A Survey on Wireless Full-Duplex: Research and Development Tracks

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Outline

• Full-duplex operation
• Incorporating FD into future systems
• Our cooperation and interface
• Conclusion
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- Incorporating FD into traditional systems
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- Conclusion
Full-Duplex Operation

- Full-duplex: simultaneous transmission and reception using the same channel

**Full-duplex transceiver:**

- Challenge: Strong loopback self-interference must be suppressed
  - Limited dynamic range in Tx and Rx
    - E.x., DAC and ADC accuracy, phase noise, I-Q imbalance,…
  - Inaccurate channel knowledge
    - Results in imperfect interference estimation

Full-duplex communication was known to be infeasible
Motivation

- **What do we gain via full-duplex?** [CHJKLM], [JCKBSSLK]
  - Bi-directional communication
    - Improved **resource efficiency** (theoretically by factor of two)
    - Effective **feedback** channel (CSI-T, Adaptive constellation,…)
    - Enhanced physical layer **security**, …
  - **Enhanced physical layer function**
  - Continuous **sensing and presence** in the environment
    - No **hidden (exposed) terminal** problem
    - Improved **primary detection**
  - **Enhanced access layer function**
  - Continuous transmission and reception ability
    - Reduced **round trip time**, reduced **network congestion**
  - **Enhanced network layer function**
Full-Duplex Operation

- Recent advances have provided reasonable isolation among Tx and RX antennas via
  - Antenna design and placement
  - RF cancellation circuit design
  - Digital processing methods
  - ...

- **Example result:** 110 dB for bandwidth of 80MHz [BMK]
  - Compliant with WiFi 802.11ac
  - Suppression down to the receiver noise floor

FD is seriously considered as a possibility for 5G and beyond!

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FD for Future Generations

Required research & development tracks to incorporate FD into future standards:

• Feasibility, hardware realization
• Where, how, and how much can this be useful?
  – Distinguish standards/usecases that benefit from FD
  – Update the classic designs for the new system
  – Theoretical bounds and achievable performance gains
• Hardware & software integration
Feasibility, Hardware Realization

• FD research tracks:
  – Feasibility, hardware realization

  Self-interference suppression

Complete interference chains

self-interference channel

RF Rx. analog (LNA,…)

ADC-Downcon.

Digital (baseband) in Rx chain

Residual self-interference

RF Tx. analog (PA, …)

DAC-Upconvert.

Digital (baseband) in Tx chain

Desired Tx signal
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Feasibility, Hardware Realization

- Self-interference suppression – Tx chain, digital domain

- Null-steering in time and frequency domain [RBHWWW:11], [HLMCG], …

- Keep average interference power within a safe range [TM13], [ZTLH12], …

- Incorporate the spatial characteristics of the residual self-interference in Tx side [DMBS], [ZTH13W], …


Feasibility, Hardware Realization

- Self-interference suppression – Tx chain, RF domain

Antenna cancellation: Null-steering with auxiliary propagation in RF:
[SJLK], [K:10], [AKSRC:12]


Feasibility, Hardware Realization

- Self-interference suppression – Passive cancellation
  - Passive interference cancellation
  - Proper placement of Rx and Tx antennas to reduce the direct interference paths (natural isolation [DS:10], [CJLK])
  - Exploit directivity of Tx and Rx (directional diversity [EDDS:11])

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Feasibility, Hardware Realization

- Self-interference suppression – Rx chain, RF domain

- Interference reconstruction via auxiliary chains
  - Rice: [DS:10], [SPS:11]
  - HHI: [AKSHK:14]

- Copying the Tx signal in RF with phase shift and delay:
  - Stanford: BALUN technique [JCKBSSLK], [BMK]

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Feasibility, Hardware Realization

- Self-interference suppression – Rx chain, RF domain (cont.)
Feasibility, Hardware Realization

- Self-interference suppression – Rx chain, RF domain (cont.)

- Interference reconstruction via auxiliary chains
  - Rice: [DS:10], [SPS:11]
  - HHI: [AKSHK:14]

- Challenge: Tx noise, more cost
- Around 85dB suppression is reported
Feasibility, Hardware Realization

- Self-interference suppression – Rx chain, RF domain (cont.)

- Copying the Tx signal in RF with phase shift and delay:
  - Stanford: BALUN technique [JCKBSSLK], [BMK]

- Challenge: Accurate phase-shift & attenuation is needed

- Around 110dB suppression is reported
Feasibility, Hardware Realization

- Self-interference suppression – Rx chain, digital domain

- Dealing with remaining interference:
  - Compensating PA non-lin effect: [BMK:13], [AKSHK:14], …
  - Joint Tx-Rx strategy, Rx antenna selection: [CWRH:14], [RWW:11], …

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**References**


[CWRH:14] Ali Cagatay Cirik, Rui Wang, Yue Rong and Yingbo Hua, MSE Based Transceiver Designs for Bi-directional Full-Duplex MIMO Systems, SPAWC

Feasibility, Hardware Realization

• Self-interference suppression – to conclude:
  – Several attempts for cancelling out the self-interference
  – Over 100 dB of suppression is feasible!
  – The cancellation must be done simultaneously in several domains.
    • Single-domain cancellation methods do not bring enough suppression

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Levels of suppression in different layers, [BMK:13]

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Example Use-Case: FD P2P

- Example FD use-case: FD point to point
  
  - Enhanced spectral efficiency, real-time feedback channel, improved access layer function, …
  - P2P FD modeling, achievable rates [DMBS:12]
  - Interference zero-forcing and power adjustment (HD vs FD trade-off) [ZTH13W]
  - Sum rate enhancement [ZTLH12], [CZHH:14]
  - Coping with CSI imperfection [ZTH:13], [CZHH:14]

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Example Use-Case: FD P2P

• Example FD use-case: **FD point to point**
  - Update the medium access layer protocols for FD nodes
    • MAC protocol IEEE 802.11: FD-MAC [SPS11], [SGPRBK11], …
    • Access layer performance analyze for FD wireless LAN [OB12]
    • Adaptive sensing-transmission-reception: [AK:14], [CZZ:11]

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Example Use-Case: FD Relaying

- Example FD use-case: FD relaying

- Reduced time slots → higher efficiency, lower delay.
- **One-way** relaying protocol → Factor of **two** in spectral efficiency, end users remain HD *(HD user-compatible)*
- **Two-way** relaying protocol → Continuous Rx, Tx in both sides, Factor of **four** in spectral efficiency, end-users need to be FD *(HD user-incompatible)*
Example Use-Case: FD Relaying

- Example FD use-case: FD relaying (cont.)

  Various FD relaying scenarios have been studied:
  - Sum rate maximization for FD, amplify-and-forward (AF) relaying [ZTH:13],
  - Sum rate maximization for FD, decode-and-forward (DF) relaying [DMBS:12],
  - Digital interference loop cancellation for FD AF relays [RWW:11], [RWW:09]
  - Efficient FD DF relaying with imperfect CSI [TM:14F], [TM:14R]

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Example Use-Case: FD Relaying

- Example FD use-cases: FD relaying (cont.)
  - Multi-user operation with FD DF Relay [TM:14R],
  - Cooperative mechanisms for distributed FD AF relaying [TM:14C], [KSSC:12], [KIAS:13], …
  - Interference alignment schemes using FD relays [MM13], [MCM:14] …

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Ex. Use-Case: Wiretap Channel

- Example FD use-case: FD wiretap channel

Alice  
\[ \text{Eavesdropper} \]  
Bob

- New achievable secrecy rates with FD operation,
  - Achievable bounds and performance analyze [GKYG10],
  - Optimal power adjustment and Tx strategy [ZKLPO:13], …

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Example Use-Case: FD Radar

- Example FD use-case: FD radar

- Significantly higher observation resolution with FD capability
  - Multiple object detection and classification via iterative cancellation [BJK13]

• Example FD use-case: FD operation in base-station:

FD base-station, HD users:

FD base-station, FD users:

• More flexible resource allocation, higher resource efficiency
  – Multi-user MIMO strategies for downlink and uplink: [NTPL13]

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Our Cooperation and Interface

• **Our expertise:** **Signal processing**
  – **System optimization** for various scenarios with FD operation
  – Theoretical bounds on system performance,
  – Rx-Tx baseband design,
  – ...

• **Main convergence points:**
  – System **model**, model verification,
  – Periodic meetings to share findings and updates,
  – Hardware, software integration.
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To Conclude..

• FD is a new, promising research area!
• High hopes for our cooperation!
Thanks for your attention!