Various Applications of Full Duplex Techniques in Wireless Communication Networks

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• Two Streams of Research on Full-Duplex

Hardware Implementation
– Self-interference cancellation
– Antenna structure
– Hardware demos

Communication Performance
– Theoretic approach
– Ideal hardware
– Perfect SIC or Simple SI Model
– Resource use in FD communication

– Various applications
– More practical SI & hardware model
– Advance protocol, new use of FD
Introduction (2)

- Simultaneous DL & UL support
- Advanced MAC protocol
- Advanced ARQ

Improved PHY layer security

Advanced-spectrum sensing
Cognitive FDR

Full-duplex multi-hop/two-way transmission

Cognitive radio network

Wireless powered network
Energy / information full-duplex

Ad-hoc network
Application of Full Duplex Technique 1

Full Duplex Communication in Cellular Networks
Simultaneous DL and UL Support by FD BS

- HD BS: orthogonal DL & UL
- FD BS: simultaneous DL & UL

Self interference

Cochannel interference

Transmission in slot 1

Effective Use of Resource

Increased Interference

Interference Management
- Scheduling
- Precoding [Nguyen2013]
**System Model**

**Assumptions**
- Single-cell FD MU-MIMO
- No CCI, no scheduling considered
- SI considered to be background noise
- BD-ZF precoder & MMSE-SIC receiver at BS

**Received Signals**

**DL:**
\[ y_{D_i} = H_{D_i} W_{D_i} s_{D_i} + \sum_{k \neq i, k=1}^{K_D} H_{D_k} W_{D_k} s_{D_k} + n_{D_i} \]

**UL:**
\[ y_U = \sum_{i=1}^{K_U} H_{U_i} s_{U_i} + \sum_{k=1}^{K_D} G_S W_{D_k} s_{D_k} + n_U \]

**Joint design of inputs for DL & UL**

**Design Objectives**
- **Spectral efficiency (SE):** network sum rate for both DL & UL
- **Energy efficiency (EE):**
  \[ \frac{\text{Total NW sum-rate}}{\text{NW total energy consumption}} \]
Spectral Efficiency Maximization

Achievable Rates

\[
R_D = \sum_{i=1}^{K_D} \log \left| \frac{N_0 I + \sum_{j=1}^{K_D} H_{D_i} W_{D_j} W_{D_j}^H H_{D_i}^H}{N_0 I + \sum_{j=1, j \neq i}^{K_D} H_{D_i} W_{D_j} W_{D_j}^H H_{D_i}^H} \right|
\]

\[
\approx \sum_{i=1}^{K_D} \log |I + H_{D_i} Q_{D_i} H_{D_i}^H|
\]

\[
R_U = \log \left| \frac{N_0 I + \sum_{k=1}^{K_D} G_{S_k} Q_{D_k} G_{S_k}^H + \sum_{i=1}^{K_U} H_{U_i} Q_{U_i} H_{U_i}^H}{N_0 I + \sum_{k=1}^{K_D} G_{S_k} Q_{D_k} G_{S_k}^H} \right|
\]

- \( W_{D_i} \in \mathbb{C}^{N_T \times N_{D_i}} \): linear precoder
- BD-ZF: \( H_{D_i} W_{D_j} = 0 \)
  - No MUI

MMSE-SIC receiver at BS

Efficient use of time + Spatial multiplexing gain

Loss of spatial degrees-of-freedom

Spectral Efficiency Maximization

maximize \( R_D + R_U \)

\( Q_{D_i}, Q_{U_j} \geq 0 \)

subject to \( \sum_{i=1}^{K_D} \text{Tr}(Q_{D_i}) \leq P_D, \)

\( \text{Tr}(Q_{U_j}) \leq q_{U_j}, \forall j = 1, \ldots, K_U. \)

\( \text{rank}(Q_{D_i}) \leq N_{D_i}. \)
Energy Efficiency Maximization

- **Linear Power Model** [Arnold2010], [Xu2011]

**Power Consumption in DL**

\[ P_D^{Total} = \frac{1}{\epsilon} P_D^{Tx} + P_D^{cir}, \quad P_D^{Tx} = \sum_{i=1}^{K_D} \text{Tr}(Q_{D_i}) \]

**Power Consumption in UL**

\[ q_U^{Total} = \frac{1}{\epsilon} q_U^{Tx} + q_U^{cir}, \quad q_U^{Tx} = \text{Tr}(Q_{U_j}) \]

**Energy Efficiency – FD BS**

\[ \eta_{FD}^{sum} = \frac{R_D + R_U}{\frac{1}{\epsilon} \sum_{i=1}^{K_D} \text{Tr}(Q_{D_i}) + \frac{1}{\epsilon} \sum_{j=1}^{K_U} \text{Tr}(Q_{U_j}) + P_{cir}^{sum}} \]

**Energy Efficiency – HD BS**

\[ \eta_{HD}^{sum} = \frac{R_D + R_U}{\frac{1}{2} \left( \frac{1}{\epsilon} \sum_{i=1}^{K_D} \text{Tr}(Q_{D_i}) + \frac{1}{\epsilon} \sum_{j=1}^{K_U} \text{Tr}(Q_{U_j}) + P_{cir}^{sum} \right)} \]

Energy Efficiency with **FD BS** < Energy Efficiency with **HD BS**
due to sub-linear increase of data rate by FD
**Simulation Results (1) – Spectral Efficiency**

- **Maximum Tx Power at BS**
  - Exploits spatial multiplexing gain
  - Max. 25% gain with small SI in case of SM
  - SIC performance is a performance limiting factor

- **Effect of Self-Interference**
Simulation Results (2) – Energy Efficiency

- **Maximum Tx Power at BS**

  - Similar EE in the low Tx power regime, but EE of SE-optimal design decreases as max. Tx power increases.

- **Effect of Self-Interference**

  - EE of HD > EE of FD
  - Simultaneous DL & DL support decreases EE
Application of Full Duplex Technique 2

MAC Layer Protocol with Full Duplex
Full Duplex Applied to MAC Protocol

**HD MAC**

- Simultaneous Tx & Rx Prohibited
- Less Spatial Reuse
- Hidden & Exposed Node Problems

**FD MAC**

- Simultaneous Tx & Rx allowed
- More Spatial Reuse
- Resolved Hidden Node Problems
- More Chance for Advanced Scheduling

**Less Spectral Efficient**

**More Spectral Efficient**

Full Duplex at (each) Node
MAC Protocol Based on FD (1)

- **Dual-Link by FD Transmission** [Singh2011]

  **Symmetric Dual-Link**

  - A starts packet transmission
  - B decodes A’s header, and transmits packet or ‘busy’ tone while receiving
  - A does not detect any transmission from B,

  → transmission to B is not successful

  **Asymmetric Dual-Link**
MAC Protocol Based on FD (2)

- **Primary Sender**
  - Initiate (dual) link
  - Transmit packet to primary receiver
- **Primary Receiver = Secondary Sender**
  - Receive packet from primary sender while transmit packet to secondary receiver
  - Only the primary receiver is allowed to initiate secondary transmission
- **Secondary Receiver**
  - Receive packet from secondary sender
Signal Transmission in Dual Link [Singh2011]

A transmits ‘busy’ tone until the end of B’s transmission to prevent neighborhood interferer.

Beginning transmission = successful decoding

B transmits packets to C while receiving packets from A.
Pros. & Cons.

• **Pros: Hidden Node Problem Resolution**

  - Rx B sends a signal while receiving
    - Prevents neighborhood nodes starting transmission
    - Perfect RTS/CTS with no Overhead

• **Cons**

  - Secondary link may not be well protected as primary link
  - Overly restrictive
    - advanced scheduling required
Simulation Results (1/2)

- Probability of Successful Transmission

- Increased packet loss probability in each individual link
- Improved combined throughput
Simulation Result (2/2)

• Throughput of One Example Network Topology

- Full-duplex nature: throughput improvement up to 30-50%
- Why not 100% improvement?
  - Increased packet loss probability
  - Full exploitation of FD may not be possible depending on traffic pattern
Application of Full Duplex Technique 3

Improved ARQ Based on Full-Duplex
Limit of FD: High Node Density Networks

Capacity Gain by Full-duplex Tx vs. Pair Interference by Simultaneous Tx

Challenges

In High Node Density ➔ Full-duplex < Half-duplex

Method: ARQ Protocol

BFD in Two-way Ad-hoc Networks with Retransmissions

Network Performance (Transmission Capacity)

Effect of ARQ Protocol

P2P Environment with High Node Density

BFD is More Efficient Way of Two-way Communication
Background – Transmission Capacity

• Transmission Capacity in Ad-Hoc Networks [Weber2005]

Channel Capacity

- Amount of **reliable transmitted information** over a channel

- Definition

\[ C = \log_2 \left( 1 + \frac{S}{N} \right) \text{ [bits/s/Hz]} \]

\[ C_0 = \log_2 (1 + \bar{\eta}), \varepsilon = P(\eta < \bar{\eta}) : \text{ outage probability} \]

Transmission Capacity

- Maximum number of successful transmission per unit area

\[ TC = \lambda (1-\varepsilon)C_0 \text{ [bits/s/Hz/m}^2] \]

Max. spatial density guaranteeing \( \varepsilon \)
Bi-Directional ARQ Protocol (1)

- Improving Reliability of BFD System (Single Feedback CH) [Kim2014]

**Conventional ARQ Protocol**

- Retransmit protocol: only error data packet is retransmitted
- Bi-directional ACK/NACK: reduced waiting time with full-duplex

**Proposed Bi-directional ARQ (Bi-ARQ) Protocol**
Bi-Directional ARQ Protocol (2)

• Aggregated Interference in BDF System with Retransmission

Performance Metric

Conventional Two-way TC
\[ TC = P\lambda(1 - P_{out}) \left[ C_{ab} + C_{ba} \right] \]

Modified Two-way TC with Bi-ARQ [Definition 3.1]
\[ TC = \frac{P\lambda}{1 + \bar{N}_{rt}} (1 - \varepsilon) \left[ C'_{ab} + C'_{ba} \right] \]

Loose: ① Normalization factor, ③ SIR degradation $\kappa_{eff} = (1 + \bar{N}_{rt})\lambda$

Gain: ② Decreased outage probability $\varepsilon = (P_{out})^{N_{rt}+1}$

$N_{rt}$: Maximum number of packet retransmissions
$\bar{N}_{rt}$: Average number of packet retransmissions
$P$: length of transmitted packet

*Assumption 1: echo-channel interference is perfectly eliminated
BFD vs. BHD Systems

- Two-Way TC of BFD System with Bi-AQR Protocol [Kim2014]

BFD: \[ T_{C}^{(F)} = \frac{P\lambda}{1+N_{rt}^{(F)}}(1-\varepsilon^{(F)}) \left[ \log_{2}(1+\bar{\eta}_{ab}^{(F)}) + \log_{2}(1+\bar{\eta}_{ba}^{(F)}) \right] \times 2 \text{ times} \]

BHD: \[ T_{C}^{(H)} = \frac{P\lambda}{1+N_{rt}^{(H)}}(1-\varepsilon^{(H)}) \left[ \log_{2}(1+\bar{\eta}_{ab}^{(H)}) + (1-\omega)\log_{2}(1+\bar{\eta}_{ba}^{(H)}) \right], 0 < \omega < 1 \]

Example (Given SIR threshold)

<table>
<thead>
<tr>
<th>( N_{rt} )</th>
<th>0</th>
<th>1</th>
<th>...</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( (P_{out}^{(F)})^{N_{rt}+1} )</td>
<td>( P_{out}^{(F)} = 0.1 )</td>
<td>0.01</td>
<td>...</td>
<td>0.00001</td>
</tr>
<tr>
<td>BFD</td>
<td>( 1 - \varepsilon )</td>
<td>0.9</td>
<td>0.09</td>
<td>0.99</td>
</tr>
<tr>
<td>( (P_{out}^{(H)})^{N_{rt}+1} )</td>
<td>( P_{out}^{(H)} = 0.05 )</td>
<td>0.0025</td>
<td>...</td>
<td>0.000003125</td>
</tr>
<tr>
<td>BHD</td>
<td>( 1 - \varepsilon )</td>
<td>0.95</td>
<td>0.0475</td>
<td>0.9975</td>
</tr>
</tbody>
</table>

\( \varepsilon = (P_{out})^{N_{RT}+1} \), \( P_{out} = \Pr(\eta < \bar{\eta}) \)
Simulation Results (1)

- Two-Way TCs of BFD & BHD vs. $N_{rt}$ (High Node Density)

1. **BFD < BHD**
   - For high node density
   - Severe pair interference

2. **BFD > BHD**
   - Optimal # of retransmissions
   - BFD > BHD
   - Benefit from outage prob.

$\Rightarrow$ BFD is More Efficient Way of Two-way Communication
Simulation Results (2)

- Two-Way TCs of BFD & BHD vs. $\lambda$ (Strict Outage Constraint)

1. BFD $<$ BHD
   - For strict outage constraint
   - High outage prob. of BFD

2. BFD $>$ BHD
   - Optimal # of retransmissions
   - BFD $>$ BHD
   - Benefit from outage prob.
   - Increased optimal node density

Low TC due to small nodes density
Low TC due to Severe interference
Application of Full Duplex Technique 4

Full Duplex Multi-Hop Networks
Full-Duplex in Multi-Hop Network

- **Typical Route**
  - Source: \( S \)
  - Relay: \( R \)
  - Destination: \( D \)
  - \( d_0 = L_0 / M_0 \)

- **Simultaneous Transmission**
  - FD used for 1-way packet relaying at a relay node
  - FD used for 2-way packet exchange in a hop

- Route throughput: avg. # of packets successfully transmitted for a given slot

- **Symbols**:
  - \( \square \): Source
  - \( \bigcirc \): Relay
  - \( \bigtriangleup \): Destination
  - \( \rightarrow \): Packet transmission within a given time slot

- **Assumptions**:
  - N antennas, rank-1 transmission, 1 hop / route at a time slot
  - Equidistance b/w nodes
  - Neglecting AWGN, perfect SIC
  - **End-to-end delay**: avg. # of slots for a packet from \( S \) to \( D \)
  - **Route throughput**: avg. # of packets successfully transmitted for a given slot
1-Way Packet Relaying (1)

- 1-Way Packet Relaying: FDR vs. HDR (1)

**HDR Mode**

<table>
<thead>
<tr>
<th>Time Slot Index</th>
<th>Transmitting Node(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>slot $t$</td>
<td>Source</td>
</tr>
<tr>
<td>slot $t+1$</td>
<td>Relay 1</td>
</tr>
<tr>
<td>slot $t+2$</td>
<td>Relay 2</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>slot $t+M-1$</td>
<td>Relay M-1</td>
</tr>
<tr>
<td>slot $t+M$</td>
<td>Source</td>
</tr>
<tr>
<td>slot $t+M+1$</td>
<td>Relay 1</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

**FDR Mode**

<table>
<thead>
<tr>
<th>Time Slot Index</th>
<th>Transmitting Node(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>slot $t$</td>
<td>Source</td>
</tr>
<tr>
<td>slot $t+1$</td>
<td>Relay 1</td>
</tr>
<tr>
<td>slot $t+2$</td>
<td>Relay 2</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>slot $t+M-1$</td>
<td>Relay M-2</td>
</tr>
<tr>
<td>slot $t+M$</td>
<td>Relay M-1</td>
</tr>
<tr>
<td>slot $t+M+1$</td>
<td>Source</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Each node transmits every $M$ slots

Each node transmits twice every $(M+1)/2$ slots
## 1-Way Packet Relaying (2)

### 1-Way Packet Relaying (2)

<table>
<thead>
<tr>
<th>FDR Mode</th>
<th>HDR Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Avg. # of Slots to Transmit a Packet</strong></td>
<td>( \frac{M + 1}{2} )</td>
</tr>
<tr>
<td><strong>Interference Measure</strong></td>
<td>( \Omega_f = p_s \pi \Gamma (1 - \delta) \Gamma (2 + \delta) l_0^2 )</td>
</tr>
<tr>
<td><strong>Hop Success Probability</strong></td>
<td>( e^{-\sigma \Omega_f} \left( 1 + \sum_{n=1}^{N-2} \frac{1}{n!} \sum_{k=1}^{n} \frac{\xi_k^n}{k!} (\sigma \Omega_f)^k \right) )</td>
</tr>
<tr>
<td><strong>End-to-End Delay</strong></td>
<td>( \frac{M + 1}{2p_s p_F (R_{th})} - M \left( \frac{M - 1}{2} \right) )</td>
</tr>
<tr>
<td><strong>Route Throughput</strong></td>
<td>( \frac{2}{(M + 1)} p_s p_F (R_{th}) )</td>
</tr>
</tbody>
</table>

### Benefit from Channel Use | Less Interference
1-Way Packet Relaying (3)

- **End-to-End Delay**

  The delay of FDR mode is smaller than that of HDR mode as interferer density is lower or required rate is smaller.

  - **Route Throughput**

    Throughput of FDR mode is larger than that of HDR mode as interferer density is lower or required rate is smaller.

  - **Throughput**

    Full duplex BF has larger throughput.

  - **Delay**

    Full duplex BF has smaller delay.

  - **FDR > HDR**

    - Low rate constraint / rare interferer
    - Channel Use > interference

  - **FDR < HDR**

    - High rate constraint / dense interferer
    - Channel Use > interference
## 2-Way Packet Exchange (1)

### 2-Way Packet Exchange

![Packet Exchange Diagram](image)

#### SIR Threshold to satisfy $R_{th}$

- **BBF Mode**
  \[ 2R_{th} - 1 \]

- **UBF Mode**
  \[ 2^{2R_{th}} - 1 - \left(4^{R_{th}} - 1\right) \]

#### Hop Success Probability

\[
e^{-\sigma_f} \left(1 + \sum_{n=1}^{N-2} \frac{1}{n!} \sum_{k=1}^{n} \frac{|\xi_{n}^{n}|}{k!} (\sigma \Omega_f)^k \right)\]

\[
e^{-\left(2^{R_{th}+1}\right) \sigma \Omega_h} \times \left(1 + \sum_{n=1}^{N-1} \frac{1}{n!} \sum_{k=1}^{n} \frac{|\xi_{n}^{n}|}{k!} \left((2^{R_{th}} + 1) \sigma \Omega_h\right)^k \right)\]

#### End-to-End Delay

- **BBF Mode**
  \[
  \frac{M}{p_s p_B(R_{th})} + M (M-1) \frac{1 - p_r p_B(R_{th})}{(p_r - p_s) p_B(R_{th})} \]

- **UBF Mode**
  \[
  \frac{M}{p_s p_U(R_{th})} + M (M-1) \frac{1 - p_r p_U(R_{th})}{(p_r - p_s) p_U(R_{th})} \]

#### Route Throughput

- **BBF Mode**
  \[
  \frac{p_s}{M} p_B(R_{th}) \]

- **UBF Mode**
  \[
  \frac{p_s}{M} p_U(R_{th}) \]

**Benefit from rate constraint**
2-Way Packet Exchange (2) - Hop Density

- End-to-End Delay vs. Hop Density

- Route Throughput vs. Hop Density

- $R_{th} = 1 : \text{BBF} = \text{UBF}$
  - Packet transmission is always successful

- $R_{th} \uparrow : \text{BBF} > \text{UBF}$
  - $p_B(R_{th}) > p_U(R_{th})$


- **Time Slot Efficiency vs. Intra-Route Interference**

**FDR Mode**

- Concurrent transmission: \(S - R_1\) pair and \(R_4 - R_5\) pair
- Guard hop: \(R_2 - R_3\) hop and \(R_3 - R_4\) hop

**BBF Mode**

- Concurrent transmission: \(S - R_1\) pair and \(R_3 - R_4\) pair
- Guard hop: \(R_1 - R_2\) hop and \(R_2 - R_3\) hop
Full Duplex in Cognitive Radio

- TranSensing for Spectrum Sharing System
- Cognitive FDR
TranSensing – System Model (1)

**MIMO Quiet Sensing**

① : Sensing Phase

SU Tx \(\rightarrow\) SU Rx

② : Transmission Phase

SU Tx \(\rightarrow\) SU Rx

**MIMO TranSensing [Heo2014]**

① : Sensing & Transmission Phase

With Self-IC

PU

SU Tx \(\rightarrow\) SU Rx

Digital IC

Antenna Isolation
TranSensing – System Model (2)

Active SU

Sensing (Mq) → Data Transmission (M-Mq) → Sensing (Mq) → Data Transmission (M-Mq)

$N_s$ Antennas

TranSensing

Sensing Antennas

Sensing (Ms) → Data Transmission (M-Ms) → Sensing (Ms) → Data Transmission (M-Ms)

$N_s$ Antennas

Data Antennas

Data Transmission (M) → Data Transmission (M-Ms)

$N_d$ Antennas

– $N_t$ transmit antenna, $N_s$ sensing antennas, $N_d$ data antennas
– Sensing antennas: Ms sensing period Ms and M - Ms data transmission period
– Data antennas: M frame duration is available for data transmission
**TranSensing – Avg. SU Achievable Rate**

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### Quiet Sensing

\[
T_{M,Q} = \left(1 - \frac{M_q}{M}\right) \left(1 - P_f(N_t, M_q)\right) E \left(\log_2 \det I_{N_r} + \frac{\text{SNR}_s}{N_t} R_t^{1/2} H R H^H R_t^{-1/2}\right) \quad N_r \times N_t \text{ MIMO Capacity}
\]

**Average SU capacity for CR environment by dividing time resources:**

\[N_r \times N_t \text{ MIMO Correlated Channel with } N - N_s \text{ times.}\]

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### MIMO TranSensing

\[
T_{M,T} = \left(1 - P_f(N_s, M_s)\right) E \left(\log_2 \det I_{N_r} + \frac{\text{SNR}_s}{N_d} \bar{R}_t^{1/2} \bar{H} R \bar{H}^H \bar{R}_t^{-1/2}\right) \quad N_r \times N_d \text{ MIMO Capacity}
\]

**Average SU capacity for CR environment by dividing spatial resources:**

\[N_r \times N_d \text{ MIMO Correlated Channel with } N \text{ times.}\]
TranSensing – Proposed Algorithm

Objective: \( \{N_d^*, \Lambda_{N_d^*}^*, M_s^*\} = \arg \max_{N_d, \Lambda_{N_d^*}^*, M_s} T_{s,T} \)

\[
\begin{aligned}
1 \leq N_d^* \leq N_t - 1 \\
1 \leq i^* \leq K = \left( \frac{N_t}{N_d^*} \right) \\
1 \leq M_s^* \leq M
\end{aligned}
\]

Antenna Selection

Sensing Duration Control

Correlation based

Sensing (Ms)

Data Transmission (M-Ms)
TranSensing – Simulation Result

- Avg. SU Capacity vs. PU SNR

- Low PU SNR region (< -2dB)
  : Correlation based antenna partitioning = full search-based antenna partitioning

- High PU SNR region (> -2 dB)
  : Sensing duration control affects the average SU throughput
Cognitive Full-Duplex Relay (1)

- **Cognitive FDR vs. Cognitive HDR**

**Cognitive HDR**
- Orthogonal transmission of SU and SR
- Interference constraint
  
  \[ b_{SP} P_S \leq I_{th}, \quad b_{RP} P_R \leq I_{th} \]

**Cognitive FDR**
- Concurrent transmission of SU and SR
- Residual self-interference at SR
- Interference constraint
  
  \[ b_{SF} P_S + b_{RP} P_R \leq I_{th} \]
Cognitive Full-Duplex Relay (2)

- Outage Probability of Secondary User

![Graph showing outage probability vs. SNR](image)

#### Graph Details:
- **Equation:** \[
\frac{1}{\sigma_{RN}^2} = \frac{1}{\sigma_{DN}^2}
\]

- **Legend:**
  - **CogFRN using EPA (\(\lambda_{RR} = \lambda_{SD} = -30\text{dB}\))**
  - **CogHRN**
  - **OPA (Analysis, \(\lambda_{RR} = \lambda_{SD} = -30\text{dB}\))**
  - **OPA (Simulation, \(\lambda_{RR} = \lambda_{SD} = -30\text{dB}\))**

---

- **Less power consumption** at SS and SR with cognitive FDR
- **Residual self-interference at SR**
- **Reduced Tx Power** (Residual SI)

**Benefit from Concurrent Tx**

**Employing FDR as SR is beneficial in spectrum-sharing system**
Application of Full Duplex Technique

**Full Duplex to Improve PHY Layer Secrecy**
Full Duplex for PHY Layer Secrecy (1)

- PHY Layer Information Protection: 1 Transmit Ant. at Source

- **Half-Duplex Nodes**
  - Cooperative nodes relaying source information & transmitting jamming signal [Dong2010]
  - Decrease in secrecy capacity due to orthogonal time allocation to relays

- **Full-Duplex Receiver**
  - Transmit jamming signal while receiving information
  - No additional helper or time slot

- **Simultaneous Tx and Rx by FD**

  - Intended message in 1st slot
  - Jamming signal in 1st slot
Full Duplex for PHY Layer Secrecy (2)

- **System Model** [Zheng2013]

\[ y_D = h_{sd}s + \sqrt{\rho}H_{si}n + n_d \]
\[ y_E = h_{se}s + H_{ed}n + n_e \]

\[ s : \text{Tx signal of source, } \mathbb{E}[|s|^2] = P_s \]
\[ n : \text{jamming signal by destination, } n \sim \mathcal{CN}(0, Q) \]

- **Destination side**
  - Received signal: \( y_D = h_{sd}s + \sqrt{\rho}H_{si}n + n_d \)
  - Linear receiver: \( r \)

- **Eavesdropper side**
  - Received signal: \( y_E = h_{se}s + H_{ed}n + n_e \)

- **Objective**
  
  Optimize \( Q \) to maximize the secrecy capacity such that
  \[ tr \{ Q \} \leq P_d \]

- **Considerations**
  - **CSI availability** at Tx side of D
    - Global CSI
    - CDI only
  - Linear receiver at D (r) is
    - Fixed receiver
    - Optimally designed w.r.t channel
  - Receiver at eavesdropper is
    - MRC w/o knowing FD of D
    - MMSE knowing FD of D
Secrecy Capacity Maximization (1)

• Secrecy Capacity
  - Max. Tx rate at which eavesdropper cannot decode any information
  - Difference S-D capacity and S-E capacity

• Global CSI & Linear Receiver at D, MRC Receiver at E (1)

Secrecy Capacity

\[ R_S = \max \begin{cases} 0, \log_2 \left( 1 + \frac{P_s |r^\dagger h_{sd}|^2}{1 + \rho r^\dagger HQ H^\dagger r} \right) & \text{(S-D Ch.)} \\ \log_2 \left( 1 + \frac{P_s \|h_{se}\|^2}{1 + \frac{h_{se}^\dagger H_{cd} Q H_{cd}^\dagger h_{se}}{\|h_{se}\|^2}} \right) & \text{(S-E Ch.)} \end{cases} \]

Properties

- Rank \( Q^* \) = 1, trace \( Q^* \) = \( P_d \)
- \( Q = P_d qq^H, \|q\| = 1 \)
- Non-interference limited
- \( R_S \) keeps increasing with \( P_s \)
Secrecy Capacity Maximization (2)

- Global CSI & Linear Receiver at D, MRC Receiver at E (2)

**Fix Receiver at D**
- Independent of $Q$
- MRC, MMSE, ...
- Change variable as $r^\dagger H qq^\dagger H^\dagger r = t$

**Optimal Receiver at D**
- Maximizes Rx SINR
- Given by $r = \frac{(\rho HQH^\dagger + I)^{-1}h_{sd}}{\| (\rho HQH^\dagger + I)^{-1}h_{sd} \|}$
- Change variable as $\frac{|h_{sd}^\dagger H q|^2}{1 + \rho P_d q^\dagger H^\dagger H q} = t$

$R_s(q) \xrightarrow{1-Dimensional Search over t} R_s(t)$

- Objective: functions of $t$
- (Quasi-) concave function of $t$
Secrecy Capacity Maximization (3)

- Global CSI & Optimal Linear Receiver at D, MMSE Receiver at E

- E aware of FD operation of D
- Defense itself from jamming by using MMSE receiver

$$r_e = \frac{(H_{ed}QH_{ed}^\dagger + I)^{-1}h_{se}}{||(H_{ed}QH_{ed}^\dagger + I)^{-1}h_{se}||}$$

Secrecy Capacity

- Assuming optimal linear MMSE receiver at D,

$$R'_s = \max(0, \log_2(1 + P_s h_{sd}^\dagger(\rho QH_{sd}^\dagger + I)^{-1}h_{sd} - \log_2(1 + P_s h_{se}^\dagger(\rho H_{ed}QH_{ed}^\dagger + I)^{-1}h_{se}))$$

Solved by **Difference of Convex Functions** Method
Secrecy Capacity Maximization (4)

- CDI on Channels to E & Linear Receiver at D

**Average Secrecy Capacity**

\[
\max_{Q, p_s, \|r\| = 1} E_{h_{se}, h_{ed}} \left( \log_2 \left( 1 + \frac{p_s |r^\dagger h_{sd}|^2}{1 + \rho r^\dagger HQH^\dagger r} \right) - \log_2 \left( 1 + \frac{p_s \|h_{se}\|^2}{1 + \frac{h_{se}^\dagger h_{ed} Q H_{ed}^\dagger h_{se}}{\|h_{se}\|^2}} \right) \right)
\]

- Channel knowledge at D: perfect \( h_{sd} \), but only CDI on E
- Suboptimal MRC receiver: \( r = \frac{h_{sd}}{\|h_{sd}\|} \)
- \( Q = \frac{p_d WW^\dagger}{M_t - 1} \), where \( r^\dagger H W = 0 \), \( W \in \mathbb{C}^{M_t \times (M_t - 1)} \), \( W^\dagger W = I_{(M_t - 1)} \)
- Approximation: expectation on each individual variables

\[
\log_2 (1 + p_s \|h_{sd}\|^2) - \log_2 \left( 1 + \frac{p_s E_{h_{se}} (\|h_{se}\|^2)}{1 + p_d E_{h_{se}, h_{ed}} \left( \frac{h_{se}^\dagger h_{ed} W W^\dagger H_{ed}^\dagger h_{se}}{(M_t - 1) \|h_{se}\|^2} \right)} \right)
\]

**Convex Function of \( \mathbf{X} \)**
Simulation Results

- Secrecy Rate vs. Total Tx. Power
- Ergodic Secrecy Rate with CDI Only

<table>
<thead>
<tr>
<th>HD Case</th>
<th>FD Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>No external helper</td>
<td>Multi-ant. at Rx help suppress SI and generate jamming</td>
</tr>
<tr>
<td>Secrecy rate saturate from low SNR</td>
<td>Secrecy rate keep increasing w/o bound</td>
</tr>
</tbody>
</table>
Application of Full Duplex Technique 7

Wireless Powered Communication Networks
Full Duplex WPCN (1/2)

- **FD H-AP**: broadcasts energy in DL and receive information in UL simultaneously
- **Pros. & Cons.**

**Pros.**
- Enlarged time for energy harvesting
- More efficient use of time
- Deterministic CW for energy signal
  - *Makes SI cancellation (SIC) easier*

**Cons.**
- SIC is required at the H-AP

---

Ju2014] Self-interference (SI) caused by energy signal

Users operating in HD

Hybrid AP operating in FD

$U_1$ $U_2$ $U_K$

$h_{D,1}$ $h_{U,1}$ $h_{D,2}$ $h_{U,2}$ $h_{D,K}$ $h_{U,K}$

Energy transfer
Information transfer
Full Duplex WPCN (1/2)

- Protocol & DL WET: HD-WPCN vs. FD-WPCN

**HD-WPCN**

![Diagram of HD-WPCN](image)

- Tx. Power of H-AP
  
  \[ P = \min\left(\frac{P_{\text{avg}}}{\tau_0}, P_{\text{peak}}\right) \]

- Harvested Energy by Users
  
  \[ E_{U_i} = \zeta_i|h_{D,i}|^2\tau_0 P \]

**FD-WPCN**

![Diagram of FD-WPCN](image)

- Tx. Power of H-AP
  
  \[ \sum_{i=0}^{K} \tau_i P_i \leq P_{\text{avg}}, P_i \leq P_{\text{peak}}, i = 0, \ldots, K. \]

- Harvested Energy by Users
  
  \[ E_{U_i} = \zeta_i|h_{D,i}|^2 \sum_{j=0}^{K} \tau_j P_j \]
UL WIT

- Transmit Power of $U_i$: $P_{U_i} = \eta_i E_{U_i} / \tau_i$
- Self-Interference Cancellation (SIC) at the H-AP
  - RF and analog domain SIC
  - Digital domain SIC based on channel estimation
  - Additional quantization noise due to finite dynamic range of receive filter of H-AP

Received Signal at the H-AP after SIC

$$\tilde{y}_{A,i} = \sqrt{P_i} h_{U,i} x_{U,i} + \sqrt{\varepsilon \varphi P_i} \tilde{g}_{A} x_{A,i} + z_{Q,i} + z_{A,i}$$

Desired signal | Residual SI Quantization Noise

Achievable Rate of $U_i$

$$R_{i}^{(F)}(\tau, P) = \tau_i \log_2 \left( 1 + \frac{\theta_i H_i}{\Gamma (\gamma P_i + \sigma^2)} \frac{1}{\tau_i} \sum_{j=0}^{K} \tau_j P_j \right)$$

- $\theta_i = \eta_i \zeta_i$: energy efficiency
- $H_i = |h_{D,i}|^2 |h_{U,i}|^2$: product channel gain
- $\gamma = \varphi (\epsilon + \beta)$: SI coefficient
WSR Maximization Problem

**WSR Maximization - General Case**

\[
\max_{\tau, P} \sum_{i=1}^{K} \omega_i R_i^{(F)}(\tau, P)
\]

s.t.
\[
\sum_{i=0}^{K} \tau_i \leq 1, \quad \sum_{i=0}^{K} \tau_i P_i \leq P_{avg},
\]
\[P_i \leq P_{peak}, \quad i = 0, \cdots, K\]
\[\tau_i \geq 0, \quad P_i \geq 0, \quad i = 0, 1, \cdots K.\]

- Non-convex due to non-convexity in objective function & avg. power constraint
- Find a suboptimal solution based on a special case with perfect SIC

**WSR Maximization – Perfect SIC**

\[
\max_{\tau, E} W(\tau, E) \triangleq \sum_{i=1}^{K} \omega_i \tau_i \log_2 \left(1 + \alpha_i \frac{1}{\tau_i} \sum_{j=0}^{K} E_{ij} \right)
\]

s.t.
\[
\sum_{i=0}^{K} \tau_i \leq 1, \quad \sum_{i=0}^{K} E_i \leq P_{avg},
\]
\[E_i - P_{peak} \tau_i \leq 0, \quad i = 0, 1, \cdots K,\]
\[E_i \geq 0, \quad \tau_i \geq 0, \quad i = 0, 1, \cdots K,\]

- Setting \( E_i = \tau_i P_i \) and \( \gamma = 0 \)
- Time & power allocation
- Avg, power constraint (non-convex)
- Sum energy constraint (affine)
- Convex problem
### Optimal Time & Energy Allocation

**Perfect SIC**

\[
(E_0^*, P_0^*) = \begin{cases} 
    P_{\text{peak}} \tau_0^* \\
    E_0^* / P_{\text{peak}}
\end{cases}
\]

\[
(E_i^*, P_i^*) = \begin{cases} 
    \min \left[ \left( P_{\text{avg}} + \frac{\tau_i^*}{\alpha_i} - \frac{\omega_i \tau_i^*}{\mu_i \ln 2} \right)^+, P_{\text{peak}} \tau_i^* \right] & (i \neq 0) \\
    \max \left[ \frac{\alpha_i}{\omega_i} \left( P_{\text{avg}} - E_i^* \right), \frac{E_i^*}{P_{\text{peak}}} \right]
\end{cases}
\]

\[
P_i^* = \frac{E_i^*}{\tau_i^*}, \quad i = 0, 1, \ldots, K
\]

\[\mu^* > 0\] and \(z_i^*\) being the solution of \(f(z_i) = \frac{\lambda \ln 2}{\omega_i} \) where

\[
f(z) \triangleq \ln(1+z) - \frac{z}{1+z}.
\]

**Imperfect SIC**

Initial Point: \((\tau^*, E^*)\)

**Update P**

(e.g. GP method)

**Update \(\tau\)**

(Lagrangian duality)

Until \(WSR^{(k)} \leq WSR^{(k-1)}\)

### Special Case with Infinite PPC

\[
(\tau^*_i, P^*_i) = \begin{cases} 
    (0, \infty) & , \quad i = 0 \\
    \left( \frac{\alpha_i}{\omega_i} P_{\text{avg}}, 0 \right) & , \quad \text{otherwise}
\end{cases}
\]

Equivalent for the cases with perfect & imperfect SIC, and even for HD-WPCN.
A Special Case – Infinite PC

- Power & Time allocation – 10 Users
  - Achievable Rate Region – 2 Users

Optimal time & power allocation optimally exploit the available multi-user channel diversity

Employing FD is more beneficial as peak power constrain is more stringent
Simulation Results

- **Avg. Sum-Rate vs. Avg. Tx. Power**

With sufficient SIC, FD-WPCN outperforms HD-WPCN thanks to more efficient time & power usage.

- **Avg. Sum-Rate vs. Number of Users**

Employing FD is more beneficial as number of users increases thanks multi-user diversity.
Concluding Remarks
Conclusion

More Advanced Protocols to Improve Various Future Wireless Communication Networks

Full-Duplex Technology

- Simultaneous Signal Tx & Rx
- New Way to Use Tx / Rx Signals
- Increased Interference
- Implementation Issues
Thank You

Any Question?

NUS
National University
of Singapore
References


