Achieving Single Channel Full-Duplex Wireless Communication

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Can a wireless node transmit AND receive at the same time on a single band?
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Status quo: NO
Current wireless radios

• In-band half-duplex

• Full-duplex through other dimensions
  • E.g. different frequencies
  • Bandwidth is a precious resource
Why not full-duplex on the same band?
Why not full-duplex on the same band?

• Very strong self-interference
  • \(~70\text{dB}~\) stronger for 802.15.4
  • Analog to Digital converter (ADC) saturates
Existing Techniques

• Digital cancellation: Subtracting known interference digital samples from received digital samples.
  ZigZag\textsuperscript{[1]}, Analog Network Coding\textsuperscript{[2]} etc.

• Hardware cancellation: RF noise cancellation circuits with transmit signal as noise reference
  Radunovic et al.\textsuperscript{[3]}

\textsuperscript{[1]} Gollakota et al. “ZigZag Decoding: Combating Hidden Terminals in Wireless Networks”, ACM SIGCOMM 2008
\textsuperscript{[3]} Radunovic et al., ”Rethinking Indoor Wireless: Lower Power, Low Frequency, Full-duplex”, WiMesh (SECON Workshop), 2010
Existing Techniques

- Digital cancellation: Subtracting known interference digital samples from received digital samples. ZigZag\(^1\), Analog Network Coding\(^2\) etc.

  Ineffective if ADC is saturated

- Hardware cancellation: RF noise cancellation circuits with transmit signal as noise reference

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Existing Techniques

- Digital cancellation: Subtracting known interference digital samples from received digital samples.
  ZigZag\(^1\), Analog Network Coding\(^2\) etc.  
  ~15 dB
  Ineffective if ADC is saturated

- Hardware cancellation: RF noise cancellation circuits with transmit signal as noise reference
  Radunovic et al.\(^3\)  
  ~25 dB

These are not enough 25 dB +15 dB < 70 dB
Our innovation: Antenna Cancellation

TX1  d  RX  d + λ/2  TX2
Our innovation: Antenna Cancellation

~30dB self-interference cancellation

Enables full-duplex when combined with Digital (15dB) and Hardware (25dB) cancellation.
Can a wireless node transmit AND receive at the same time on a single band?
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YES, IT CAN!

Full-duplex prototype achieves 92% of the throughput of an “ideal” full-duplex system.
Talk Outline

- Design of Full-Duplex Wireless
- 3 Techniques: Antenna, Hardware and Digital Cancellation
- Analyzing Antenna Cancellation
- Performance Results
- Implications to Wireless Networks
- Limitations of Design, Future Work
Talk Outline

• Design of Full-Duplex Wireless
• 3 Techniques: Antenna, Hardware and Digital Cancellation
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• Limitations of Design, Future Work
Three techniques give ~70dB cancellation

- Antenna Cancellation (~30dB)
- Hardware Cancellation (~25dB)
- Digital Cancellation (~15dB)
Antenna Cancellation: Block Diagram
Hardware and Digital Cancellation

Hardware Cancellation

• Use existing interference cancellation circuits (QHx220)*

Digital Cancellation

• Subtract known transmit samples from received digital samples

Bringing It Together

Antenna Cancellation

Hardware Cancellation

Digital Cancellation

ADC

RX Signal

QHX220

TX Samples

Clean RX samples

RF

Baseband
Bringing It Together

- **Antenna Cancellation**
  - TX Signal
  - TX Samples
  - Clean RX samples

- **Hardware Cancellation**
  - RX

- **Digital Cancellation**
  - QHX220
  - ADC

- **Baseband**

- **RF**
Bringing It Together

Antenna Cancellation

Hardware Cancellation

ADC

Digital Cancellation

Clean RX samples

TX Signal

QHX220

RX

∑

TX Samples

±
Our Prototype

Antenna Cancellation

Digital Interference Cancellation

Hardware Cancellation
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Antenna Cancellation: Performance

Position of Receive Antenna (cm)

RSSI (dBm)

TX1

TX2

Only TX1 Active

0 5 10 15 20 25
Antenna Cancellation: Performance

RSSI (dBm)

TX1

TX2

Position of Receive Antenna (cm)

Only TX1 Active

Only TX2 Active
Antenna Cancellation: Performance

RSSI (dBm)

Position of Receive Antenna (cm)

-60 -55 -50 -45 -40 -35 -30 -25

0 5 10 15 20 25

TX1

Only TX1 Active

Both TX1 & TX2 Active

Only TX2 Active

TX2

Null Position
Antenna Cancellation: Performance

-25 -20 -15 -10 -5 0 5 10 15 20 25
RSSI (dBm)

<table>
<thead>
<tr>
<th>Position of Receive Antenna (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX1 Active</td>
</tr>
<tr>
<td>TX2 Active</td>
</tr>
<tr>
<td>Only TX1 Active</td>
</tr>
<tr>
<td>Both TX1 &amp; TX2 Active</td>
</tr>
<tr>
<td>Only TX2 Active</td>
</tr>
</tbody>
</table>

Antenna Cancellation: Performance ~25-30dB

Null Position

~25-30dB
Sensitivity of Antenna Cancellation

Amplitude Mismatch between TX1 and TX2

Placement Error for RX
Sensitivity of Antenna Cancellation

Amplitude Mismatch between TX1 and TX2

30dB cancellation < 5% (~0.5dB) amplitude mismatch
< 1mm distance mismatch
Sensitivity of Antenna Cancellation

- Amplitude Mismatch between TX1 and TX2
- Placement Error for RX

- Rough prototype good for 802.15.4
- More precision needed for higher power systems (802.11)
Bandwidth Constraint

A $\lambda/2$ offset is precise for one frequency
Bandwidth Constraint

A $\lambda/2$ offset is precise for one frequency not for the whole bandwidth
Bandwidth Constraint

A $\lambda/2$ offset is precise for one frequency, not for the whole bandwidth.

\[ f_c \pm B \]

\[ d_1 \]

\[ d_1 + \lambda - B/2 \]

\[ d \]

\[ d + \lambda/2 \]

\[ d_2 \]

\[ d_2 + \lambda + B/2 \]
Bandwidth Constraint

A $\lambda/2$ offset is precise for one frequency not for the whole bandwidth

WiFi (2.4G, 20MHz) => $\sim0.26$mm precision error
Bandwidth Constraint

![Graph showing reduction limits for different frequencies (300 MHz, 2.4 GHz, 5.1 GHz) vs. signal bandwidth (MHz). The x-axis represents the signal bandwidth in MHz, ranging from 0 to 100, and the y-axis represents the reduction limit in dB, ranging from -70 to -10 dB.]
Bandwidth Constraint

- WiFi (2.4GHz, 20MHz): Max 47dB reduction
- Bandwidth $\uparrow$ => Cancellation $\downarrow$
- Carrier Frequency $\uparrow$ $\Rightarrow$ Cancellation $\uparrow$
What about attenuation at intended receivers? 
Destructive interference can affect this signal too!
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- Different transmit powers for two TX helps

**Deep Nulls at 20-30m**
What about attenuation at intended receivers? Destructive interference can affect this signal too!

- Different transmit powers for two TX helps
What about attenuation at intended receivers? Destructive interference can affect this signal too!

- Different transmit powers for two TX helps
- Diversity gains in indoor environments
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Experimental Setup

- 802.15.4 based signaling on USRP nodes
- Two nodes at varying distances placed in an office building room and corridor
Half-Duplex :- Nodes interleave transmissions

Node 1 → 2
Node 2 → 1

milliseconds

Full-Duplex :- Nodes transmit concurrently

Node 1 → 2
Node 2 → 1

milliseconds

• Full-duplex should double aggregate throughput
Throughput

- Median throughput 92% of ideal full-duplex

Throughput (Kbps)

- Half-Duplex
- Full-Duplex
- Ideal Full-Duplex

Throughput

- 45
Throughput

Performance loss at low SNR
Little loss in link reliability: 88% of half-duplex on average
• Loss at High SNR: Due to spurious signal peaks in USRP
- Loss at High SNR: Due to spurious signal peaks in USRP
- Loss at low SNR: Due to imprecisions in prototype
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The prototype gives 1.84x throughput gain with two radios compared to half-duplex with a single radio

So what? PHY gains similar to 2x2 MIMO
The prototype gives 1.84x throughput gain with two radios compared to half-duplex with a single radio.

So what? PHY gains similar to 2x2 MIMO.

True benefit lies beyond the physical layer.
Implications to Wireless Networks

• Breaks a basic assumption in wireless
• Can solve some fundamental problems with wireless networks today
  • Hidden terminals
  • Primary detection in whitespaces
  • Network congestion and WLAN fairness
  • Excessive latency in multihop wireless
Mitigating Hidden Terminals

Current networks have hidden terminals

- CSMA/CA can’t solve this
- Schemes like RTS/CTS introduce significant overhead
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- CSMA/CA can’t solve this
- Schemes like RTS/CTS introduce significant overhead

Full Duplex solves hidden terminals

Since both sides transmit at the same time, no hidden terminals exist
Primary Detection in Whitespaces

Secondary transmitters should sense for primary transmissions before channel use.

Traditional nodes may still interfere during transmissions.
Primary Detection in Whitespaces

Secondary transmitters should sense for primary transmissions before channel use.

Full-duplex nodes can sense and send at the same time.
Without full-duplex:

- \( \frac{1}{n} \) bandwidth for each node in network, including AP

**Downlink Throughput** = \( \frac{1}{n} \)  
**Uplink Throughput** = \( \frac{(n-1)}{n} \)
Network Congestion and WLAN Fairness

Without full-duplex:
- \( \frac{1}{n} \) bandwidth for each node in network, including AP

\[
\text{Downlink Throughput} = \frac{1}{n} \quad \text{Uplink Throughput} = \frac{(n-1)}{n}
\]

With full-duplex:
- AP sends and receives at the same time

\[
\text{Downlink Throughput} = 1 \quad \text{Uplink Throughput} = 1
\]
Reducing Round-Trip Times

Long delivery and round-trip times in multi-hop networks

Solution: Wormhole routing

Half-duplex

Full-duplex
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• Bandwidth Constraint
  Working on a frequency independent signal inversion technique

• Time-varying wireless channel
  Auto-tuning of the hardware cancellation circuit

• Multi-path
  Estimate and incorporate in digital cancellation: Some existing work does this

• Single stream
  Extension to MIMO-like systems
Summary

• Prototype for achieving in-band full-duplex wireless

• Constraints of current prototype can be overcome with some neat ideas and careful engineering

• Rethinking of wireless networks

  • We’ve discussed some applications like mitigating hidden terminals and WLAN fairness

  • Many more possibilities