Coexistence with MIMO and Potential in Legacy LTE Systems

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Current wireless radios are half duplex
• Current wireless radios are half duplex
• Same band Full duplex is hard
  – Self interference is very high: \(\approx 75 \text{ dB for } 15 \text{ dBm Tx power}\)
  – Transmitted signal is known \(\rightarrow\) self interference cancellation
  – Self interference can be significantly reduced by adding a
cancellation circuit: e.g., a cancelling antenna
• Current wireless radios are half duplex
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  – Self interference is very high: ≈75 dB for 15 dBm Tx power
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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

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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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Full Duplex vs. MIMO

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

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

SI loss: 6 dB  Ant Correlation: 0.1

![Graph showing capacity vs. number of antennas](image)

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Full Duplex vs. MIMO

- Hardware complexity, performance, size, cost metrics
  - SI loss: 6 dB  Ant Correlation: 0.1

- Antenna Conserved (AC): Same

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

- Significant **FD gains** in RC model
- Limited **FD gains** with small # antennas in AC model higher gains with more antennas

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MIDU: MIMO full-DUplex

- Symmetric antenna placement

![Diagram of MIDU: MIMO full-DUplex](image)

Input Signal
• Symmetric antenna placement

• 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
MIDU: MImo full-DUplex

- 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
Experimental Evaluations

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- Performance metric: SNR and the corresponding Shannon capacity

Virtex-IV Pro FPGA
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
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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• Issue: How does symmetric antenna placement impact the far-field users?
Impact of MIDU on Far-Field Users

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• Achieved SNR can be up to 4 dB higher/lower
Impact of MIDU on Far-Field Users

- **Issue:** How does symmetric antenna placement impact the far-field users?
- **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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*Graph showing signal strength vs. location ID with two groups: Single Antenna and TX Cancellation.*
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Cancellation

• Issue: Is 2-level cancellation additive? Is MIDU scalable?

• Connect the receiver to a spectrum analyzer
Cancellation

- Issue: Is 2-level cancellation additive? Is MIDU scalable?

- 22 – 30 dB cancellation on each level separately

- Cancellation remains relatively unchanged with Tx power
Cancellation

• Issue: Is 2-level cancellation additive? Is MIDU scalable?

• Phase shifter on each path to handle insertion loss and delay
Cancellation

- Issue: Is 2-level cancellation additive? Is MIDU scalable?

- Phase shifter on each path to handle insertion loss and delay

- RX cancellation on top of TX cancellation is additive
• Issue: Is 2-level cancellation additive? Is MIDU scalable?

• Phase shifter on each path to handle insertion loss and delay

• 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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Experimental Evaluations

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Comparison with MIMO

• Compare MIDU to MU-MIMO
  – RF-Chain conserved model
  – Multi-user beamforming/filtering for MU-MIMO in each direction
  – UL $\rightarrow$ DL interference in MIDU

• Metric: Shannon capacity of the measured SNR
Comparison with MIMO

- Compare MIDU to MU-MIMO
  - RF-Chain conserved model
  - Multi-user beamforming/filtering for MU-MIMO in each direction
  - UL → DL interference in MIDU

- Full duplex gains diminish as the number of streams is scaled

Graph showing capacity (bps/Hz) for different numbers of UL and DL streams (M and N) in comparison with MIMO and MIDU.
Comparison with MIMO

• Compare MIDU to MU-MIMO
  – RF-Chain conserved model
  – Multi-user beamforming/filtering for MU-MIMO in each direction
  – UL → DL interference in MIDU

• 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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Comparison with MIMO

- Compare MIDU to MU-MIMO
  - RF-Chain conserved model
  - Multi-user beamforming/filtering for MU-MIMO in each direction
- 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 disproportionate

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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

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

1 m

BS

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
• 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

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