Experiment-Driven Characterization of Full-Duplex Wireless Systems

Melissa Duarte
Advisor: Ashutosh Sabhawal

Department of ECE
Rice University

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• Same time same frequency band

• Assumed to be impossible due to large self interference

• Revisit this assumption using techniques for interference cancellation

• Can full-duplex achieve higher data rates than half-duplex?

• Characterize amount of cancellation and achievable rate performance
Interference Problem

• Theory
  • Interference $>>$ Signal
  • Strong interference regime
  • Interference is known, estimate channel, cancel, done
Interference Problem

- Implementation
Interference Problem

Node 1

\[ x[n] \xrightarrow{DAC} \text{Tx RF} \]

\[ y[n] \xleftarrow{ADC} \text{Rx RF} \]

\[ x(t)e^{jwt} \]

\[ y(t)e^{jwt} \]

\[ h_I \]

\[ h_S \]

Node 2

\[ x'(t)e^{jwt} \]

- Implementation
Interference Problem

Node 1

\[ y[n] \rightarrow \text{DAC} \rightarrow \text{Tx RF} \]

\[ \underbrace{y(t)}_{x(t)e^{jwt}} \]

\[ \underbrace{y[n] \rightarrow \text{ADC} \rightarrow \text{Rx RF}} \]

\[ y(t) = h_S x'(t) + h_I x(t) + z(t) \]

Node 2

\[ x'(t)e^{jwt} \]

\[ h_I \]

\[ h_S \]

- Implementation

- Received signal
Interference Problem

- Implementation

- Received signal

\[ y(t) = h_S x'(t) + h_I x(t) + z(t) \]

- Quantized received signal

\[ y[n] = h_S x'[n] + h_I x[n] + z[n] \]
**Interference Problem**

Node 1

\[ x[n] \rightarrow \text{DAC} \rightarrow \text{Tx RF} \]

\[ y(t) \rightarrow \text{ADC} \rightarrow \text{Rx RF} \]

\[ y[n] = h_I x[n] + h_S x'[n] + z[n] \]

\[ y(t) = h_S x'(t) + h_I x(t) + z(t) \]

**Implementation**

**Received signal**

**Quantized received signal**

**After removing interference**

**Quantization noise**
Interference Problem

- Implementation
  - Interference >> Signal : Quantization noise
  - Full-duplex assumed to be impossible due to large self interference

- Real systems SIR
  - Distance between nodes decreases
  - More than 20 dB cancellation has been reported in radar systems
  - Revisit this assumption using passive and active techniques for interference cancellation
Passive Cancellation

• Antenna Separation

• Antenna Directionality

• Antenna Cancellation

• Device Cancellation
Passive Cancellation

- Antenna Separation
  Separation $d$ between same node Tx and Rx antennas

- Antenna Directionality

- Antenna Cancellation

- Device Cancellation
Passive Cancellation

- **Antenna Separation**
  Separation $d$ between same node Tx and Rx antennas

- **Antenna Directionality**
  Used in Full-duplex Relays


- **Antenna Cancellation**

- **Device Cancellation**
Passive Cancellation

- **Antenna Separation**
  
  Separation $d$ between same node Tx and Rx antennas

- **Antenna Directionality**
  
  Used in Full-duplex Relays


- **Antenna Cancellation**
  
  2 Tx and 1 Rx per node, Tx at $d$ and $d+\lambda/2$


- **Device Cancellation**
Passive Cancellation

• Antenna Separation
  Separation $d$ between same node Tx and Rx antennas

• Antenna Directionality
  Used in Full-duplex Relays

• Antenna Cancellation
  2 Tx and 1 Rx per node, Tx at $d$ and $d+\lambda/2$

• Device Cancellation
  Place antennas at opposite sides of the device
Passive Cancellation

- **Antenna Separation**
  
  Separation $d$ between same node Tx and Rx antennas
  - We use antenna separation with $d = 10\text{cm}$, $20\text{cm}$, $40\text{cm}$
  - Worse case interference
  - Minimum resources for passive cancellation

- **Antenna Directionality**
  Used in Full-duplex Relays
  

- **Antenna Cancellation**
  
  $2\text{ Tx}$ and $1\text{ Rx}$ per node, Tx at $d$ and $d+\lambda/2$
  

- **Device Cancellation**
  
  Place antennas at opposite sides of the device
  
Active Analog Cancellation

- Using QHx220 chip

- Using extra Tx RF chain (without a power amplifier)
Active Analog Cancellation

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- Tuning algorithm to control gain and delay that chip applies to its input
- Suitable for wideband frequency flat $h_I$


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- Using extra Tx RF chain (without a power amplifier)
  - Estimate $h_I$ and design $c$ for analog cancellation
  - Suitable for wideband frequency flat and frequency selective $h_I$
  - Uses off-the-shelf MIMO radios
Active Analog Cancellation

- Using QHx220 chip
- Tuning algorithm to control gain and delay that chip applies to its input
- Suitable for wideband frequency flat $h_I$
  

- Used in our experiments
- Using extra Tx RF chain (without a power amplifier)
  - Estimate $h_I$ and design $c$ for analog cancellation
  - Suitable for wideband frequency flat *and* frequency selective $h_I$
  - *Uses off-the-shelf MIMO radios*

Active Digital Cancellation

- Without analog cancellation

- Combined with analog cancellation
Active Digital Cancellation

- Without analog cancellation
  - Estimate $h_I$ and cancel $h_I x$ in the digital domain

- Combined with analog cancellation
Active Digital Cancellation

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  - Estimate $h_I$ and cancel $h_I x$ in the digital domain

- Combined with analog cancellation
  - Estimate residual interference and cancel in the digital domain
Active Digital Cancellation

- Without analog cancellation
  - Estimate $h_I$ and cancel $h_I x$ in the digital domain

- Combined with analog cancellation
  - Estimate residual interference and cancel in the digital domain

- We have considered the two options above
  - Allows us to characterize the effect in total cancellation when concatenating cancellation mechanisms
Full-Duplex Systems Considered

- We have implemented the following full-duplex systems
  - Antenna Separation + Digital Cancellation
  - Antenna Separation + Analog Cancellation
  - Antenna Separation + Analog Cancellation + Digital Cancellation
Summary of Results

• Characterization of self-interference cancellation mechanisms
  • Amount of cancellation
  • Impact on full-duplex achievable rate performance

• Comparison with half-duplex systems
  • Demonstrated that full-duplex can achieve higher rates than half-duplex

Experiment Setup

Node 1

Node 2

8.5 m
Experiment Setup

Node 1

TX

RX

Node 2

TX

RX

$d = 10 \text{ cm}, 20 \text{ cm}, 40 \text{ cm}$

$d$

8.5 m
Experiment Setup

- **TX**: Transmitting node
- **RX**: Receiving node
- **d**: Distance between nodes
- **$P_{TX} = [0, 5, 10, 15]$ dBm**
- **d = 10 cm, 20 cm, 40 cm**

Node 1 and Node 2 are placed 8.5 m apart, with transmission power levels of $0$, $5$, $10$, and $15$ dBm. The distance between the nodes is varied at 10 cm, 20 cm, and 40 cm.
• WARP with 3 radios

• WARPLab = WARP + Matlab, to generate/analyze signals

• Narrowband tests, 0.65 MHz

• Recent extension to OFDM 10MHz @ Rice

Experiment Setup

- WARP with 3 radios
- WARPLab = WARP + Matlab, to generate/analyze signals
- Narrowband tests, 0.65 MHz
- Recent extension to OFDM 10MHz @ Rice
Characterization of Average Cancellation

- Digital cancellation
- Analog cancellation
- Analog and digital cancellation
Characterization of Average Cancellation

- Digital cancellation
- Analog cancellation
- Analog and digital cancellation

\[ P_{IRX} \]
Characterization of Average Cancellation

- Digital cancellation
- Analog cancellation
- Analog and digital cancellation
Characterization of Average Cancellation

- Digital cancellation
- Analog cancellation
- Analog and digital cancellation

\[ \alpha_{AC} = P_{IRX} - P_{IAC} \]
Characterization of Average Cancellation

- Digital cancellation
  \[ \alpha_{DC} = P_{IRX} - P_{IDC} \]

- Analog cancellation
  \[ \alpha_{AC} = P_{IRX} - P_{IAC} \]

- Analog and digital cancellation
Characterization of Average Cancellation

- Digital cancellation
  \[ \alpha_{DC} = P_{IRX} - P_{IDC} \]

- Analog cancellation
  \[ \alpha_{AC} = P_{IRX} - P_{IAC} \]

- Analog and digital cancellation
  \[ \alpha_{ACDC} = P_{IRX} - P_{IACDC} \]

\[ x \rightarrow DAC \rightarrow Tx RF \]
\[ c \rightarrow DAC \rightarrow Tx RF \]
\[ y_{ACDC} \leftarrow DC \rightarrow ADC \rightarrow Rx RF \]
Characterization of Average Cancellation

- **Digital cancellation**
  \[ \alpha_{DC} = P_{IRX} - P_{IDC} \]

- **Analog cancellation**
  \[ \alpha_{AC} = P_{IRX} - P_{IAC} \]

- **Analog and digital cancellation**
  \[ \alpha_{ACDC} = P_{IRX} - P_{IACDC} \]
Characterization of Average Cancellation

- Digital cancellation
  \[ \alpha_{DC} = P_{IRX} - P_{IDC} \]

- Analog cancellation
  \[ \alpha_{AC} = P_{IRX} - P_{IAC} \]

- Analog and digital cancellation
  \[ \alpha_{ACDC} = P_{IRX} - P_{IACDC} \]
Characterization of Average Cancellation

• Digital cancellation

\[ \alpha_{DC} = P_{IRX} - P_{IDC} \]

![Graph showing dB cancelled vs. P_{IRX} (dBm) for digital cancellation]

• Analog cancellation

\[ \alpha_{AC} = P_{IRX} - P_{IAC} \]

![Graph showing dB cancelled vs. P_{IRX} (dBm) for analog cancellation]

• Analog and digital cancellation

\[ \alpha_{ACDC} = P_{IRX} - P_{IACDC} \]

![Graph showing dB cancelled vs. P_{IRX} (dBm) for analog and digital cancellation]
Characterization of Average Cancellation

- Digital cancellation
  \[ \alpha_{DC} = P_{IRX} - P_{IDC} \]

- Analog cancellation
  \[ \alpha_{AC} = P_{IRX} - P_{IAC} \]

- Analog and digital cancellation
  \[ \alpha_{ACDC} = P_{IRX} - P_{IACDC} \]

- We want a simple model for the average cancellation
  - Option 1: Fit the data to a constant model
  - Option 2: Fit the data to a linear model
Characterization of Average Cancellation

- Digital cancellation
  \[ \alpha_{DC} = P_{IRX} - P_{IDC} \]

- Analog cancellation
  \[ \alpha_{AC} = P_{IRX} - P_{IAC} \]

- Analog and digital cancellation
  \[ \alpha_{ACDC} = P_{IRX} - P_{IACDC} \]

- **Result 1:**
  - As received interference power \( P_{IRX} \) increases amount of cancellation increases

- **Reason:**
  - Cancellation is based on channel measurement
  - Higher \( P_{IRX} \) means higher SNR for channel estimation
  - Better estimation and hence increased cancellation
Characterization of Average Cancellation

• Digital cancellation

\[ \alpha_{DC} = P_{IRX} - P_{IDC} \]

• Analog cancellation

\[ \alpha_{AC} = P_{IRX} - P_{IAC} \]

• Analog and digital cancellation

\[ \alpha_{ACDC} = P_{IRX} - P_{IACDC} \]

• Result 2:

(a) Concatenation of cancellation mechanisms does not result in a sum of their individual cancellations
Characterization of Average Cancellation

- Digital cancellation

\[ \alpha_{DC} = P_{IRX} - P_{IDC} \]

- Analog cancellation

\[ \alpha_{AC} = P_{IRX} - P_{IAC} \]

- Analog and digital cancellation

\[ \alpha_{ACDC} = P_{IRX} - P_{IACDC} \]

\[ \begin{align*}
P_{IRX} \text{ (dBm)} & \quad \text{dB cancelled} \\
-45 & \quad 40 \\
-20 & \quad 20 \\
\end{align*} \]

Max cancellation: 27 dB

Max cancellation: 35 dB

Max cancellation: 36 dB

\[ \begin{align*}
\alpha_{DC} \text{ experiments} & \quad \alpha_{DC} \text{ constant model} \\
\alpha_{DC} \text{ linear model} & \quad \alpha_{AC} \text{ constant model} \\
\alpha_{AC} \text{ linear model} & \quad \alpha_{ACDC} \text{ constant model} \\
\alpha_{ACDC} \text{ linear model} & \quad \alpha_{ACDC} \text{ experiments} \\
\end{align*} \]

Result 2:

(a) Concatenation of cancellation mechanisms does not result in a sum of their individual cancellations
Characterization of Average Cancellation

- Digital cancellation
  \[ \alpha_{DC} = P_{IRX} - P_{IDC} \]

- Analog cancellation
  \[ \alpha_{AC} = P_{IRX} - P_{IAC} \]

- Analog and digital cancellation
  \[ \alpha_{ACDC} = P_{IRX} - P_{IACDC} \]

- Result 2:
  (a) Concatenation of cancellation mechanisms does not result in a sum of their individual cancellations
  (b) As the performance of analog cancellation gets better, the effectiveness of digital cancellation after analog cancellation reduces (observed on average and per frame)
Characterization of Average Cancellation

- Average performance
  \[ \alpha_{DC} = \alpha_{ACDC} - \alpha_{AC} \]

- Per frame performance
  \[ \alpha_{DC}[f] = \alpha_{ACDC}[f] - \alpha_{AC}[f] \]

**Result 2:**

(a) Concatenation of cancellation mechanisms does not result in a sum of their individual cancellations

(b) As the performance of analog cancellation gets better, the effectiveness of digital cancellation after analog cancellation reduces (observed on average and per frame)
Characterization of Average Cancellation

- Average performance
  \[ \alpha_{DC} = \alpha_{ACDC} - \alpha_{AC} \]

- Per frame performance
  \[ \alpha_{DC}[f] = \alpha_{ACDC}[f] - \alpha_{AC}[f] \]

- Reasons for Result 2:
  - As residual interference becomes smaller the effectiveness of cancelling the residual reduces
  - If analog cancellation could achieve \( \infty \) dB of cancellation then digital cancellation would be unnecessary
  - Furthermore applying digital cancellation would increase the noise
Summary of Results

- Characterization of self-interference cancellation mechanisms
  - Amount of cancellation
  - Impact on full-duplex achievable rate performance

- Comparison with half-duplex systems
  - Demonstrated that full-duplex can achieve higher rates than half-duplex

Computation of Achievable Sum Rate

- Achievable Sum Rate (ASR) b/s/Hz computed based on post processing SINR

- Compute SINR per frame

\[ \text{SINR}[f] = \frac{E[|s|^2]}{E[|s - \hat{s}|^2]} \]

- Compute achievable rate

\[ \text{AR} = E[\log(1 + \text{SINR}[f])] \]

- Sum rate full-duplex

\[ \text{ASR} = \text{AR}_{12} + \text{AR}_{21} \]

- Sum rate half-duplex

\[ \text{ASR} = \frac{1}{2} \text{AR}_{12} + \frac{1}{2} \text{AR}_{21} \]
Result 3:

- For a fixed $\text{SIR}$ at Rx antenna, increasing the transmit power increases the total achievable rate.

Reasons for Result 3 ...
**Achievable Sum Rate Analysis**

Without active cancellation

\[ y = h_S x' + h_I x + z \]

With active cancellation

\[ y = h_S x' + (h_I - \hat{h}_I) x + z \]

With active cancellation rewrite as

\[ y = h_S x' + h_R \sqrt{\frac{\Omega}{\alpha}} x + z \quad \rightarrow \quad \text{SINR} = \frac{1}{\frac{1}{\alpha \text{SIR}} + \frac{1}{\text{SNR}}} \]

- \( h_R \) : normalized residual channel
- \( \Omega \) : due to antenna separation
- \( \alpha \) : due to active cancellation

Achievable Sum Rate Analysis

- Achievable sum rate

\[ \text{ASR} = \log (1 + \text{SINR}_1) + \log (1 + \text{SINR}_2) \]

\[ \text{SINR}_i = \frac{1}{\alpha_i \text{SIR}_i + \frac{1}{\text{SNR}_i}} \]
Achievable Sum Rate Analysis

- Achievable sum rate

\[
\text{ASR} = \log (1 + \text{SINR}_1) + \log (1 + \text{SINR}_2)
\]

\[
\text{SINR}_i = \frac{1}{\alpha_i \text{SIR}_i + \frac{1}{\text{SNR}_i}}
\]

- Result 3:
  - For a fixed SIR at Rx antenna, increasing the transmit power increases the total achievable rate.

- Reasons for Result 3:
  - If \( P_{TX} \) at both nodes increases by same amount then
    - SIR doesn’t change
    - \( \alpha \) increases (from Result 1)
    - SNR increases

\[\rightarrow \text{SINR increases} \rightarrow \text{Achievable rate increases}\]
Achievable Sum Rate Analysis

• Result 3 demonstrated in experiments and simulation

- FD-AC: Full-duplex with antenna separation and Analog Cancellation
- FD-ACDC: Full-duplex with antenna separation and combined Analog and Digital Cancellation
Achievable Sum Rate Analysis

• Result 3 demonstrated in experiments and simulation

\[ y = h_S x' + h_R \sqrt{\frac{\Omega}{\alpha}} x + z \]

\[ \text{SNR} = \infty \quad \text{SIR} = \text{Measured in experiments} \quad \alpha = \text{Linear fit} \]

• Simulation results obtained using model

• FD-AC: Full-duplex with antenna separation and Analog Cancellation

• FD-ACDC: Full-duplex with antenna separation and combined Analog and Digital Cancellation

• Linear fit model seems reasonably accurate
Achievable Sum Rate Analysis

• Result 4:
  • Best performance is achieved when applying digital cancellation selectively based on measured suppression values

• Reasons for Result 4:
  • For each frame decide if digital cancellation after analog cancellation should be applied or not as follows
    • Use training at the beginning of the frame to estimate $\alpha_{AC}[f]$ and $\alpha_{ACDC}[f]$
    • Apply digital cancellation after analog cancellation during frame $f$ only if
      $$\alpha_{ACDC}[f] - \alpha_{AC}[f] > 0$$
Achievable Sum Rate Analysis

• Result 4:
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• Reasons for Result 4:
  - Follows from Result 2:
    (a) Concatenation of cancellation mechanisms does not result in a sum of their individual cancellations
    (b) As the performance of analog cancellation gets better, the effectiveness of digital cancellation after analog cancellation reduces (observed on average and per frame)

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    $$\alpha_{ACDC}[f] - \alpha_{AC}[f] > 0$$
Achievable Sum Rate Analysis

- **Result 4:**
  - Best performance is achieved when applying digital cancellation selectively based on measured suppression values

- **Experiment results**

  - **FD-AC:** Full-duplex with antenna separation and Analog Cancellation
  - **FD-ACDC:** Full-duplex with antenna separation and combined Analog and Digital Cancellation
  - **FD-ACSDC:** Full-duplex with antenna separation and combined Analog and Selective Digital Cancellation
Achievable Sum Rate Analysis

• Result 4:
  • Best performance is achieved when applying digital cancellation selectively based on measured suppression values

• Experiment results

![Graph showing achievable sum rate vs. P_{Tx} (dBm) for FD-AC, FD-ACDC, and FD-ACSDC]

• FD-AC: Full-duplex with antenna separation and Analog Cancellation
• FD-ACDC: Full-duplex with antenna separation and combined Analog and Digital Cancellation
• FD-ACSDC: Full-duplex with antenna separation and combined Analog and Selective Digital Cancellation

• Benefits of selective digital cancellation
  • Uses digital cancellation as a safety net in frames where analog cancellation delivers poor performance
  • Avoids adding noise to the system when analog cancellation delivers good performance
  • Results in largest average achievable sum rate
Achievable Sum Rate Analysis

- **Result 4:**
  - Best performance is achieved when applying digital cancellation selectively based on measured suppression values.

- **Experiment results**

  ![Graph showing achievable sum rate vs. P Tx (dBm)]

  - **FD-AC:** Full-duplex with antenna separation and Analog Cancellation
  - **FD-ACDC:** Full-duplex with antenna separation and combined Analog and Digital Cancellation
  - **FD-ACDC:** Full-duplex with antenna separation and combined Analog and Selective Digital Cancellation

- **Benefits of selective digital cancellation**
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Achievable Sum Rate Analysis

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• Experiment results

  ![Graph showing achievable sum rate vs. TX power (dBm)]

  • FD-AC: Full-duplex with antenna separation and Analog Cancellation
  • FD-ACDC: Full-duplex with antenna separation and combined Analog and Digital Cancellation
  • FD-ACDC: Full-duplex with antenna separation and combined Analog and Selective Digital Cancellation

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Full-Duplex vs. Half-Duplex

Compare half-duplex and full-duplex systems that use same resources

<table>
<thead>
<tr>
<th></th>
<th>Full-duplex with analog cancellation</th>
<th>Half-duplex 2x1 Alamouti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antennas per node</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Tx RF radios per node</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Rx RF radios per node</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Tx power per antenna</td>
<td>$P_{TX}$</td>
<td>$P_{TX}$</td>
</tr>
</tbody>
</table>

Node 1

$\begin{align*}
  x & \quad \text{DAC} & \quad \text{Tx RF} \\
  c & \quad \text{DAC} & \quad \text{Tx RF} \\
  y & \quad \text{ADC} & \quad \text{Rx RF}
\end{align*}$

Node 2

$\begin{align*}
  x' & \quad \text{Tx RF} & \quad \text{DAC} \\
  c' & \quad \text{Tx RF} & \quad \text{DAC} \\
  y' & \quad \text{Rx RF} & \quad \text{ADC}
\end{align*}$
Full-Duplex vs. Half-Duplex

- $d = 10$ cm
- $d = 20$ cm
- $d = 40$ cm

![Graph showing achievable sum rate vs. $P_{TX}$ (dBm) for full-duplex and half-duplex experiments and simulations.]
Full-Duplex vs. Half-Duplex

- $d = 10$ cm
- $d = 20$ cm
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- Full-duplex can achieve higher rates than half-duplex
- The linear fit model is reasonable accurate
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- The linear fit model is reasonably accurate
- Close antennas imply in some scenarios half-duplex wins-out
**Full-Duplex vs. Half-Duplex**

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- $d = 20$ cm
- $d = 40$ cm

- Full-duplex can achieve higher rates than half-duplex
- The linear fit model is reasonable accurate
- Close antennas imply in some scenarios half-duplex win-out

- Full-duplex without analog cancellation and only digital cancellation always performs worse than half-duplex due to quantization noise
Conclusions

• Full-duplex can achieve higher rates than half-duplex.

• Amount of active cancellation increases as the received self-interference power increases.

• At a constant SIR@Rx antenna more interference is actually good. It allows better cancellation and thus improved rates.

• Digital cancellation is more effective when applied selectively after analog cancellation.
Conclusions

- Full-duplex can achieve higher rates than half-duplex.
- Amount of active cancellation increases as the received self-interference power increases.
- At a constant SIR@Rx antenna more interference is actually good. It allows better cancellation and thus improved rates.
- Digital cancellation is more effective when applied selectively after analog cancellation.

Recent and ongoing work at Rice

- Asynchronous full-duplex.
  - Receive-while-sending.
  - (not send-while-receiving)
- Antenna design and MAC protocols.
- MIMO and OFDM analysis.