# Coexistence with MIMO and Potential in Legacy LTE Systems

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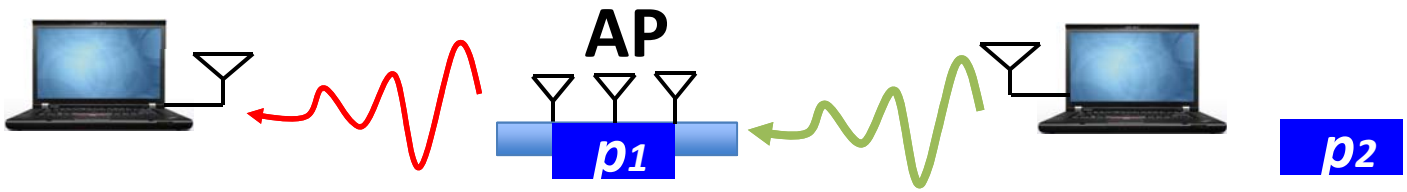
# Background

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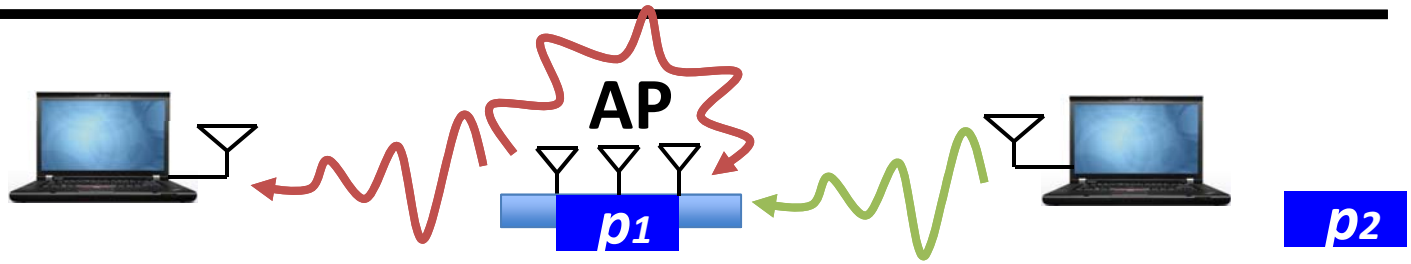


- Current wireless radios are half duplex
- Same band Full duplex is hard
  - Self interference is very high: ≈75 dB for 15 dBm Tx power
  - Transmitted signal is known → self interference cancellation
  - Self interference can be significantly reduced by adding a cancellation circuit: e.g., a cancelling antenna

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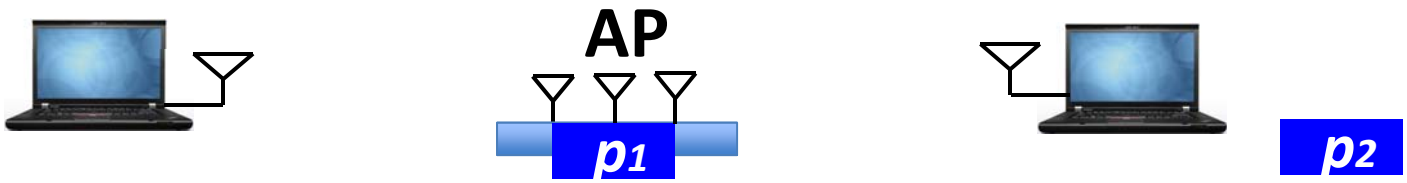


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***Can full duplex wireless double the capacity?***

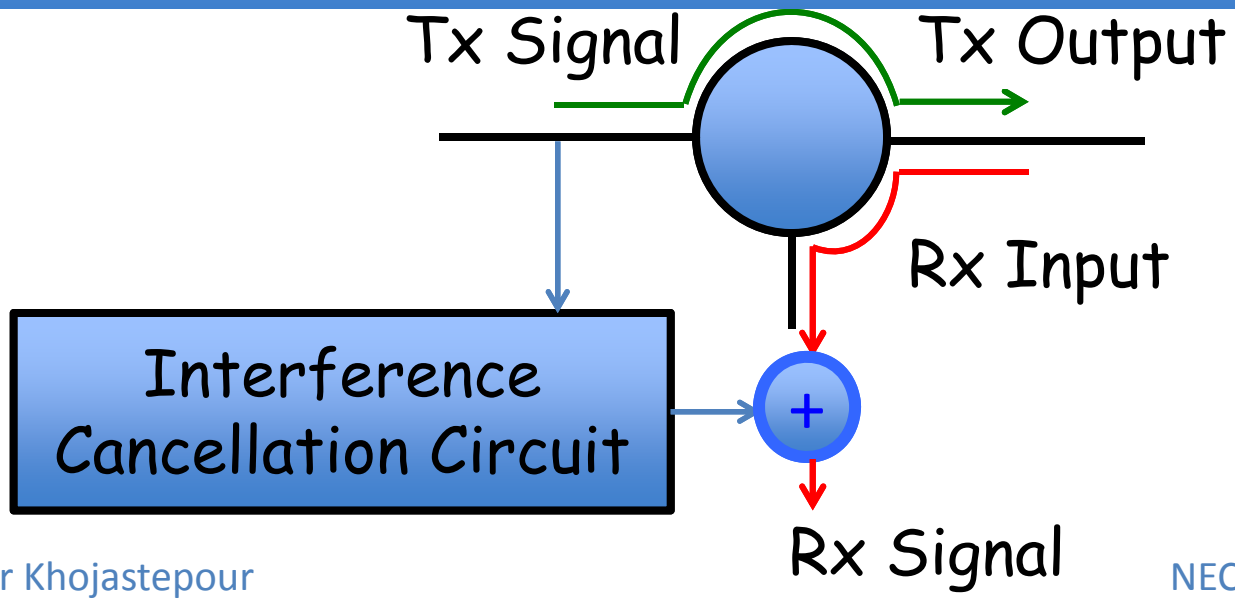
# Outline

- Background
- Related works
- Design of MIDU
- Experimental Evaluation
- Real world implementation
  - Legacy-LTE Basestation
  - Half duplex clients
- Conclusion

# Related Work

- Single-antenna full duplex
  - M. Knox, "Self-jamming for full duplex"

*Enhanced Circulator design for full duplex wireless*

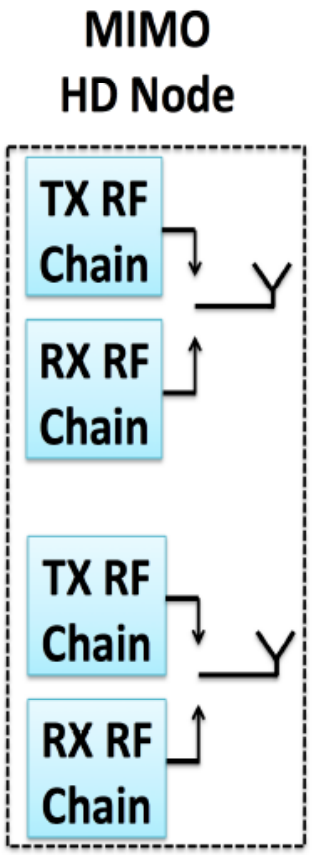


# Related Work

- Single-antenna full duplex
  - M. Knox, “Self-jamming for full duplex”
- Antenna Cancellation
  - A. Khandani, “Two-way (true full duplex) wireless”
- Asymmetric Antenna cancellation
  - J. Choi, et. al., “Achieving single channel full duplex”
- Analogue cancellation
  - M. Jain, et. al., “Practical full duplex”
  - M. Durate, et. al., “Full duplex with off-the-shelf radios"

# Full Duplex vs. MIMO

- Hardware complexity, performance, size, cost metrics



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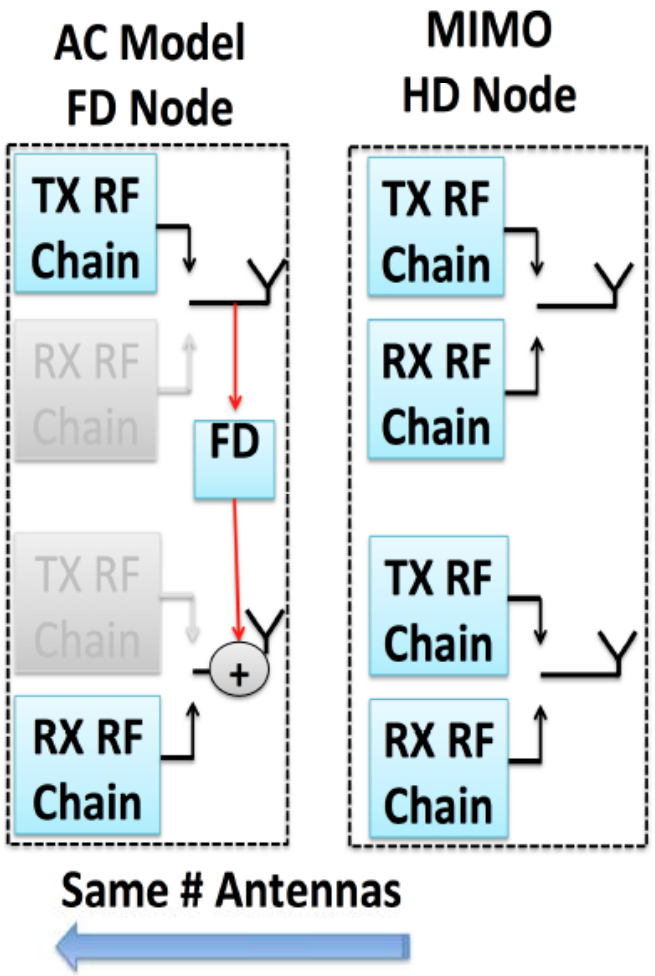
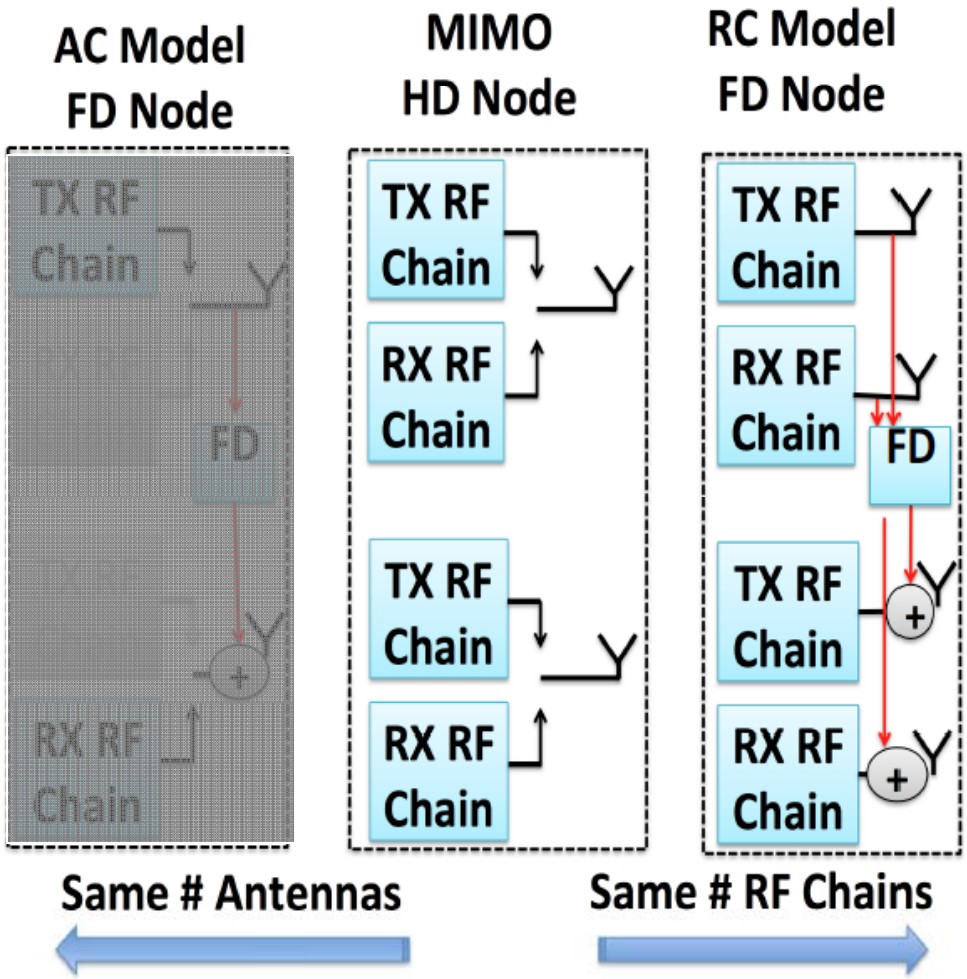
- Antenna Conserved (AC): Same # antennas



# Full Duplex vs. MIMO

- Hardware complexity, performance, size, cost metrics
- Antenna Conserved (AC): Same # antennas
- RF-Chain Conserved (RC): Same # chains



# Full Duplex vs. MIMO

- Hardware complexity, performance, size, cost metrics

SI loss: 6 dB  Ant Correlation: 0.1

- Antenna Conserved (AC): Same # antennas
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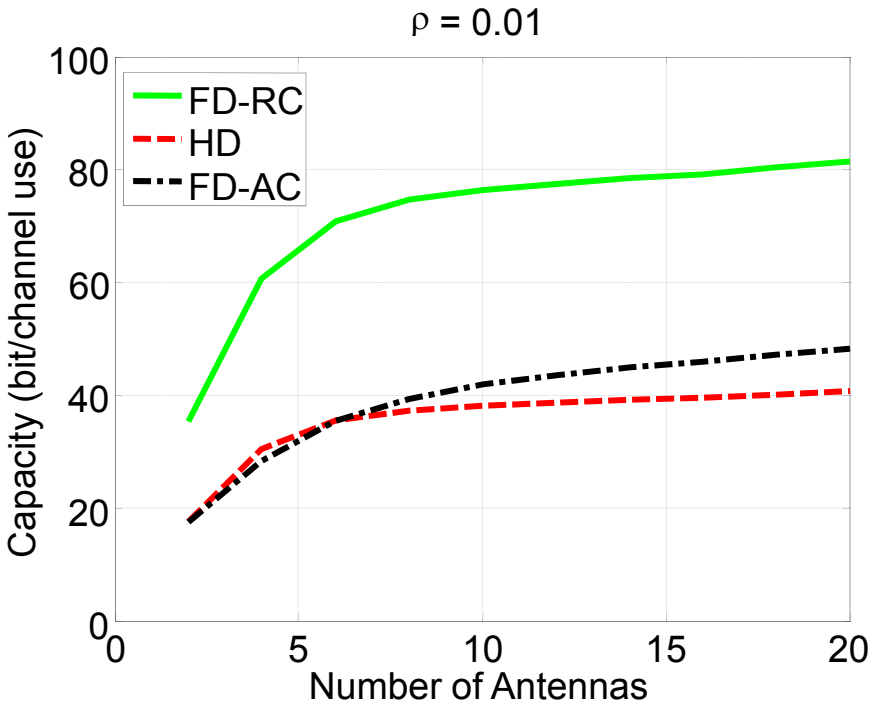
- Significant **FD gains** in **RC model**
- **Limited** FD gains with **small # antennas** in AC model higher **gains** with **more antennas**



# Full Duplex vs. MIMO

- Hardware complexity, performance, size, cost metrics

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*Regions of pronounced full duplex gains in both RC and AC models*

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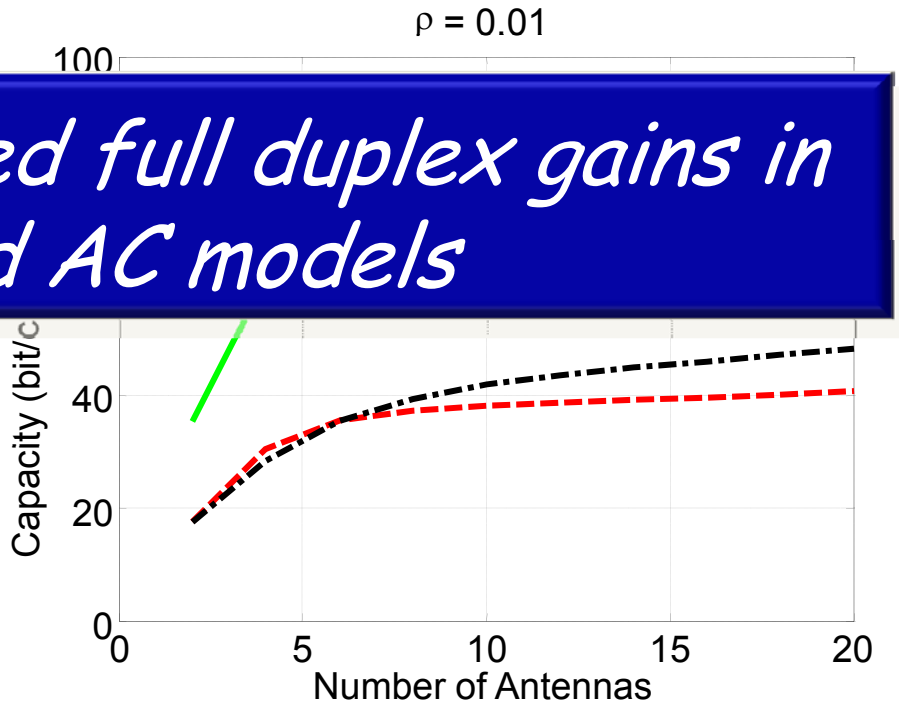
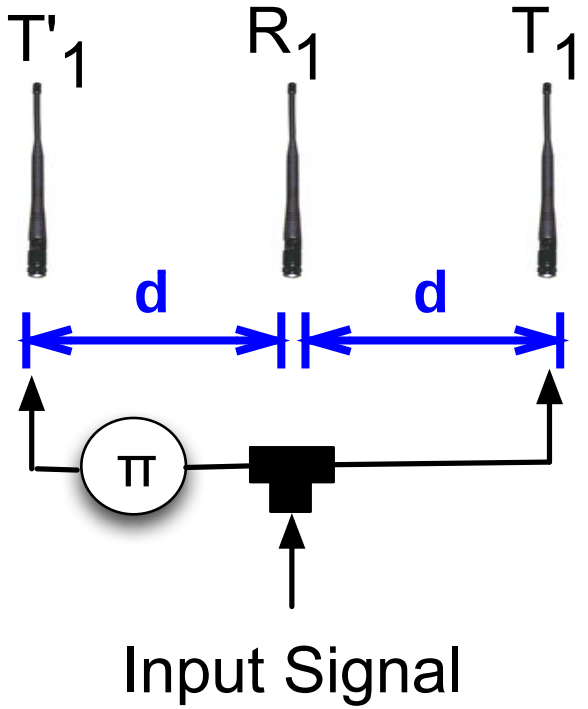


# MIDU: MImo full-DUplex

- Symmetric antenna placement



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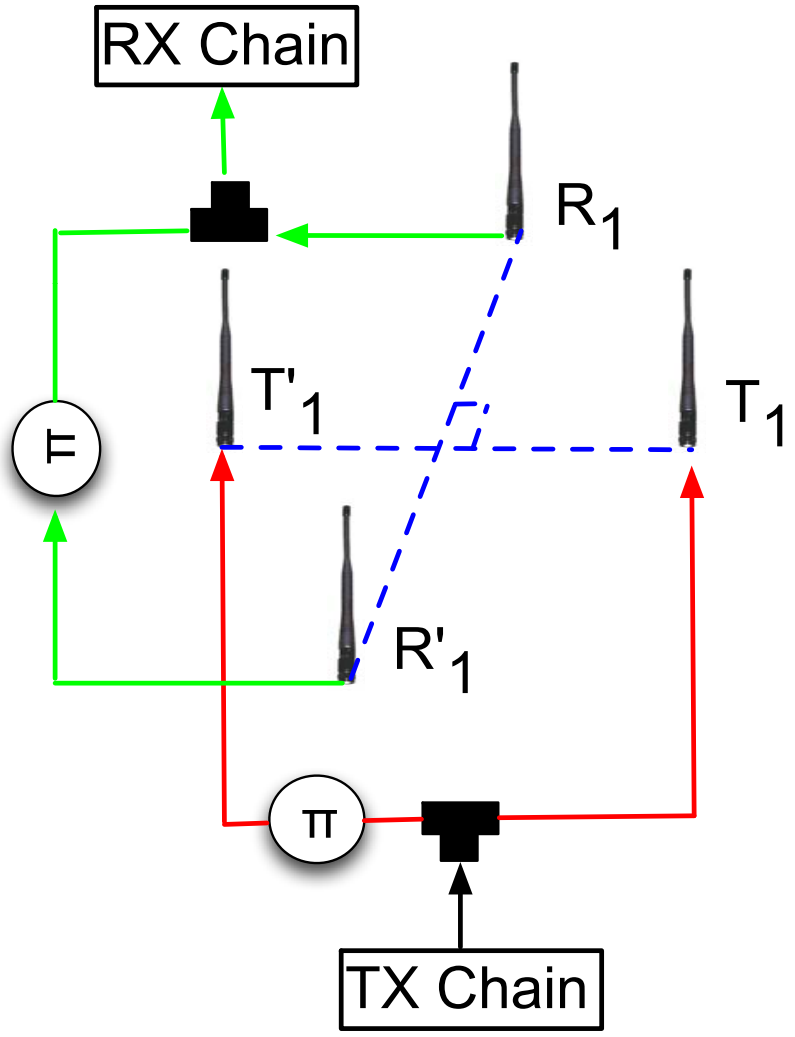
- 2-level of antenna cancellation
  - Tx cancellation followed by Rx cancellation
  - Proved in theory to have additive gains under imbalanced gains/phase or imprecise placement



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- Symmetric antenna placement
- 2-level of antenna cancellation
  - Tx cancellation followed by Rx cancellation
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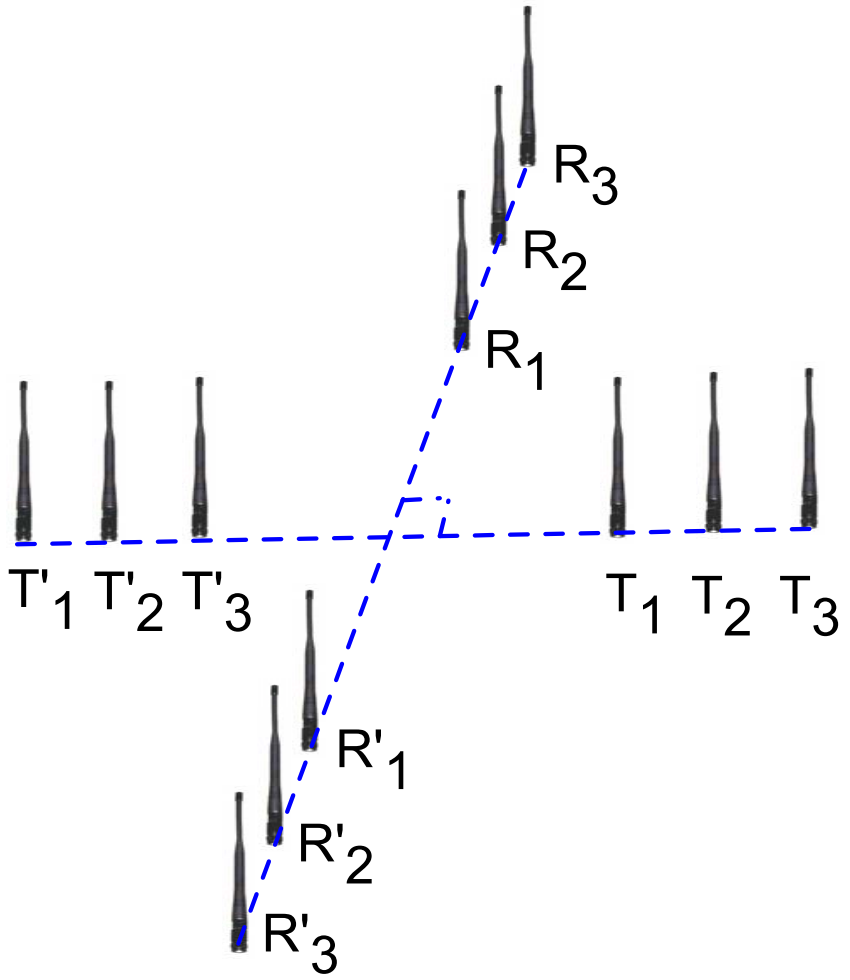
- Easy scalability to MIMO



# Experimental Evaluations

- WarpLab implementation
  - Narrow-band 625 KHz
  - Open space environment
  - MIDU vs. MU-MIMO

Virtex-IV Pro FPGA

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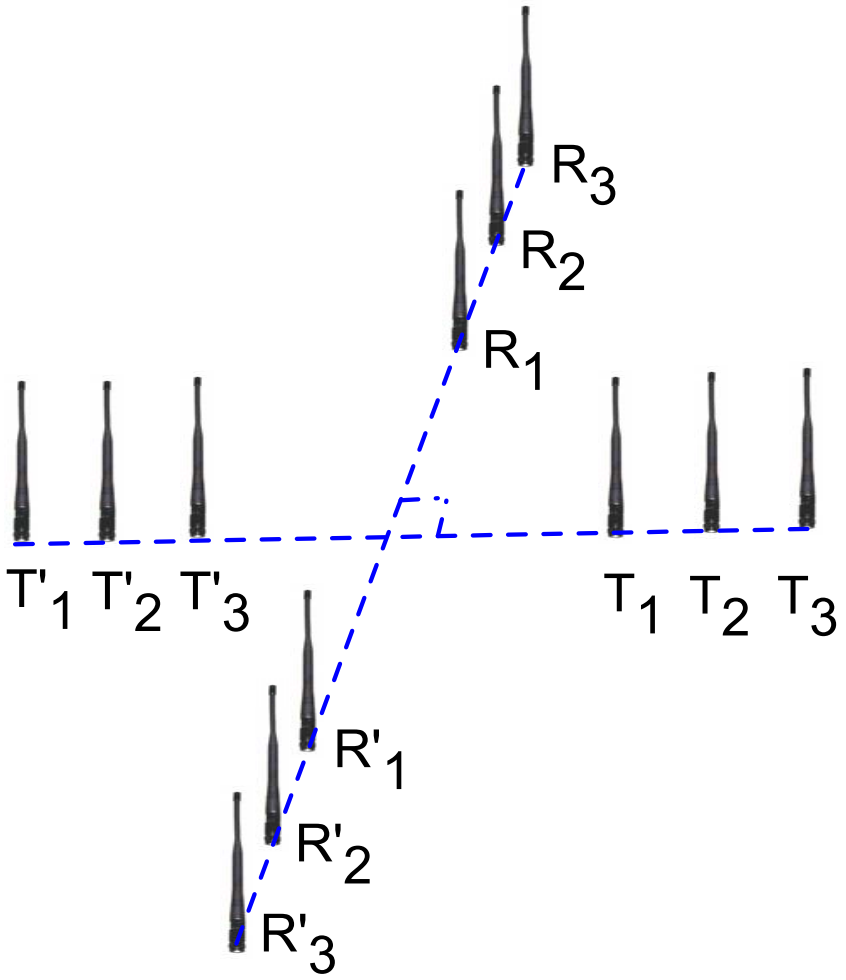
# Experimental Evaluations

- WarpLab implementation
  - Narrow-band 625 KHz
  - Open space environment
  - MIDU + MU-MIMO
- Performance metric: SNR and the corresponding Shannon capacity
- Spectrum analyzer based measurement or the SNR reported by WARP

Virtex-IV Pro FPGA

# Experimental Evaluations

- **Feasibility**
  - *Channel–distance relationship*
  - Stability
  - Impact on far-field users
- **Cancellation**
  - Single-level
  - *2-level and MIMO*
- **Comparison with MIMO**
  - Single link
  - *Single cell*



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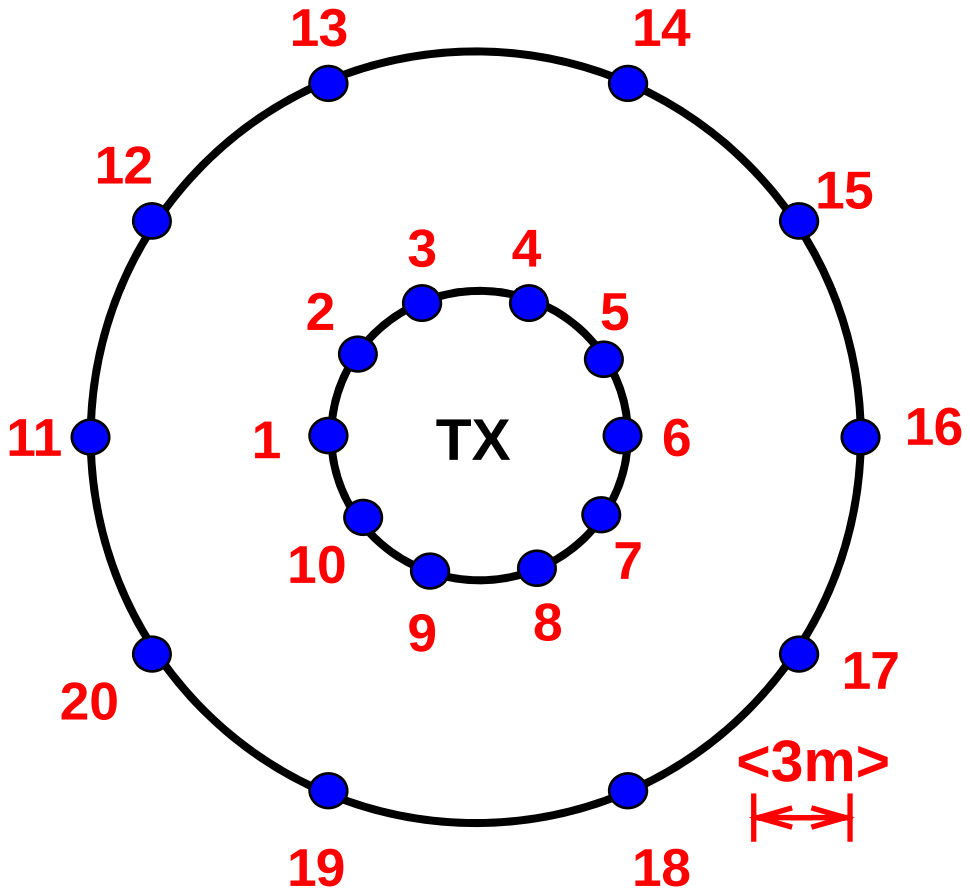

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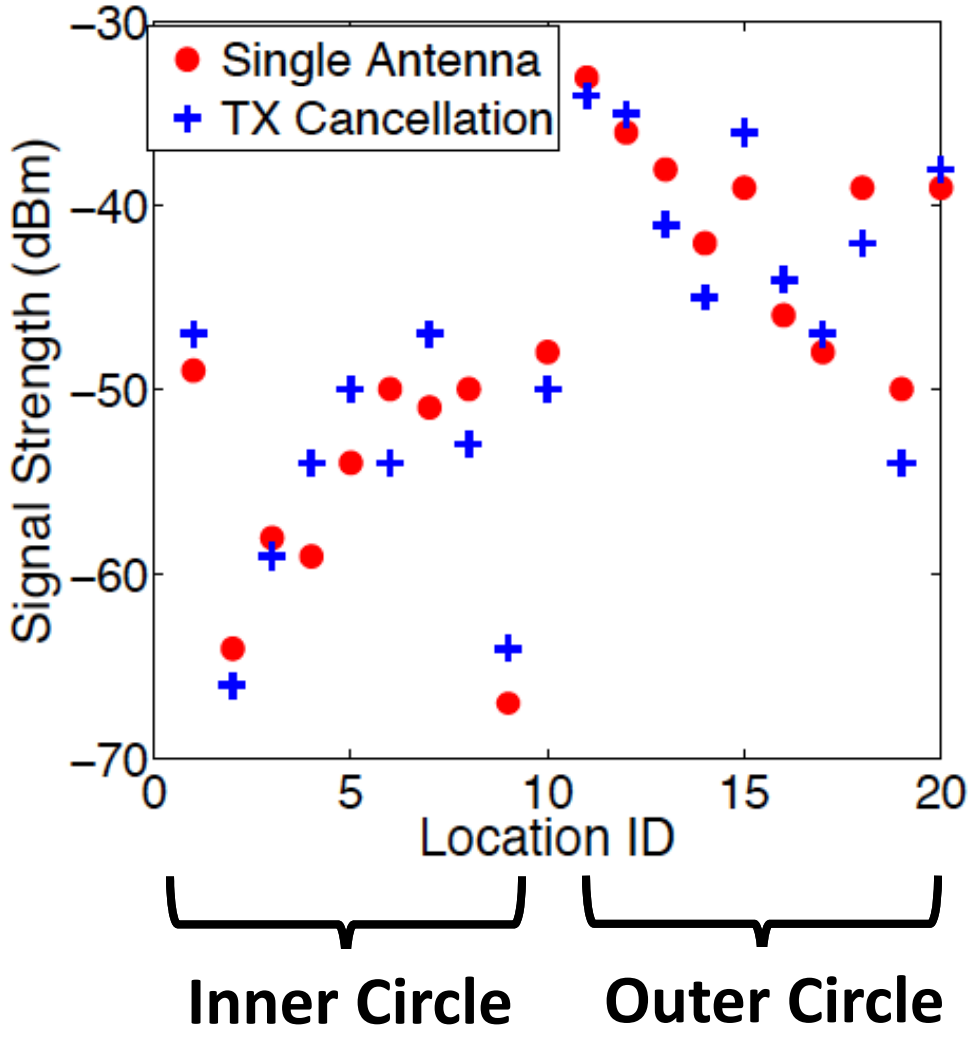
- Achieved SNR can be up to 4 dB higher/lower



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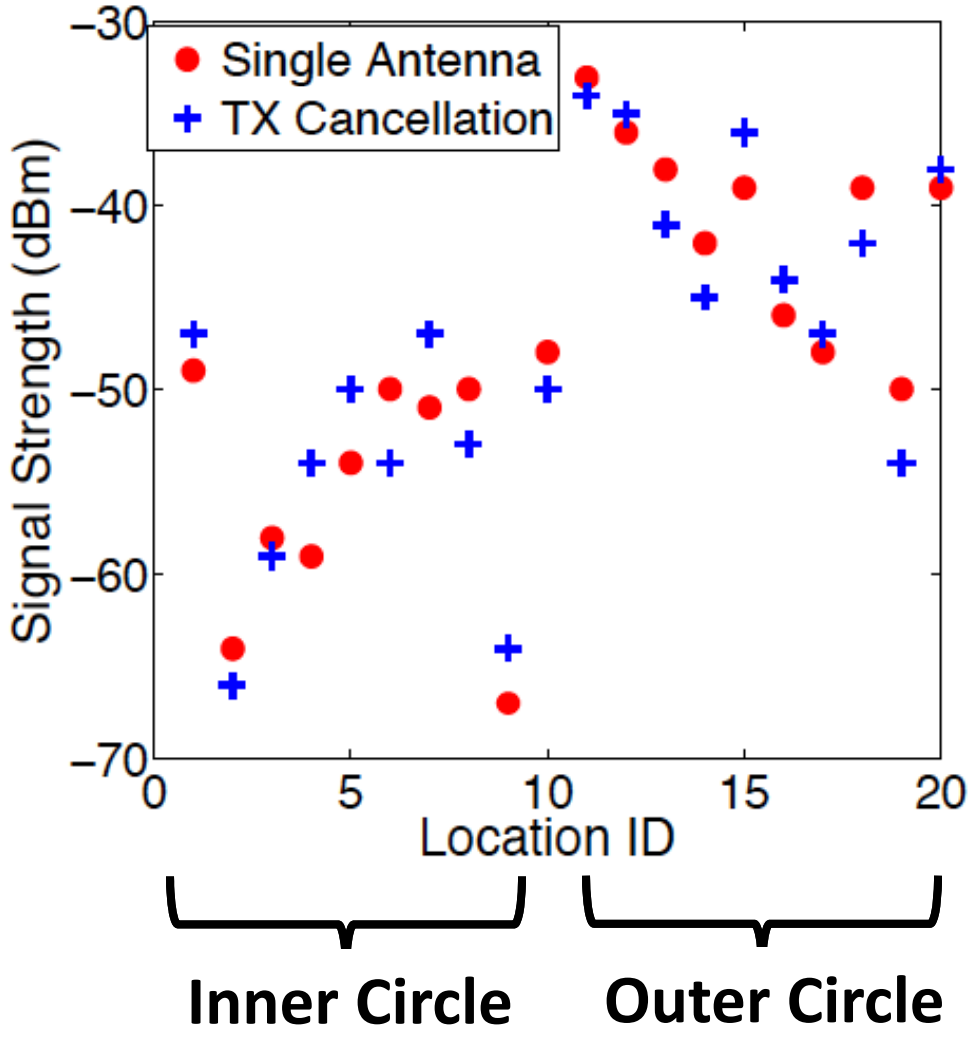
- Achieved SNR can be up to 4 dB higher/lower
- In far-field antenna cancellation has very limited effect due to signal scattering (fading)
- Similar results hold for RX cancellation



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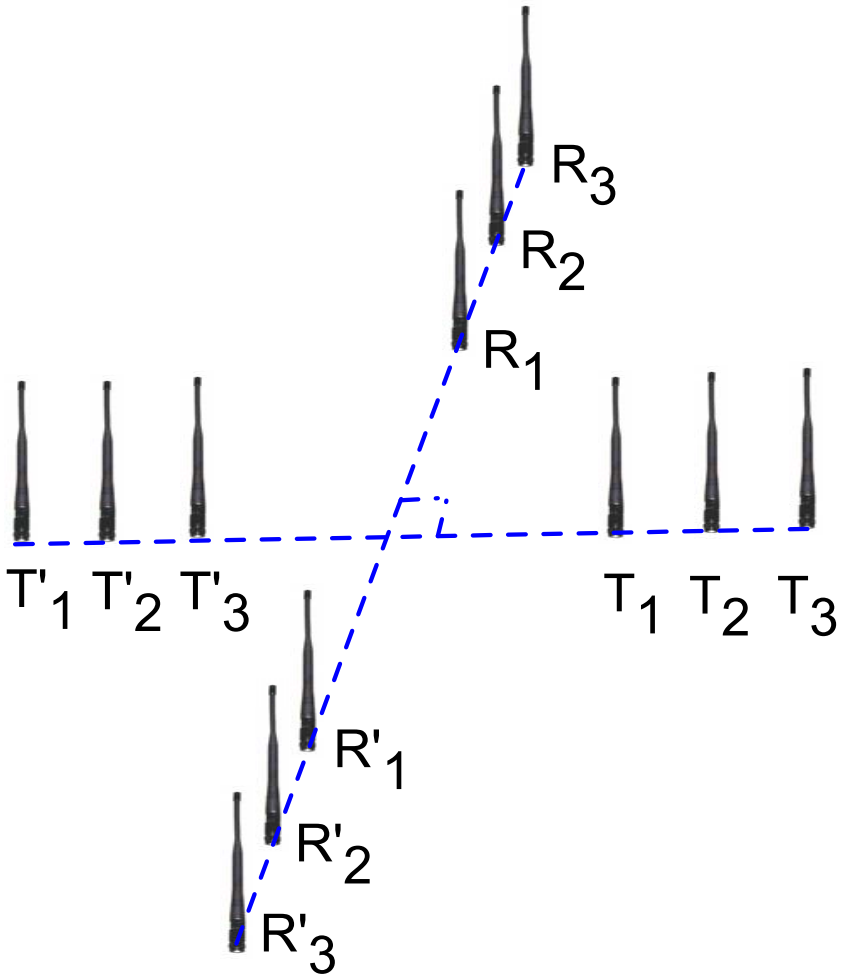
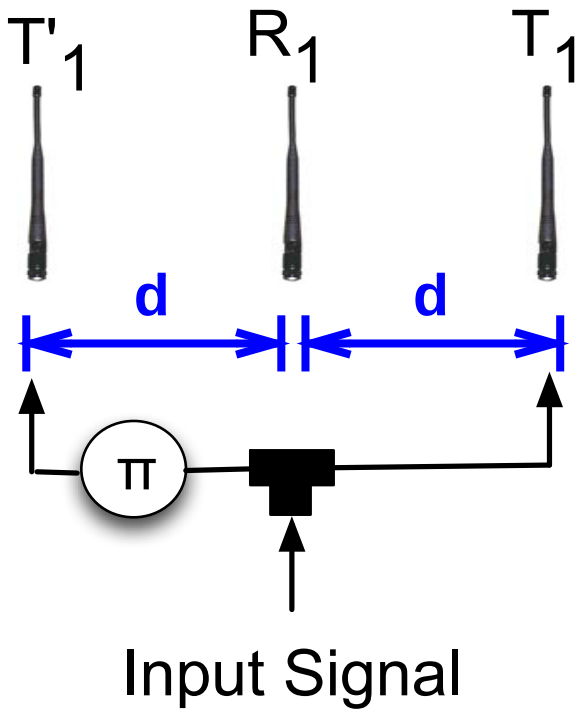


# Cancellation

- Issue: Is 2-level cancellation additive? Is MIDU scalable?
- Connect the receiver to a spectrum analyzer



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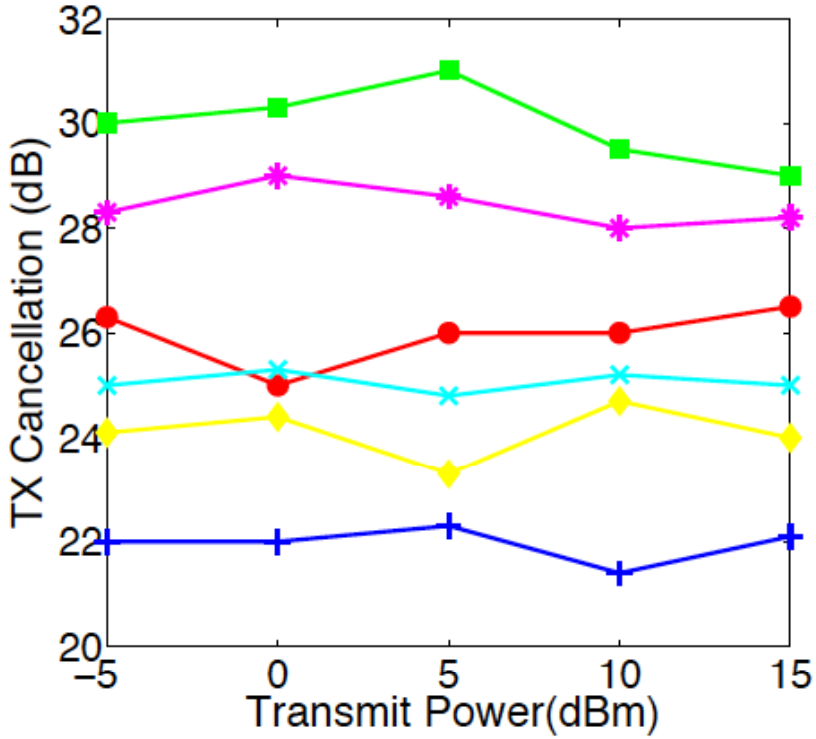
- **22 – 30 dB cancellation on each level separately**
- **Cancellation remains relatively unchanged with Tx power**



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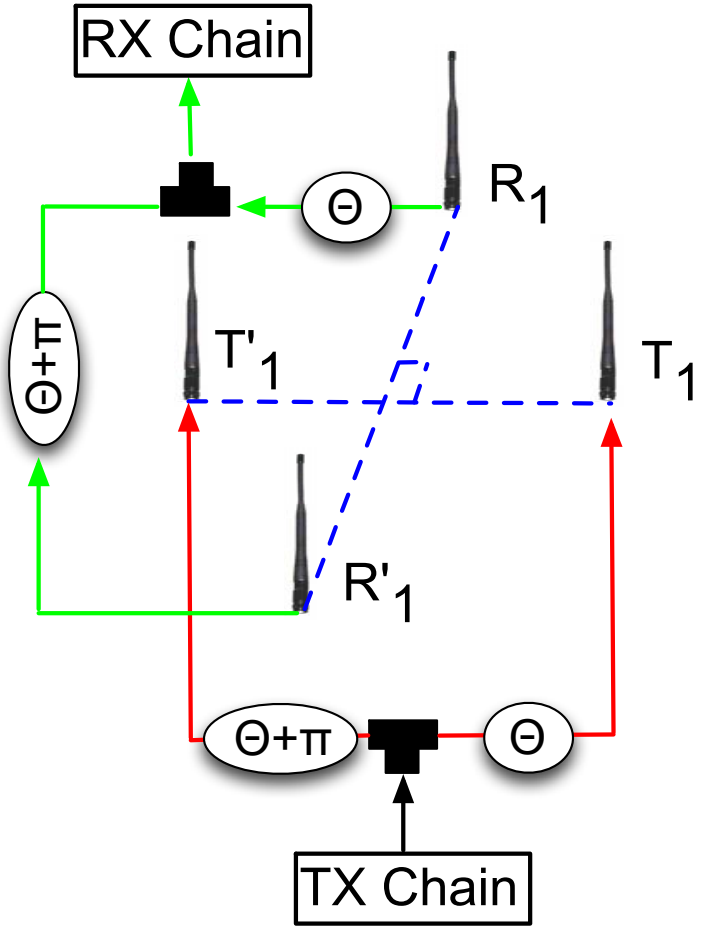

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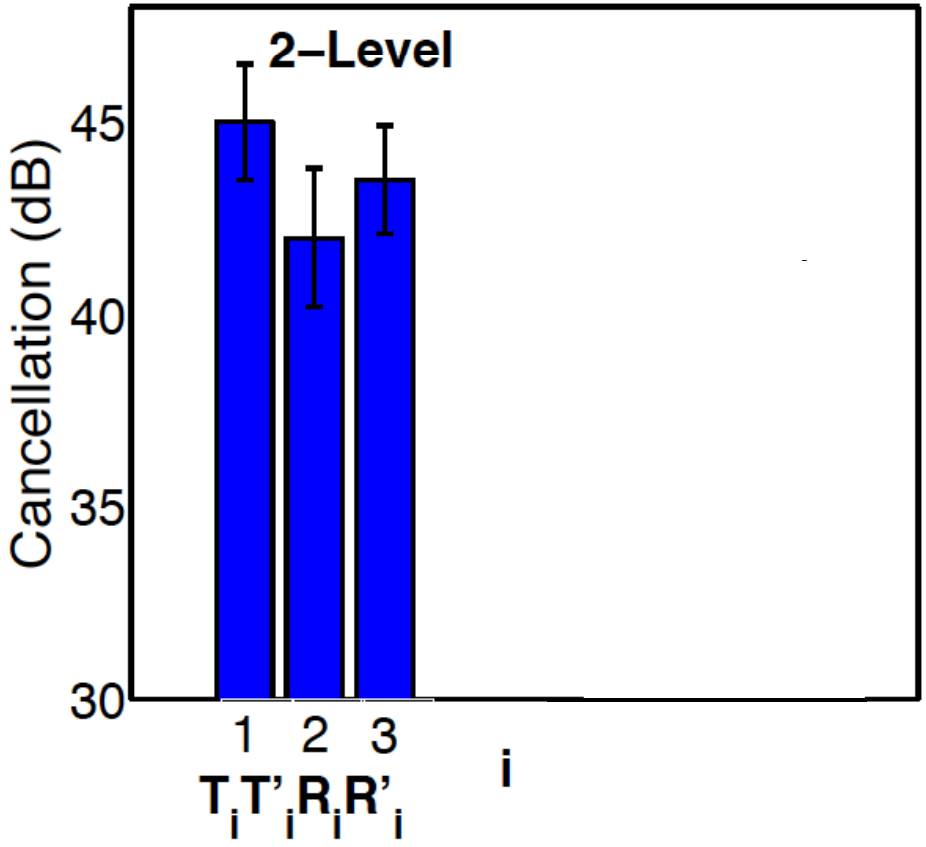

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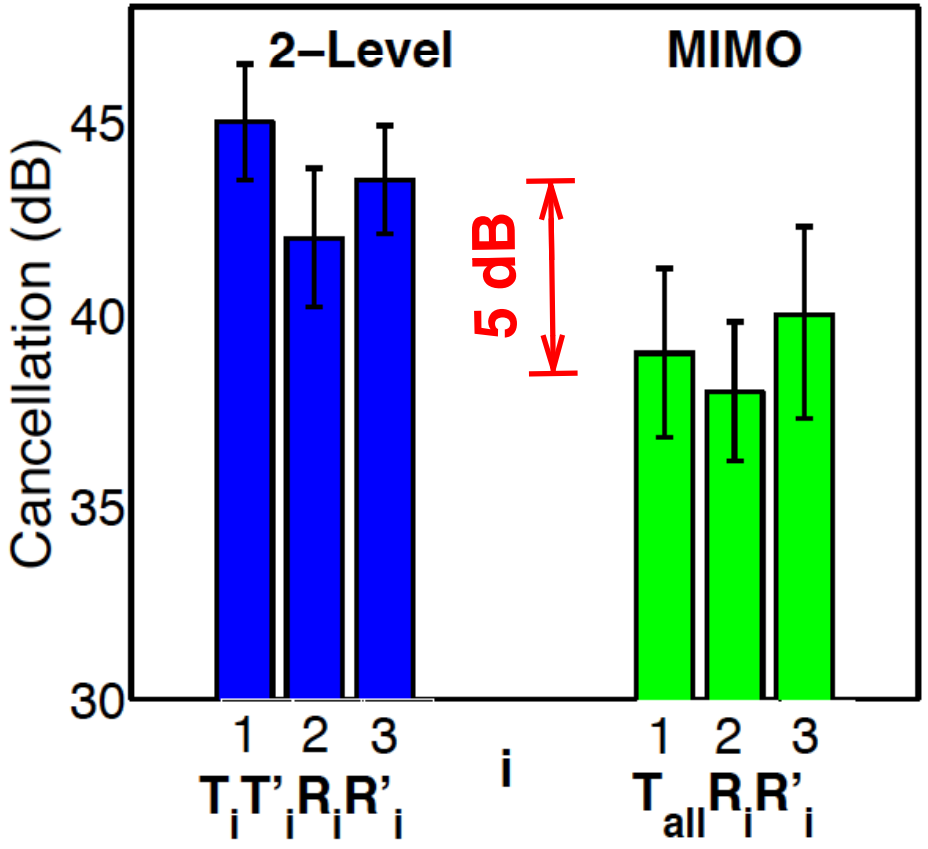
- RX cancellation on top of TX cancellation is **additive**
- 4 dB decrease in cancellation for the first added pair**, 5 dB with 3 total pairs**



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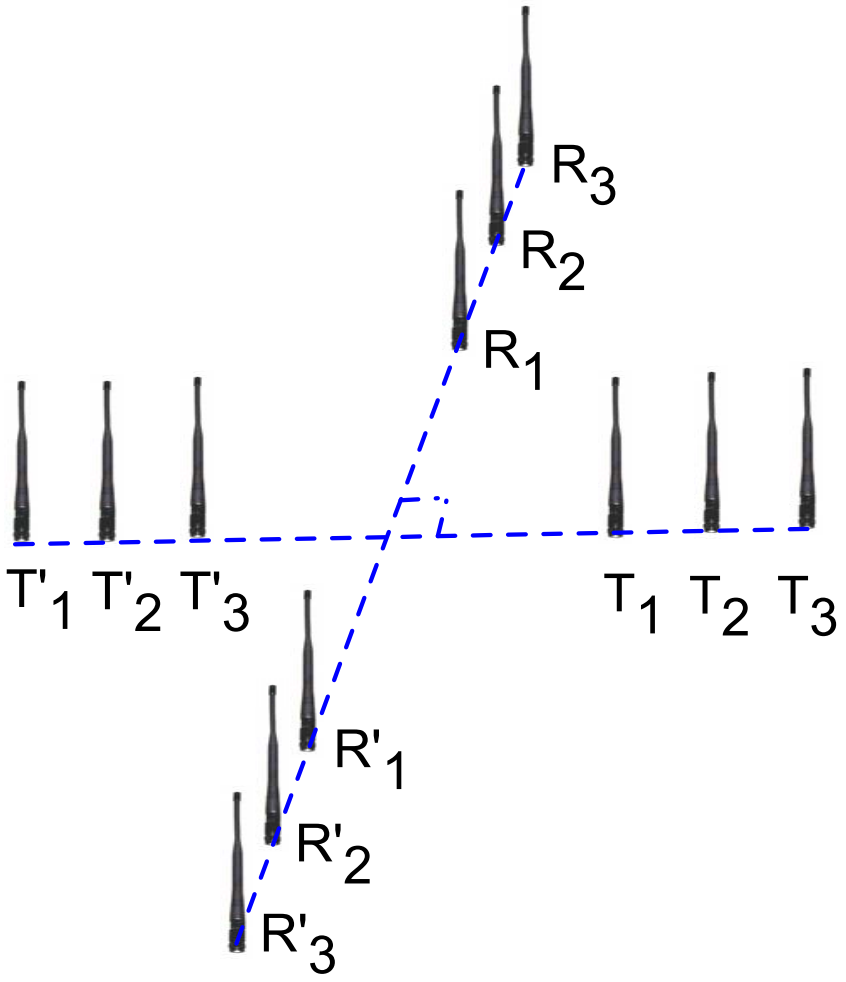
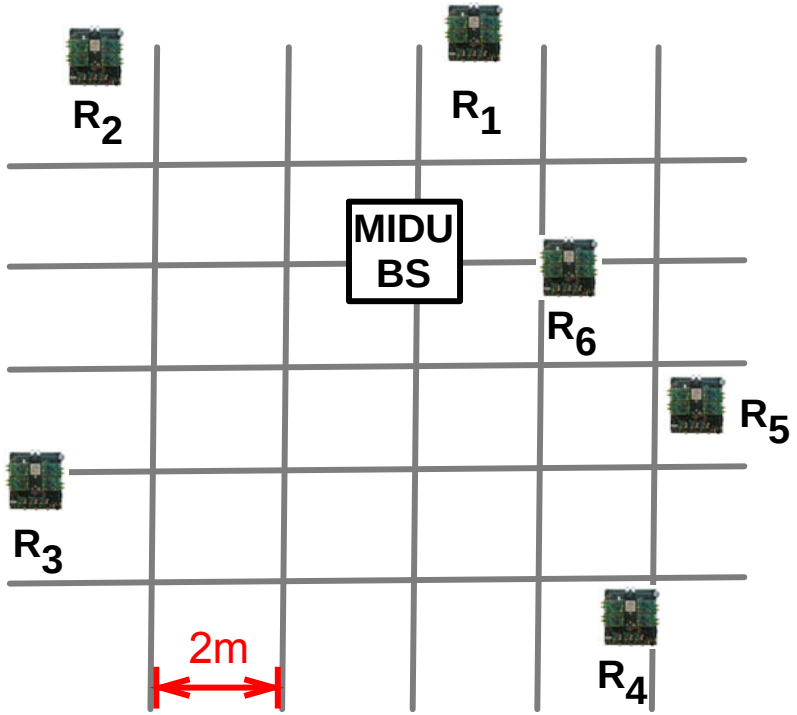


# Comparison with MIMO

- Compare MIDU to MU-MIMO
  - RF-Chain conserved model
  - Multi-user beamfoming/filtering for MU-MIMO in each direction
  - UL ➔ DL interference in MIDU
- Metric: Shannon capacity of the measured SNR



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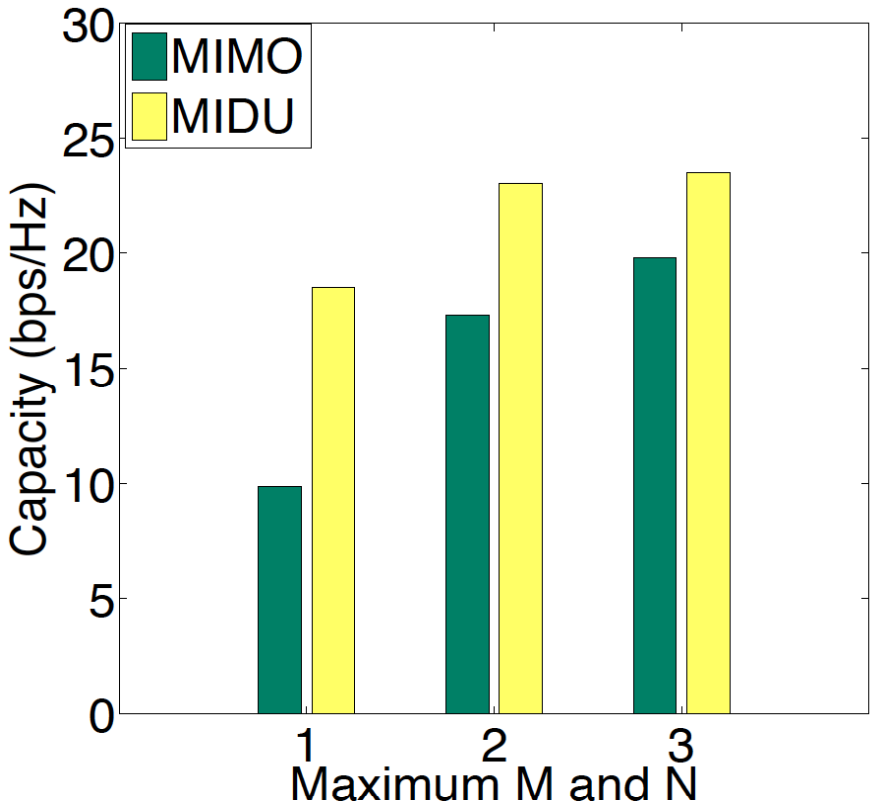
*M: #UL Streams N: #DL Streams*



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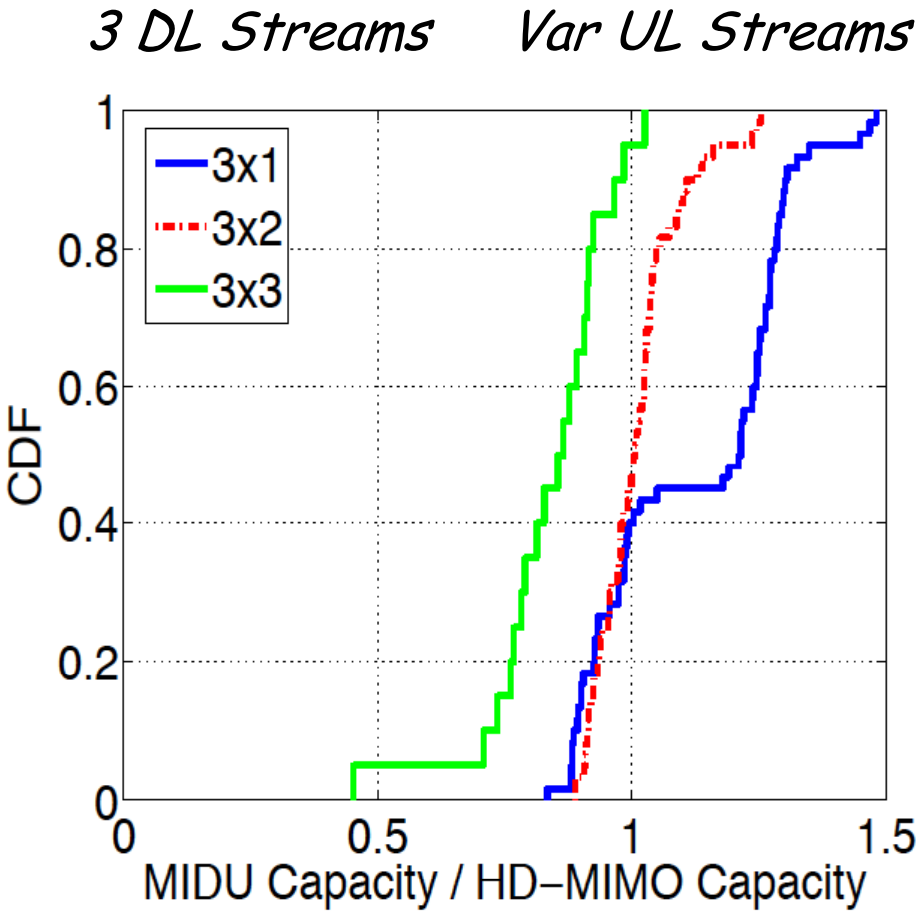
- Full duplex gains diminish as the number of streams is scaled
- For maximum full duplex gains, the **number of streams** between UL and DL should be **dis-proportionate**



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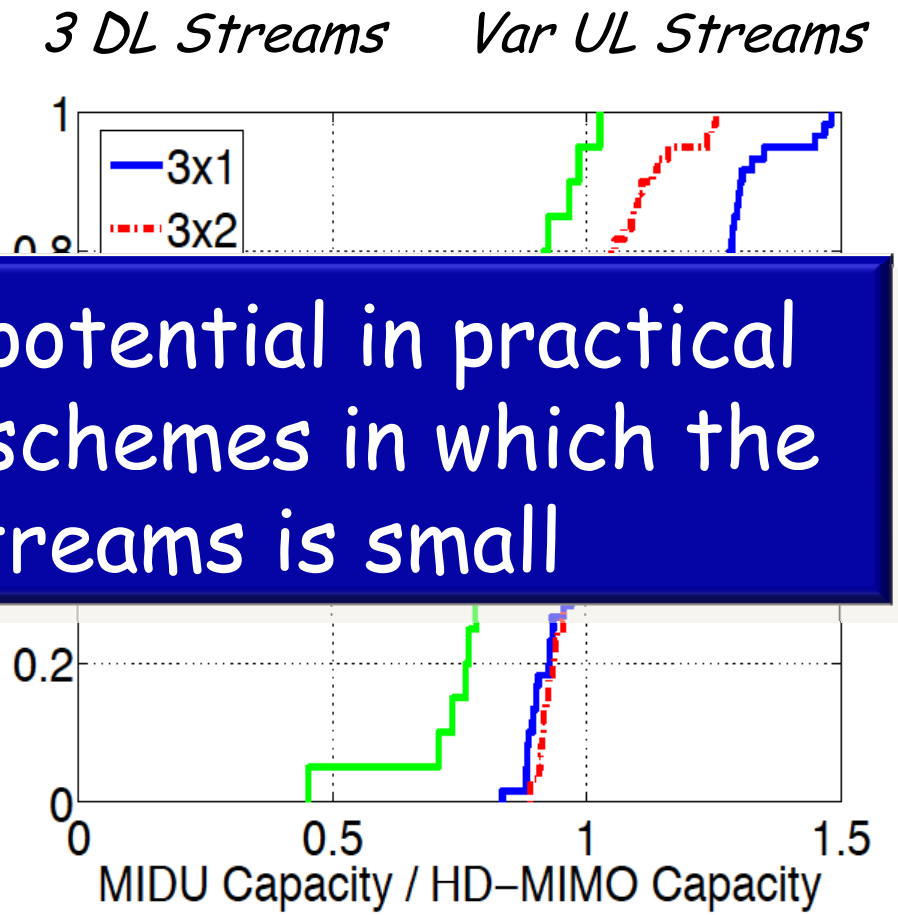



**Full duplex has great potential in practical single cell MU-MIMO schemes in which the number of UL streams is small**

- For maximum full duplex gains, the **number of streams** between UL and DL should be **dis-proportionate**

# FD for Legacy-LTE

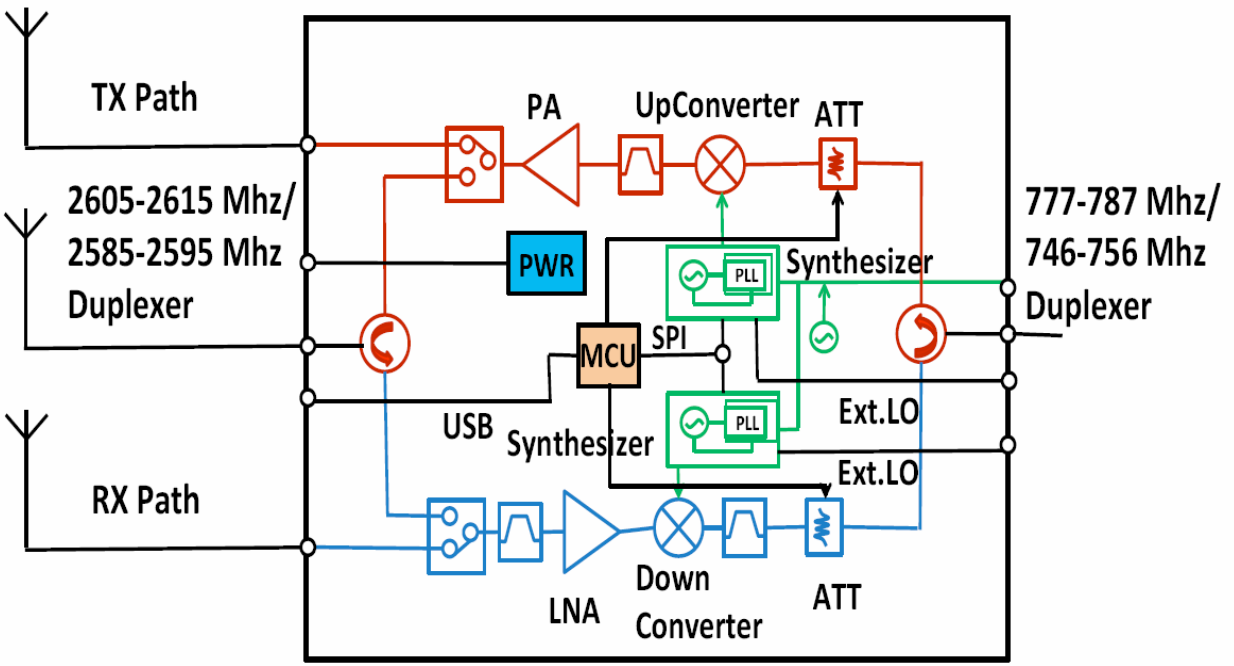
- Is it possible to enable FD in legacy LTE systems?
  - What changes are required?
    - Handset sides and network (base-station) side
  - New hardware?
  - New firmware?
  - Change in standard?

# Challenges

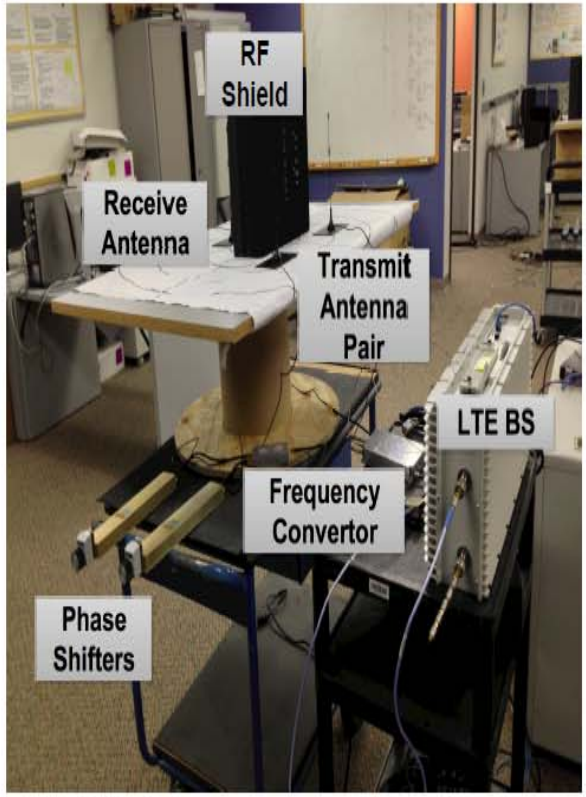
- SI cancellation
  - Is analog cancellation sufficient?
  - What range/data rate could be achieved?
  - Passive cancellation or need for Active cancellation?
- Integration with legacy BS equipment
  - Can we keep the BS hardware and/or firmware unchanged?
  - Handling multiple frequency bands
- Transparency to half-duplex client

# Frequency Converter Circuit

- We use the following circuit to enable FD without modifying basestation, user equipment or standards
- A circuit has to be used in the basestation as well as a complementary circuit at the user equipment

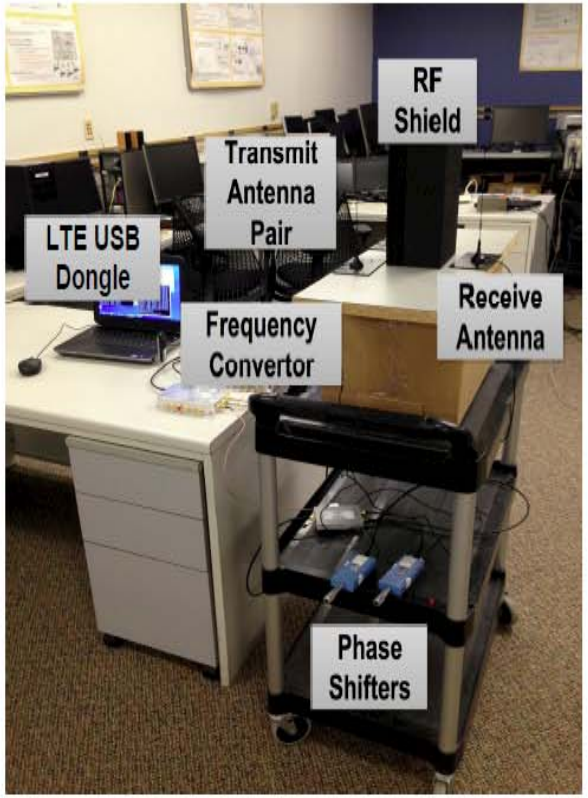


# Full Duplex LTE Testbed




b) FD LTE base station

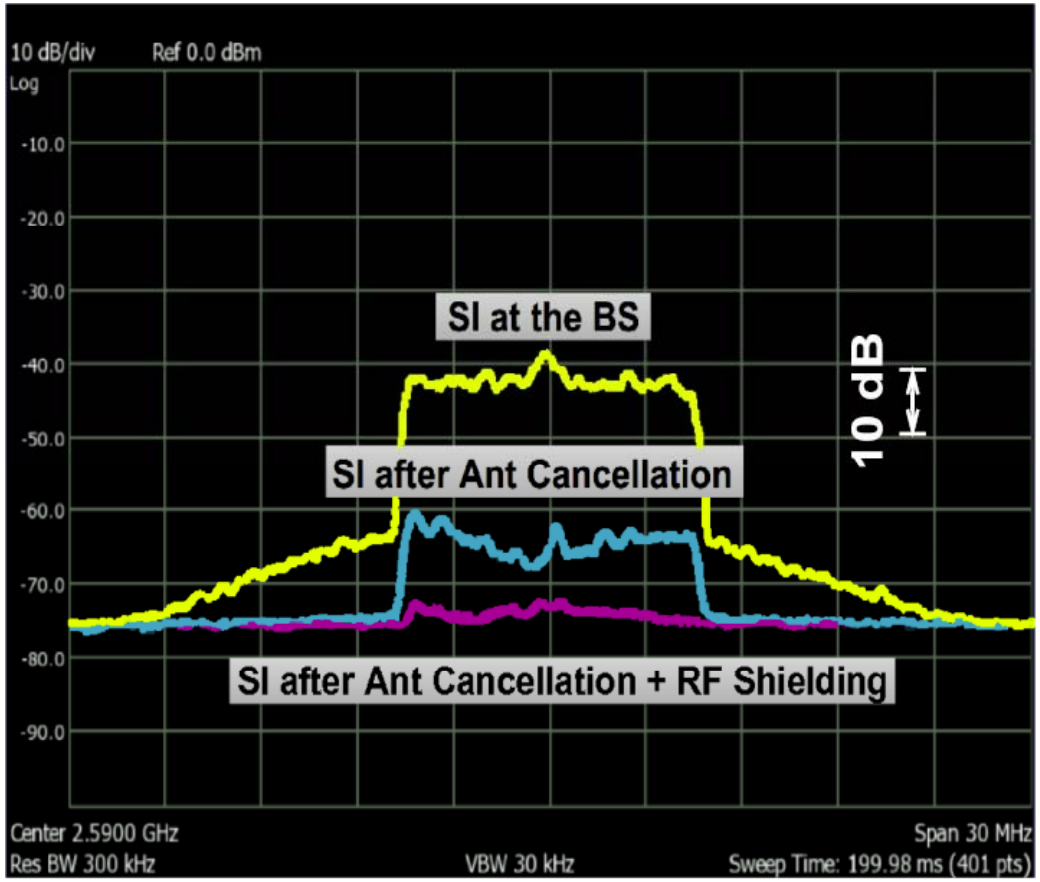

a) LTE EPC network




c) FD LTE client

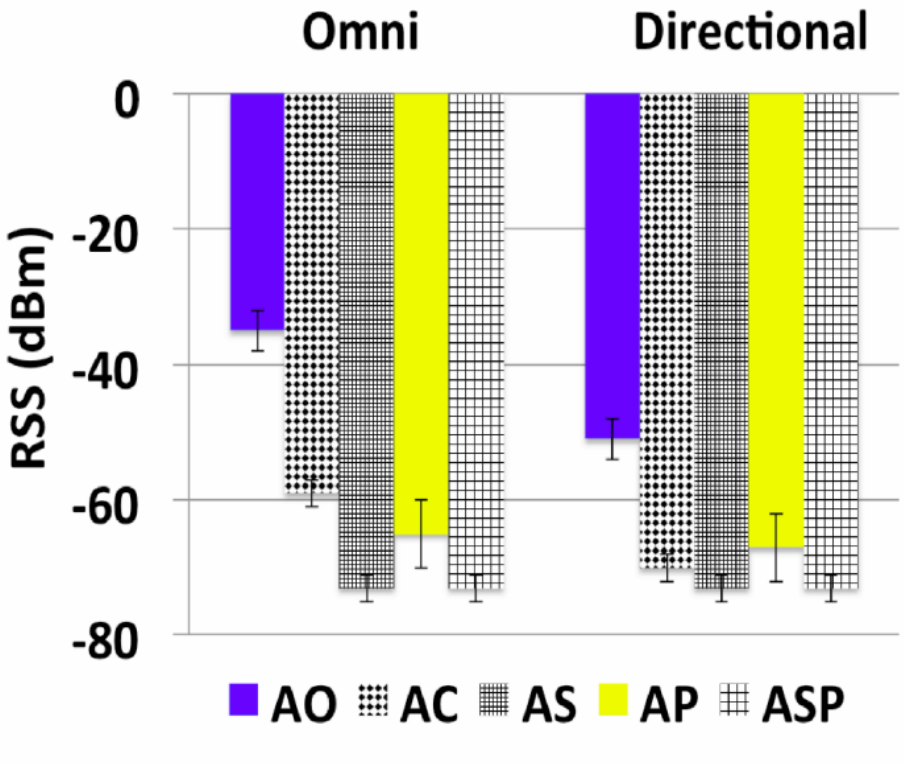
# SI Cancellation at BS

- SI power without any cancellation -42dBm
- SI after antenna cancellation -64dBm
- SI after antenna cancellation and using antenna shielding -73dBm



# Indoor SI Cancellation Evaluation

- AO: antenna separation only
- AC: antenna cancellation
- AS: antenna cancellation plus antenna shielding
- AP: antenna cancellation plus polarization
- ASP: antenna cancellation plus polarization plus shielding



# Outdoor SI Cancellation Evaluation

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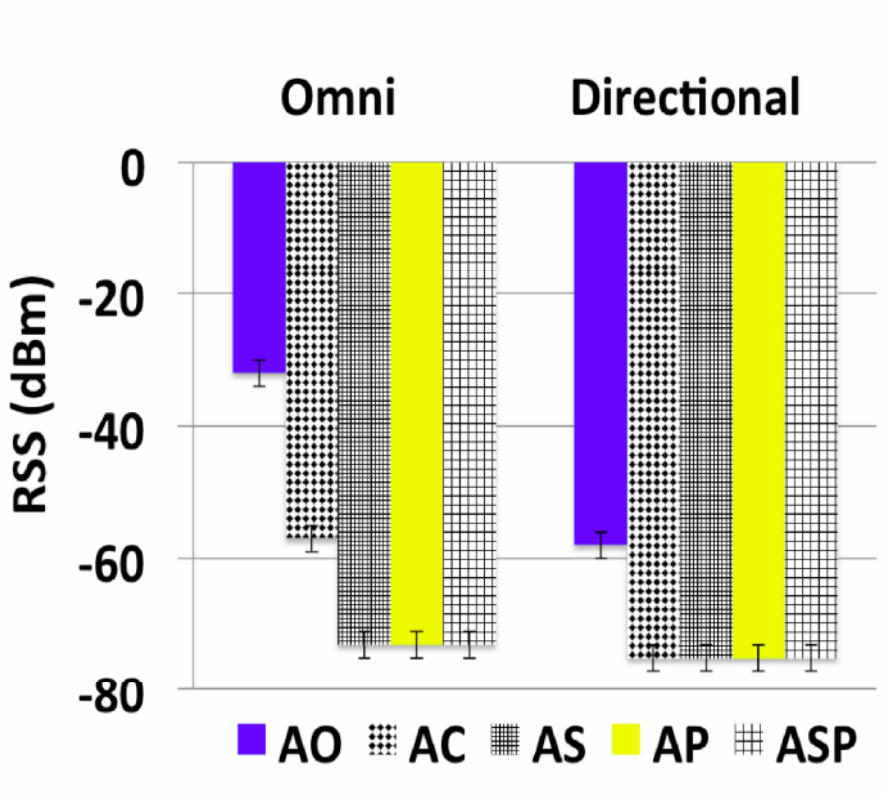
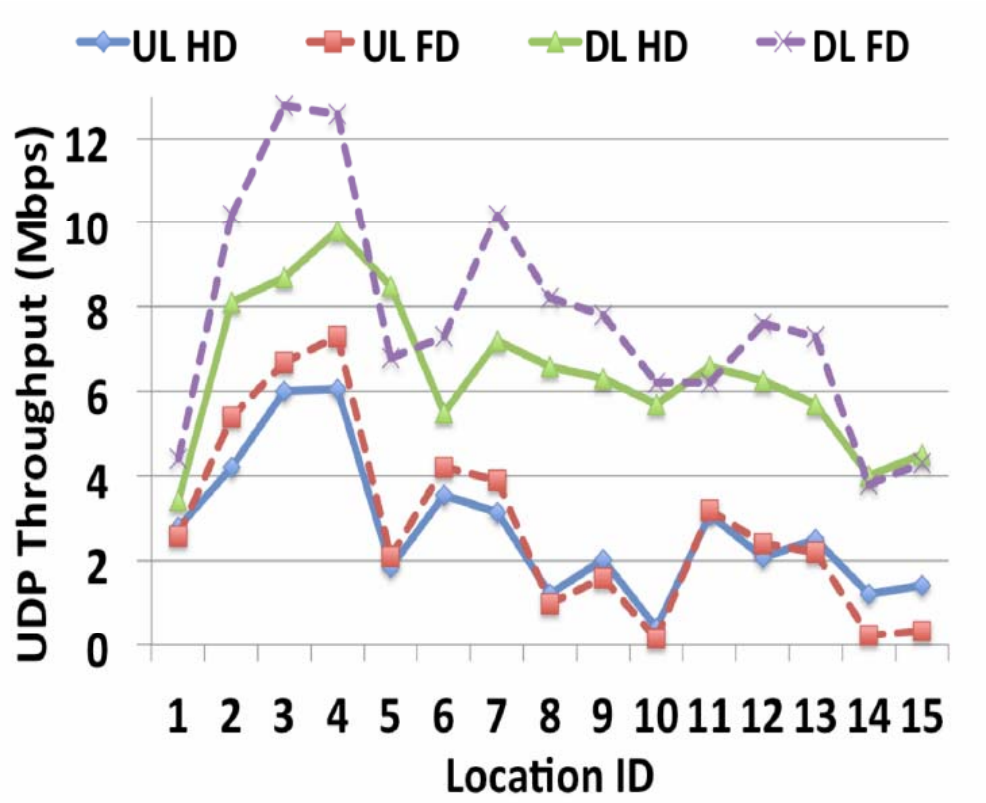


# Experiment Layout

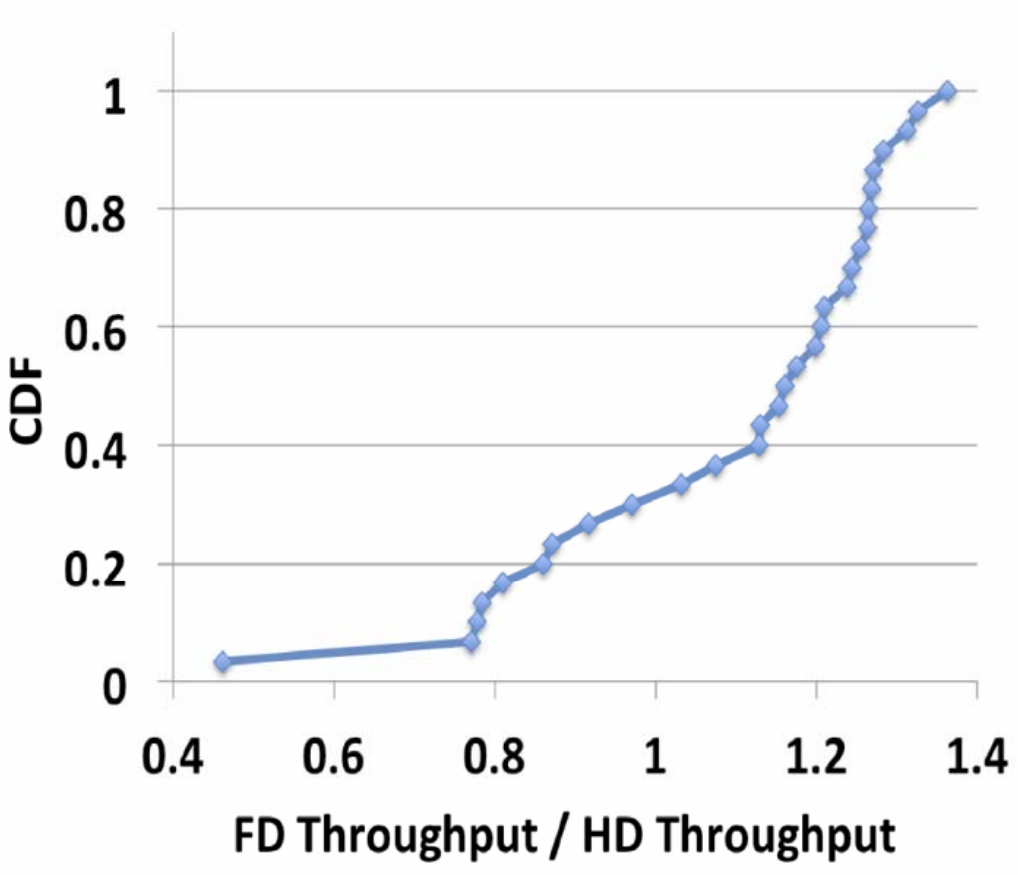
# UDP Throughput

- DL FD outperforms DL HD for almost all locations
- UL FD outperforms UL HD for about 60% locations with an average gain of 23%



# CDF of Total FD (UL+DL) to Total HD Throughput

- In about 65% of the locations FD has gain over HD
- In about 40% of the locations the gain is between 20%-40%



# In Summary

- Designed and implemented MIDU, the first MIMO full duplex wireless system
- Enabled two stages of antenna cancellation with additive gains that provided as high as 45 dB self-interference cancellation
- Built a prototype of MIDU with joint operation of 3x3 MIMO + Full Duplex in practice
- Implementation using Legacy-LTE basestation and possibility to use half-duplex clients