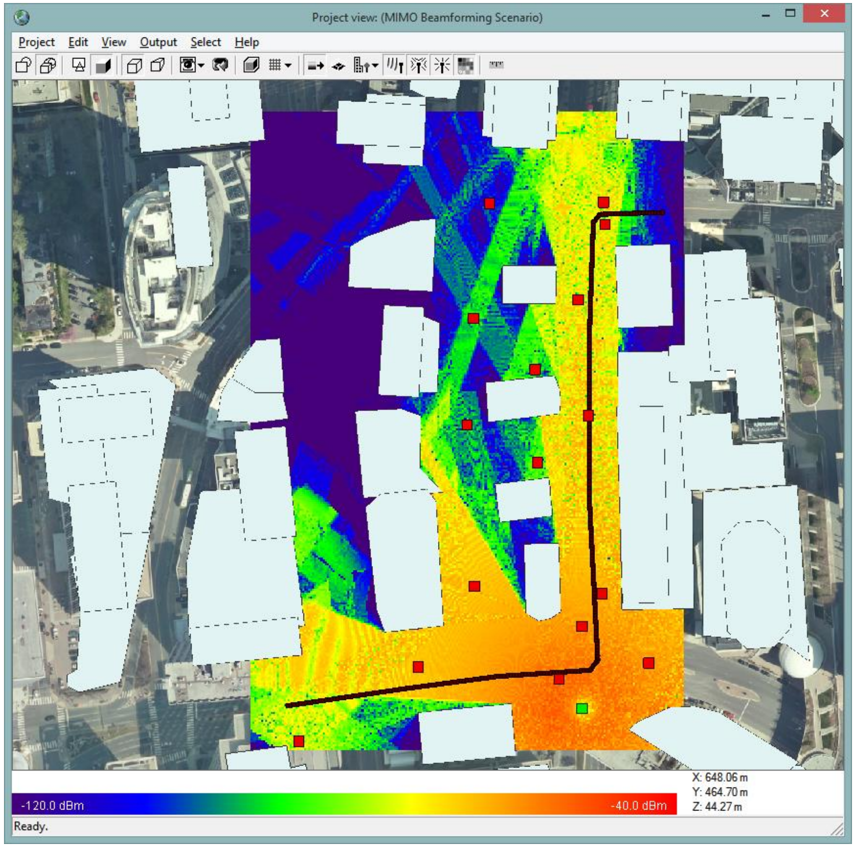


Massive MIMO Antenna

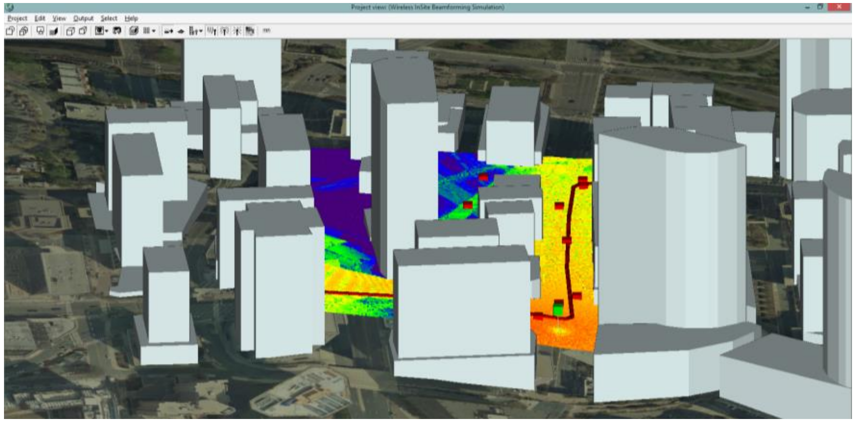
- Frequency: 28 GHz
- 128 antennas
  - 8x8 w/cross-pol
  - Dipoles (for simplicity)
- Dimensions
  - ½-λ spacing (1.07cm)
  - 4.3cm x 4.3cm



Field Map for a Single Element

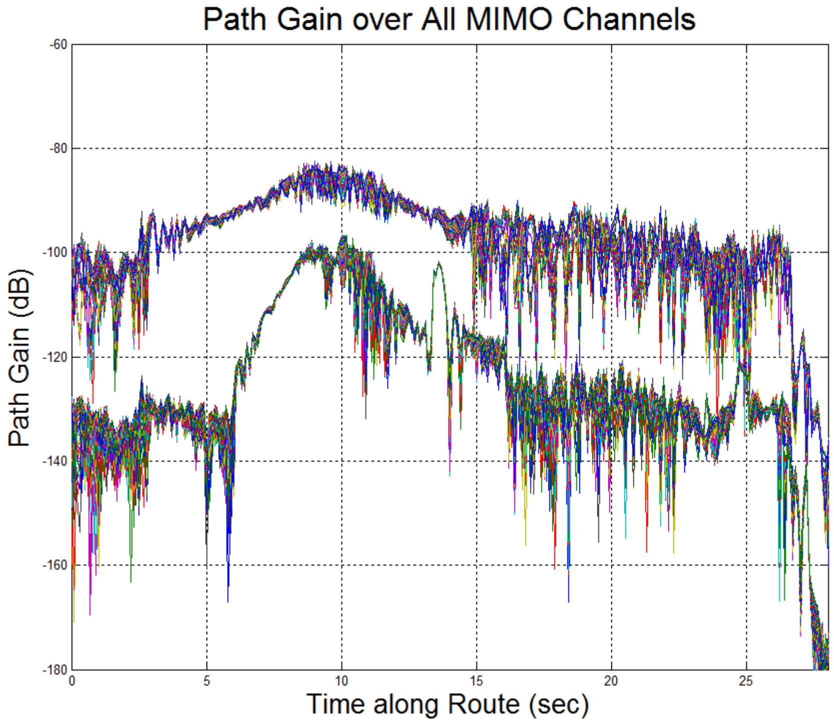


- Field map shows significant multipath
  - Strongest in LOS North & West of base station
  - Multipath extends into street to Northwest



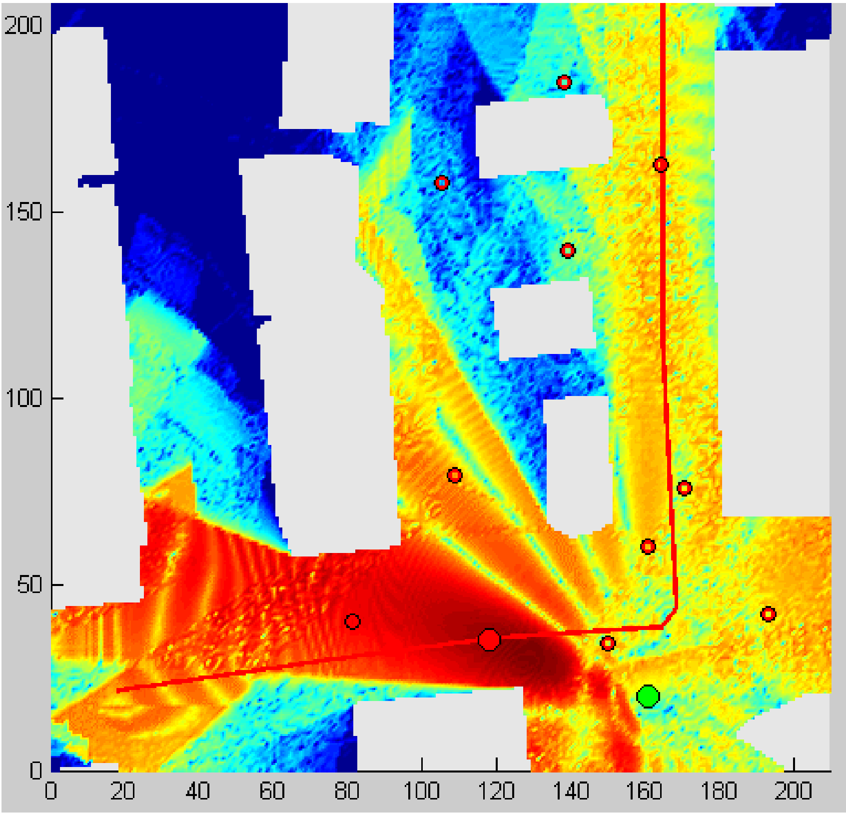
Path Gain

- Path gain is sum total of all paths (with phase)
  - Hundreds of paths to each point
  - Significant variation in magnitude & phase
- Plot overlays path gain on route for 128 elements
  - Higher cluster: vertically-polarized elements (co-pol)
  - Lower: horizontal (cross-pol)
- Complex path gain is input to beamforming algorithms

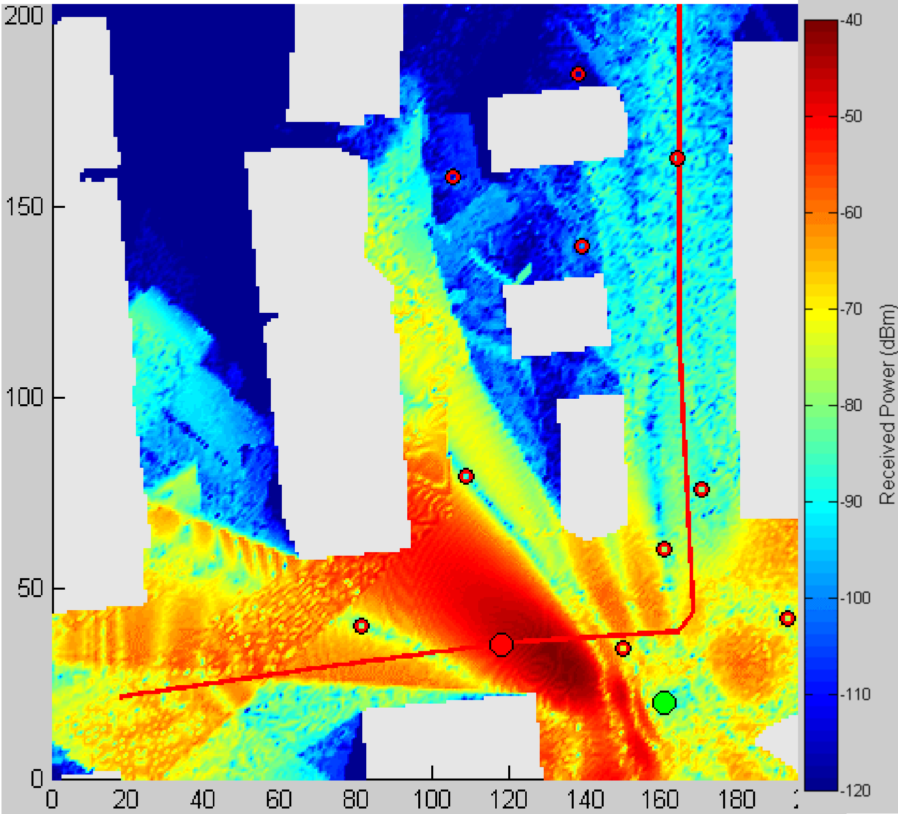


Comparing Beamforming Techniques

MRT: maximizes beam to device, ignoring interference to others



Zero-Forcing: minimizes interference to other devices (clear difference)



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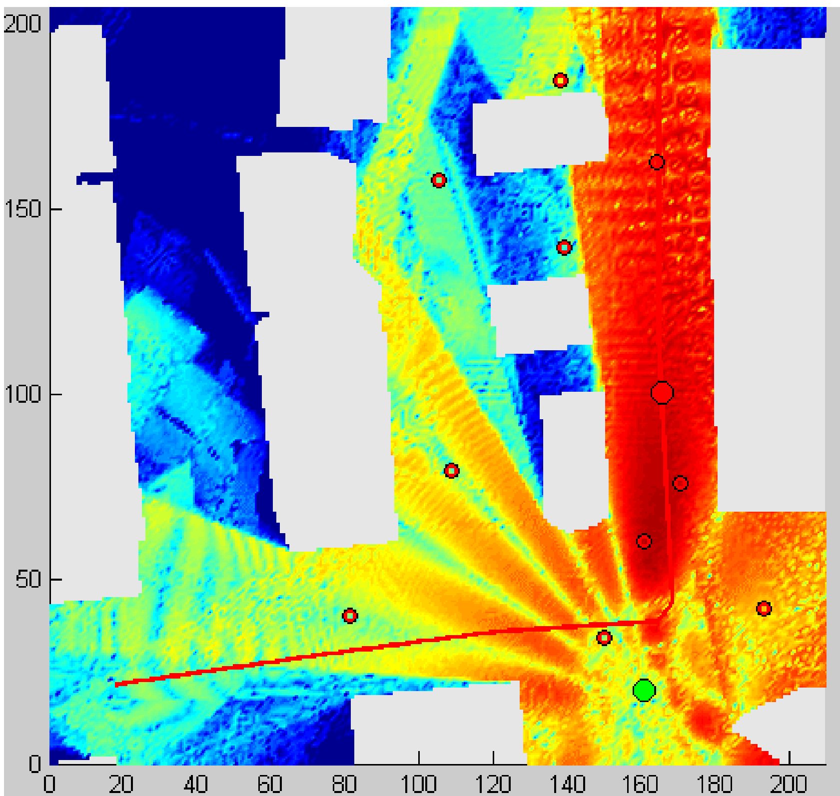

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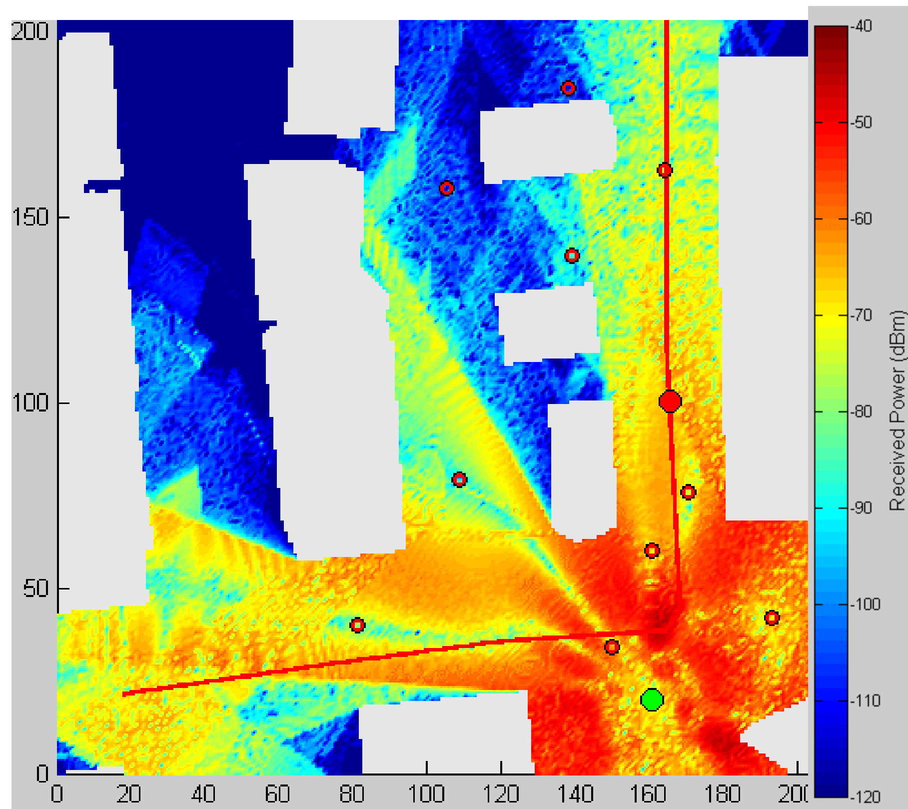
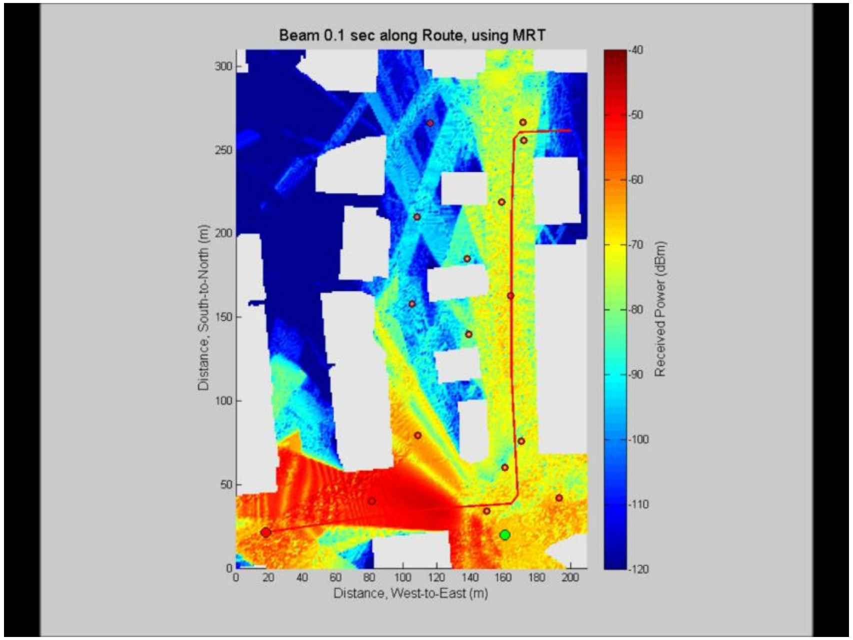
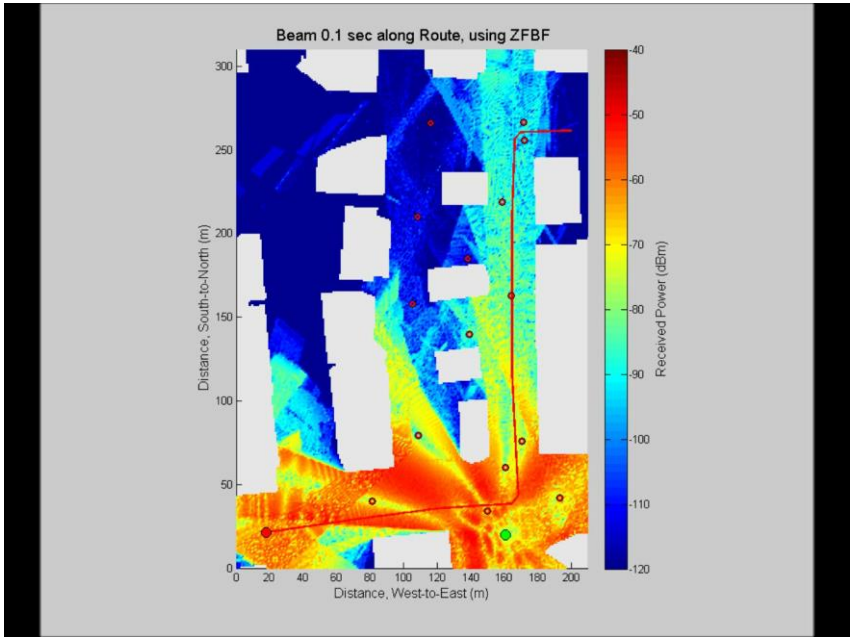


Movies: MIMO Beamforming in Motion

Maximum Ratio Transmission (MRT) Beamforming

Zero Forcing (ZF) Beamforming





Click to watch the movie.

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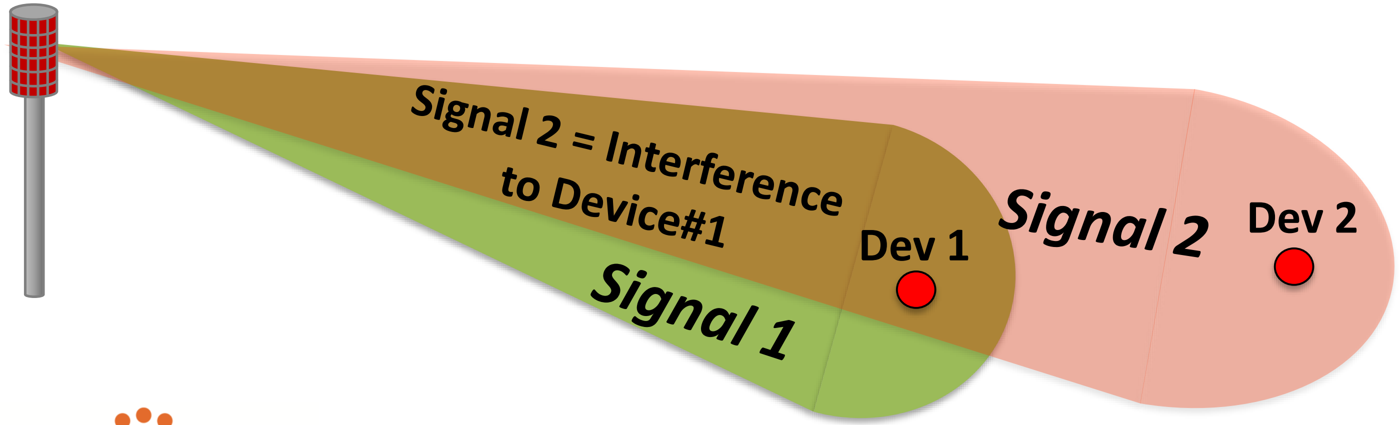
Signal-to-Interference+Noise (SINR)

- SINR is a key measure for determining capacity of a channel

$$\text{SINR} = \frac{\text{Signal}}{\text{Interference + Noise}}$$

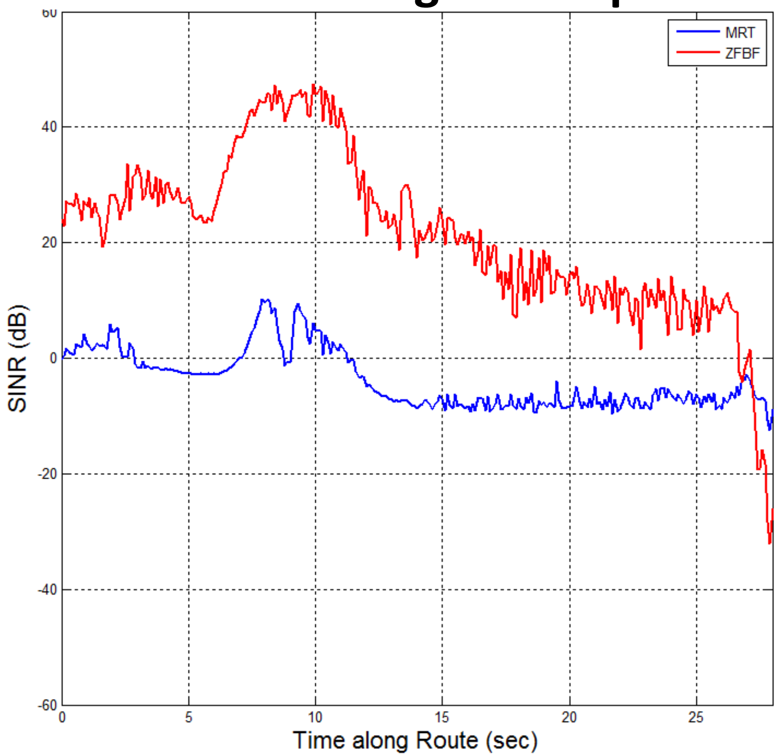
- *Interference* is the total power of signals received by a device that are part of beams directed to other devices



Signal-to-Interference+Noise

- Calculated SINR
  - Power: assumed 10W over Tx array
  - Interference: summed power of beams to all other devices
  - Noise: -87dBm, using [6]
- ZF much better than MRT for this scenario
  - 15-40dB higher over most of route

Comparing SINR for MRT and ZF Beamforming Techniques



Details on Power, Interference & SINR

- MRT delivers more power, but ZF suppresses interference, providing much higher SINR

Table 2: Received Power and SINR for moving Device

Mean Over Route	MRT	ZF
Received Power (dBm)	-49.0	-63.0
Interference (dBm)	-47.9	Negl.*
SINR (dB)	-3.7	21.6

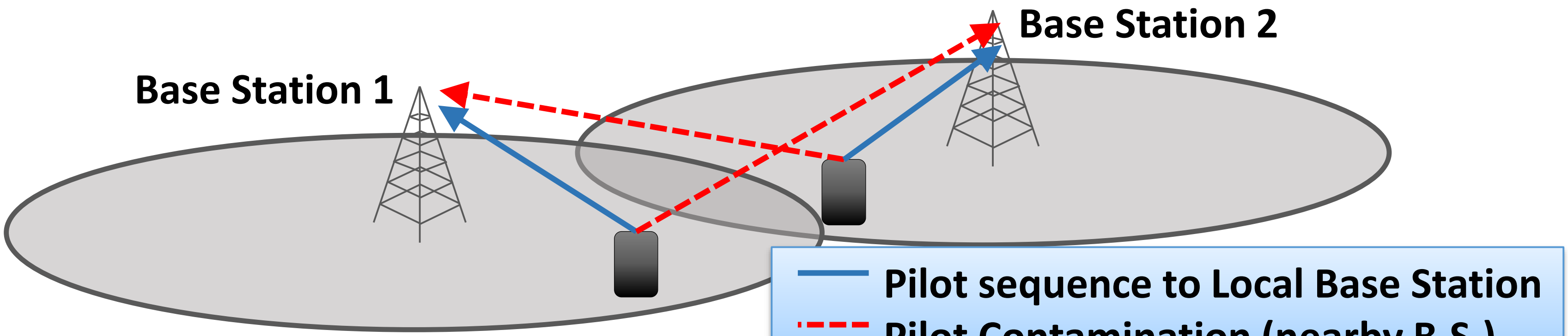
**Interference for ZF was negligible (well below noise floor)*

MRT: 14dB higher power

ZF: 25dB higher SINR

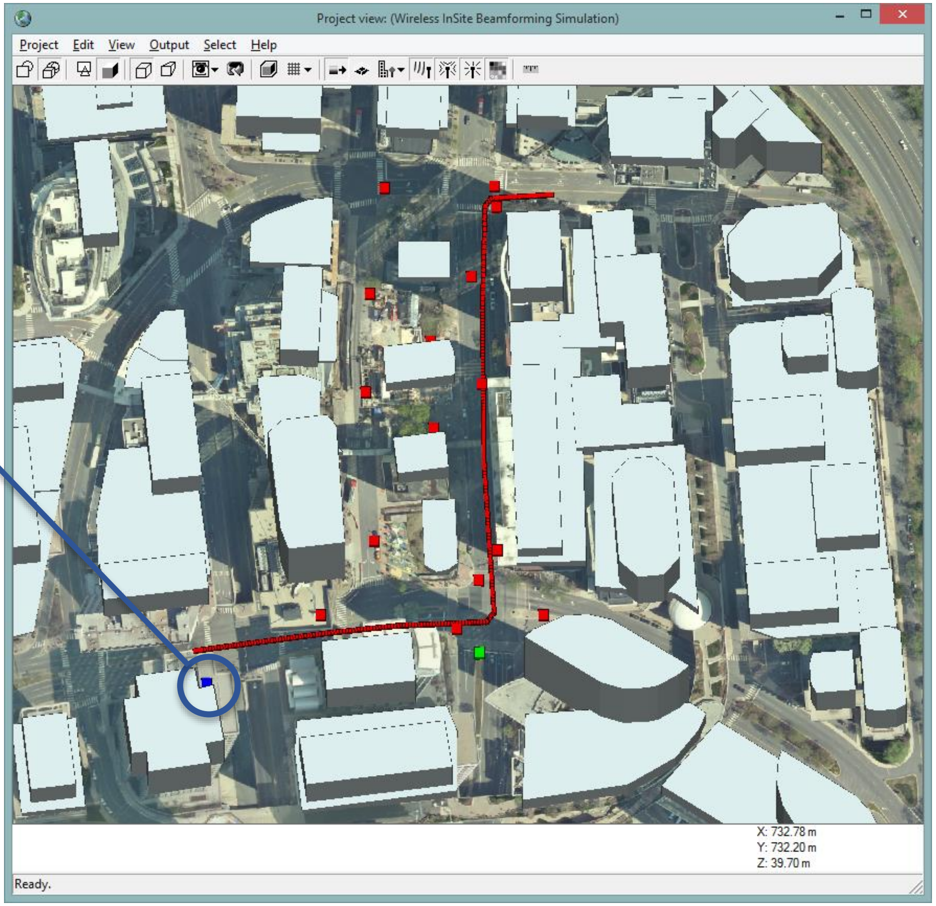
Pilot Contamination

- MIMO system uses pilot sequences to estimate channels
  - Because possible orthogonal sequences limited by channel coherence time, adjacent cells likely to overlap
- Same pilot from multiple terminals degrades channel estimate
  - May reduce SINR to user in cell
  - May direct more interference toward user in adjacent cell



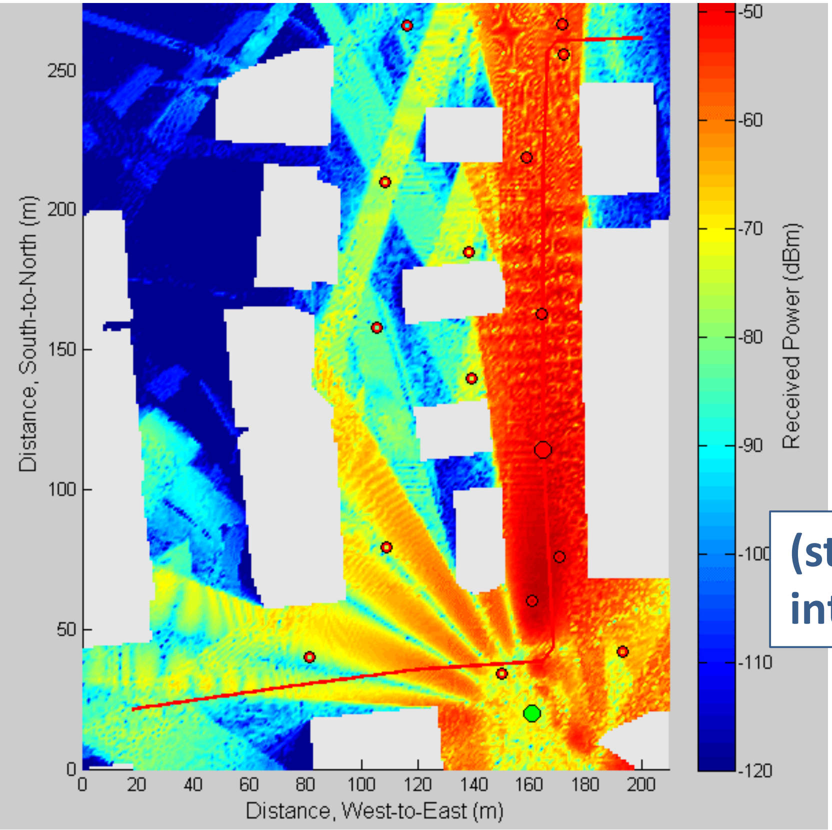
Pilot Contamination Scenario

Device in nearby cell shares pilot signal with moving device (pilot contamination)

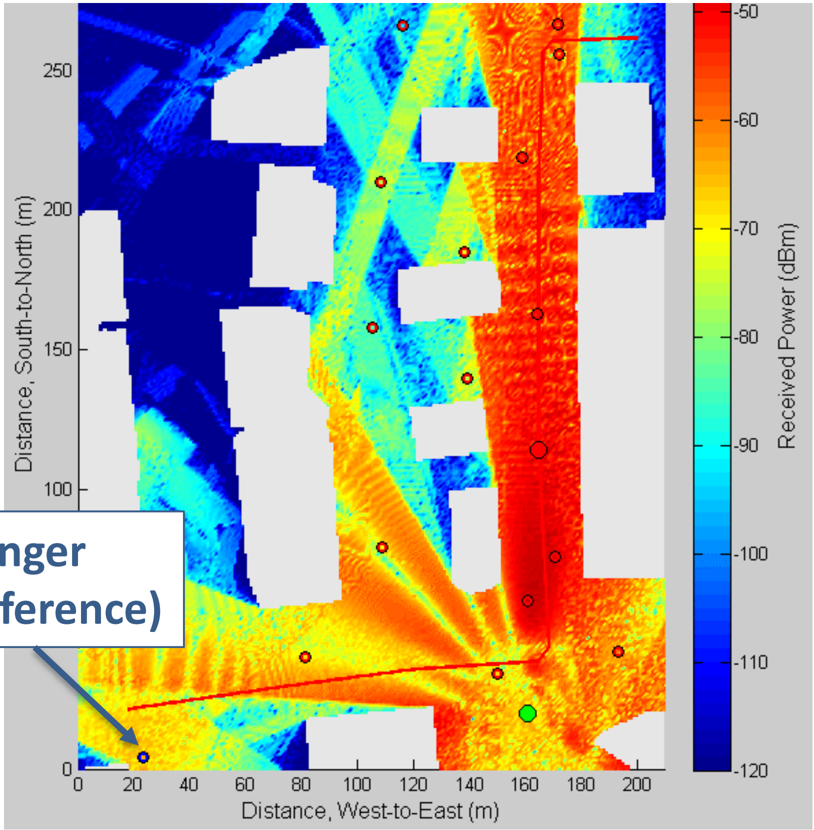


Pilot Contamination: Impact to MRT

MRT to sample point on route (before pilot contamination)



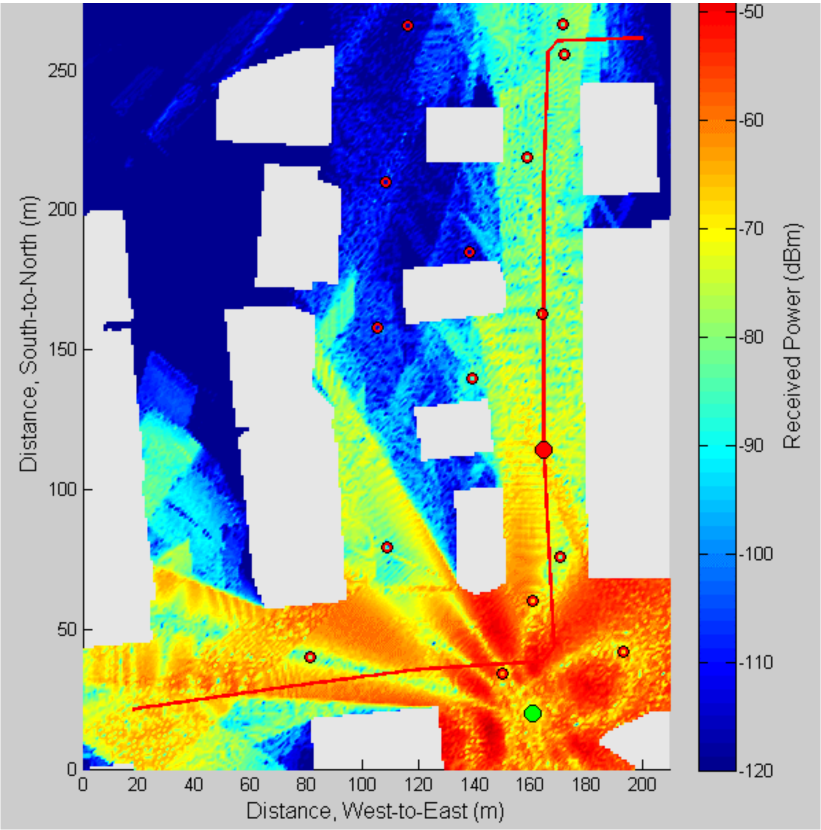
After pilot contamination: some of beam diverted to neighboring dev.



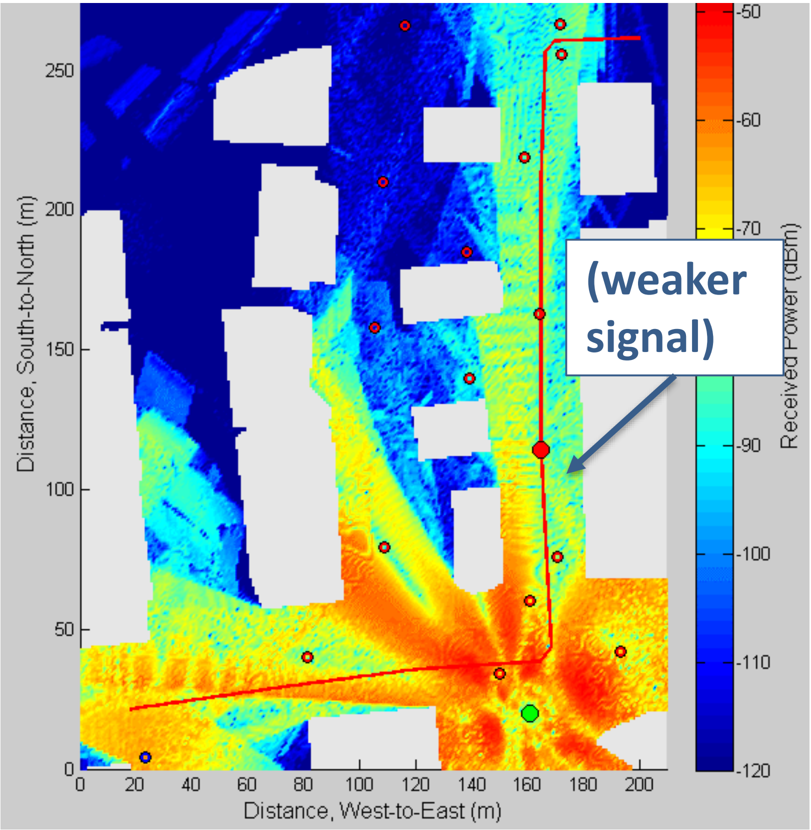
(stronger interference)

Pilot Contamination: Impact to ZF

ZF to sample point on route (before pilot contamination)

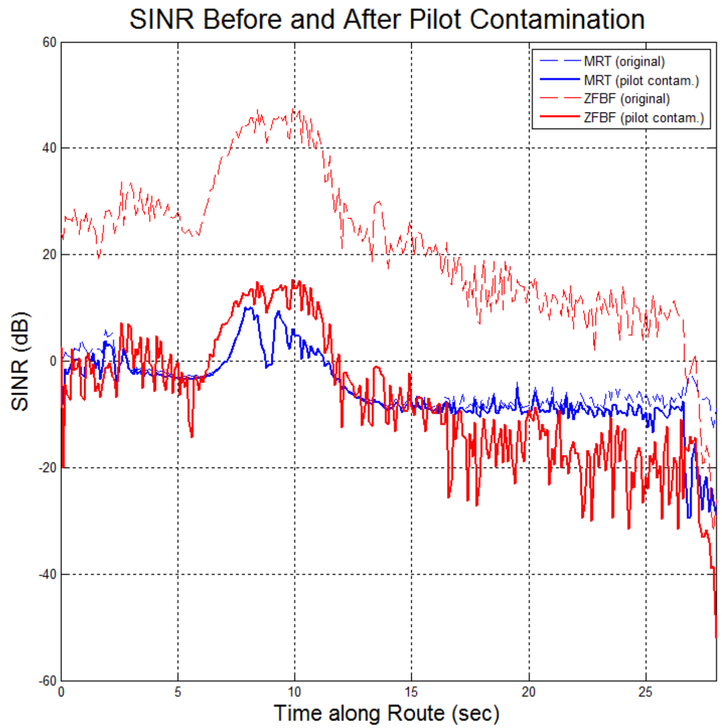


After pilot contamination: power to intended device noticeably reduced

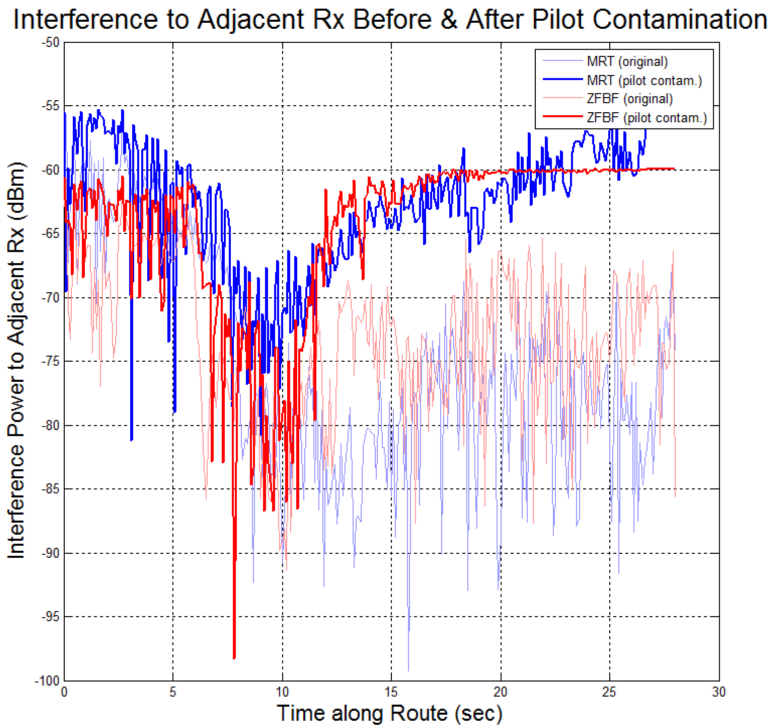


Pilot Contamination: Impact to SINR

Significantly reduces SINR for ZF (little effect on MRT)



Increases interference to neighboring Rx for both MRT & ZF



Pilot Contamination: Impact to SINR

Table 1: Effect on Local Cell

Beam	Mean Values Over Route	Orig.	Pilot Cont	Change
MRT	Rcvd. Pwr. (dBm)	-49.0	-51.0	-1.9
	Interference (dBm)	-47.9	-47.9	0
	SINR (dB)	-3.7	-5.6	-1.9
ZF	Rcvd. Pwr. (dBm)	-63.0	-68.6	-5.6
	Interference (dBm)	Neg.*	-64.2	High*
	SINR (dB)	21.6	-7.6	-29.1

Interference for ZF increases from well below noise floor to above signal, significantly reducing SINR.

MRT: minor impact to SINR

ZF: small reduction in power; big increase to interference
Result: SINR 29dB lower!

Table 2: Interference to Neighboring Device

Beam	Mean Values Over Route	Orig.	Pilot Cont	Change
MRT	Interference (dBm)	-75.1	-62.6	+12.4
ZF	Interference (dBm)	-73.3	-64.5	+8.8

Both techniques increase interference (9-12dB)

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Value of Simulation Optimizations

- Recorded run times for sims in this study
  - High-end PC: Intel i7-3770, 32GB RAM, Quadro K620 GPU
  - Recorded sim times for 3 cases
- Estimated baseline without optimizations (1 sim/antenna)
- **Result: *51X – 94X faster*** than traditional (brute-force) approach
- Makes sims like beamforming field map possible

Table: Estimated Run Time Optimization

Simulation Case	Mobile Devices 317 pts	Field Map 66K pts
Single Antenna (SISO)		
• **Before optimizations**	36 sec	36 min
• **APG accelerated**	30 sec	9 min
Optimized MIMO	96 sec	49 min
MIMO estimate *without* optimizations	79 min	4,572 min (~3 days)
Speed improvement	**51X**	**94X**

Conclusions

- Presented new, efficient method for predicting detailed channel characteristics for massive MIMO
  - Optimizations to Wireless InSite model allow results with only small increase in run time over un-optimized, single-antenna sims
- Study: extracted channel matrices from simulations and computed beams using MRT & ZF beamforming
  - Evaluated power, interference, SINR
  - Showed how pilot contamination degrades performance
  - Study provides insight into MIMO beams in urban settings
- Results demonstrate value of new MIMO capability and show how it can be applied to practical problems for research and assessment of MIMO performance

References

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