In-band Full Duplex Radios and System Performance

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</table>
Outline

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  ● Demerit
  ● Classification of self-interference cancellation (SIC) Technology
  ● State of the art in SIC

❖ System Performance
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    ➢ TDD vs. Pairwise IFD
  ● Residential scenario
    ➢ System-level simulation environment
    ➢ Evaluation result
  ● Outdoor large BSS scenario
    ➢ System-level simulation environment
    ➢ Evaluation result

❖ Summary
Feasibility of In-band Full Duplex (IFD)
What are current wireless radios?

- **Frequency Division Duplexing (FDD)**
  - In other words, Out-band Full Duplex (OFD)

- **Time Division Duplexing (TDD)**
  - In other words, In-band Half Duplex (IHD)

**Problem**
- There is no full resource utilization.
  - FDD wastes frequency resource, i.e. Frequency 2.
  - TDD wastes time resource, i.e. Timeslot 2.

**What is one of solutions to resolve the problem?**
- That is “In-band Full Duplex (IFD)”. 
Concept of IFD

- IFD radio can simultaneously transmit and receive on the same frequency channel.

- IFD does not waste frequency and time resources, i.e. Frequency 2 and Timeslot 2.
Merit: Spectral Efficiency

- Basic operating scenario of bi-directional IFD communications with single antenna

![Simultaneous Transmission Diagram]

- Theoretical Ergodic capacities of ideal IFD and OFD/IHD
  - \( C_{IFD} = 1 \times C_{ab}^{(1\times1)} + 1 \times C_{ba}^{(1\times1)} \)
  - \( C_{OFD/IHD} = \frac{1}{2} \times C_{ab}^{(1\times1)} + \frac{1}{2} \times C_{ba}^{(1\times1)} \), where \( C_{xy}^{(1\times1)} = \log_2 \left( 1 + SNR_{xy}^{(1\times1)} \right) \)
  - The link capacity of IFD is double than that of OFD/IHD.
Demerit: Self-Interference

Basic transceiver structure

- Self-interference (i.e. self transmitted signal) is generated as below.

- Very strong self-interference signal [1]
  - ~110dB stronger than desired received signal strength for IEEE 802.11 Wi-Fi and LTE-A Small Cell
Demerit: Co-Channel Interference

- **Operating scenario of IFD capable AP supporting IHD capable user nodes** [2],[3]
  - It can be a priority for AP only to have IFD capability in terms of power supplying and backward compatibility.
  - Co-channel interference (CCI) occurs.
  - Requires further information (e.g. CCI) to setup the secondary link.

![Diagram showing co-channel interference](image)
Classification of SIC Technology

- **Physical SIC** in antenna domain
- **Analog SIC** in circuit domain
- **Digital SIC** in baseband domain
Inefficiency of propagation SIC (PSIC)

- Mainly using physical isolation between Tx and Rx antennas \(^{[4]}\)
  - Any propagation SIC technologies are not recommended because
    - the merit of IFD in terms of spectral efficiency over OFD/IHD disappears
    - The form-factor size of IFD transceiver becomes larger.
  - Thus, single antenna is recommended to realize the merit of spectral efficiency
    - That is to say, no propagation SIC gain in antenna domain

Importance of analog SIC (ASIC)

- Protecting analog-to-digital converter (ADC) saturation
- Analog SIC technology is the crux of IFD commercialization.

Non-linear component in digital SIC (DSIC)

- Dependent on surrounding environment of IFD transceiver, non-linear component self-interference signal cannot be sufficiently cancelled in analog domain. In this case, there is no successful decoding without this component cancellation.
State of the art in SIC \[2\]

-\[Slide 11\]

**Stanford**
- 60 dB [2010]
- 73 dB [2011]

**Stanford**
- Rice
- \(~80\ dB\)
- \( \sim 110 \text{ dB! Cancellation} \)
# State-of-the-art SIC Performance Comparison

<table>
<thead>
<tr>
<th>Institute</th>
<th>Year (Standard)</th>
<th>Freq. (GHz)</th>
<th>BW (MHz)</th>
<th>PSIC</th>
<th>ASIC</th>
<th>DSIC</th>
<th>Total SIC</th>
</tr>
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<tbody>
<tr>
<td>NEC (Japan)</td>
<td>2011</td>
<td>5</td>
<td>10</td>
<td>55dB</td>
<td>none</td>
<td>20dB</td>
<td>75dB</td>
</tr>
<tr>
<td>Rice University (US)</td>
<td>2011</td>
<td>2.4</td>
<td>10</td>
<td>57dB</td>
<td>24dB</td>
<td>none</td>
<td>81dB</td>
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<tr>
<td></td>
<td>2012</td>
<td>2.4</td>
<td>20</td>
<td>65dB</td>
<td>20dB</td>
<td>85dB</td>
<td></td>
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<tr>
<td></td>
<td>2012</td>
<td>2.4</td>
<td>20</td>
<td>71dB</td>
<td>24dB</td>
<td>95dB</td>
<td></td>
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<tr>
<td>Stanford University</td>
<td>2010</td>
<td>2.48</td>
<td>5</td>
<td>30dB</td>
<td>25dB</td>
<td>15dB</td>
<td>70dB</td>
</tr>
<tr>
<td>Kumu networks [1] (US)</td>
<td>2011</td>
<td>2.4</td>
<td>10</td>
<td>45dB</td>
<td>28dB</td>
<td>73dB</td>
<td></td>
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<tr>
<td></td>
<td>2013</td>
<td>2.4</td>
<td>80</td>
<td>none</td>
<td>60dB</td>
<td>50dB</td>
<td>110dB</td>
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<tr>
<td>DUPLO [6]</td>
<td>2014</td>
<td>2.45</td>
<td>6</td>
<td>none</td>
<td></td>
<td>50dB</td>
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<tr>
<td>RF Window (Korea)</td>
<td>LTE WCDMA</td>
<td>2</td>
<td>20</td>
<td>60dB</td>
<td>none</td>
<td>10dB</td>
<td>70dB</td>
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<tr>
<td>WITHUS (Korea)</td>
<td>LTE WCDMA</td>
<td>2</td>
<td>10</td>
<td>35dB</td>
<td>none</td>
<td>35dB</td>
<td>70dB</td>
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<tr>
<td>AirPoint (Korea)</td>
<td>LTE TDD</td>
<td>2.2</td>
<td>55dB</td>
<td>none</td>
<td>35dB</td>
<td>90dB</td>
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<tr>
<td>SOLiD (Korea)</td>
<td>2</td>
<td>65dB</td>
<td>none</td>
<td>35dB</td>
<td>100dB</td>
<td></td>
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</table>
ETRI View and Result on SIC

- **Propagation SIC**
  - No need to achieve double spectral efficiency, that is, single shared antenna

- **Analog SIC**
  - Supporting wide bandwidth e.g. 100MHz
  - Achieving at least stable 80dB SIC to reduce quantization error in digital domain
    - RF analog FIR filter is needed

- **Digital SIC**
  - Designing residual nonlinear component SIC as well as linear-component SIC for successful decoding

- **Result based on S/W simulator**
  - Condition (refer to the right figure)
    - Single antenna, Circulator/Antenna channel modelling, Low Pass Filter modelling, nonlinear amplifier modelling
    - No consideration in other hardware impairments
  - We see more than 110dB SIC with our SIC technologies.
System Performance and Summary
Introduction

 IFD with single antenna is coming
  ● Feasibility of IFD communication now proved \[1\]
  ● *Dream of simultaneous transmission and reception (STR) coming true!!*

 When IFD is employed in wireless communication networks,
  ● Up to *2x* spectral efficiency
  ● Advanced MAC protocols to resolve various problems in half duplex (HD) counterparts
  ● Self-Interference
  ● Increased co-channel interference (CCI) by STR

 Performance IFD-based wireless communication networks by system level simulation (SLS)
Duplex Mode – TDD vs. 3 Node IFD

TDD

3 Node Form IFD (3n-IFD) [2][3]

**DL case 1**

**UL case 1**
Duplex Mode – TDD vs. Pairwise IFD

**TDD**

**Pairwise IFD (P-IFD)** [2][3]
Residential Scenario

- **SLS Environment** [5]
  - Residential building layout
    - 5 floors, 3m height / floor
    - 2×10 apartments / floor
    - Apartment size: 10m×10m×3m
  - Parameter
    - 100 APs in the building (1 AP / room)
    - 2 STAs / room
    - Carrier frequency: 2.4GHz
    - Bandwidth: 20MHz
    - Noise Figure: 7dB
    - TDD mode
      - AP: 2 Tx and 2 Rx antennas
      - STA: 1 Tx and 1 Rx antennas
    - IFD mode
      - AP: 2 shared antennas
      - STA: 1 shared antenna
Residential Scenario

❖ SLS Environment (Contd.)

- General P-IFD case
  - AP: random deployment in room (uniform)
  - STA: random deployment in room (uniform)

- Space-Scheduled (SSC) P-IFD & 3n-IFD
  - AP: random deployment in room (uniform)
  - STA
    - Random deployment (uniform)
      - minimum distance between STAs is 2m
      - minimum distance between AP and STA is x m
Residential Scenario

- Evaluation Result (1)
  - Effect of CCI

Signal power 20dBm
-42dB
300dB SIC = CCI only

Noise level -90dBm

- It means in this CCI level, the achievable throughput with 80-dB SIC case is close to that with perfect SIC case.
Residential Scenario

Evaluation Result (2)

- Throughput

Max. throughput of IFD \approx 2 \times \text{max. throughput of TDD.}

- SSC is effective to enhance throughput of IFD.
Residential Scenario

- Evaluation Result (3)

  - Areal Throughput

  - *50% enhancement* of areal throughput by 3n-IFD with sufficient SIC
  - *300% enhancement* of areal throughput by P-IFD with sufficient SIC
  - Minimum SIC requirement for P-IFD: 50dB for STA, 70dB for AP
  - Noticeable areal throughput enhancement by SSC
Outdoor Large BSS Scenario

- **SLS Environment** [5]
  - BSSs’ layout
    - 19 hexagonal grids of cells
    - Inter cell distance (ICD) = 130m
  - Location
    - 1 AP at the center of each cell
    - 2 randomly distributed STAs / cell
    - Heights: $h_{AP}=10m$, $h_{STA}=1.5m$
  - Parameter
    - Carrier Frequency : 2.4GHz
    - Bandwidth : 20MHz
    - Noise Figure : 7dB
    - TDD mode
      - AP: 2 Tx and 2 Rx antennas
      - STA: 1 Tx and 1 Rx antennas
    - IFD mode
      - AP: 2 shared antennas
      - STA: 1 shared antenna
Outdoor Large BSS Scenario

- **SLS Environment (Contd.)**
  - **General P-IFD**
    - Random deployment (uniform)
    - Minimum distance b/w AP & STA : 10m
    - Minimum distance b/w STAs : 10m
  - **SSC P-IFD**
    - Random deployment (uniform)
    - Distance b/w AP & STA: 10 m ~ y m
    - Minimum distance b/w STAs : 10m
  - **SSC 3n-IFD**
    - Random deployment (uniform)
    - Odd STA : random deployment within boundary
    - Even STA : reflection of odd STA
    - Distance b/w AP & STA: 10 m ~ y m
Outdoor Large BSS Scenario

Evaluation Result (1)

- Throughput

- Max. throughput of IFD $\approx 2 \times$ max. throughput of TDD.
- SSC is effective to enhance throughput of IFD in low SINR regime
- Even with SSC, SIC more than 80dB required
Outdoor Large BSS Scenario

Evaluation Result (2)

- Areal throughput

- **100%** areal throughput enhancement by 3n-IFD with sufficient SIC
- **300%** areal throughput enhancement by P-IFD with sufficient SIC
- Minimum SIC requirement for P-IFD: 80dB for STA, 100dB for AP
- Noticeable areal throughput enhancement by SSC
Summary

- Simultaneous transmission and reception is coming.

- When deployed in Wi-Fi networks, the system throughput with 80dB SIC case approached that with perfect SIC case (indoors).

- When STA density is low, extra SIC performance can further enhance the system throughput (outdoors).

- System level simulations show that with sufficient SIC performance, IFD leads to severalfold throughput enhancements compared to conventional half duplex counterpart.

- (Spatial) scheduling plays a key role to enhance performance of IFD-based Wi-Fi networks.
References

1. IEEE 802.11-13/1421r1, “STR radios and STR media access.”
2. IEEE 802.11-13/1122r1, “Considerations for In-Band Simultaneous Transmit and Receive (STR) Feature in Hew”
3. IEEE 802.11-14/0838r0, “Discussion on Dual-Link STR in IEEE 802.11 ax”
5. IEEE 802.11-14/0980r4, “TGax Simulation Scenarios.”
Appendix
Using IEEE 802.11n

- Spatial streams = 1
- Bandwidth = 20MHz
- Residential Scenario 400ns GI
- Outdoor Large BSS Scenario 800ns GI

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### MCS table

<table>
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<th>MCS index</th>
<th>Modulation type</th>
<th>Coding rate</th>
<th>Data rate (Mbits/s)</th>
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<td>0</td>
<td>BPSK</td>
<td>1/2</td>
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<td>3/4</td>
<td>39, 43.3</td>
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<td>64-QAM</td>
<td>2/3</td>
<td>52, 57.8</td>
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<td>64-QAM</td>
<td>3/4</td>
<td>58.5, 65</td>
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<td>7</td>
<td>64-QAM</td>
<td>5/6</td>
<td>65, 72.2</td>
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Residential Scenario

- Other Simulation Results (2)
  - SINR
    - DL
      - with 120 dB SIC, the SINR of pairwise IFD ≈ TDD
      - 5 dB gain with SSC
    - UL
      - Increase of CCI between APs,
      - Both IFD schemes show inferior performance to TDD even with 120 dB SIC
Residential Scenario

- Other Simulation Results (3)
  - Spectral Efficiency
Outdoor Large BSS Scenario

- Other Simulation Results (1) (SSC, 1.SINR, 2. Thr, 3.SE)
Outdoor Large BSS Scenario

- Other Simulation Results (2)
  - SINR
Outdoor Large BSS Scenario

❖ Other Simulation Results (2)
  ● Spectral Efficiency