Considerations for In-Band Simultaneous Transmit and Receive (STR) feature in HEW

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</table>
Abstract

Self-Interference cancellation technology for enabling in-band simultaneous transmit and receive (STR), often referred as full-duplexing, is advancing.

Adoption of STR technology is expected to provide gains in WLAN MAC efficiency. However, it will necessarily involve modifications to the current WLAN MAC.

We present a summary of the state of the STR technology, and ask (straw poll) whether the group is willing to consider the MAC changes to accommodate in-band STR.
In-Band Simultaneous Transmit and Receive (STR)

The ability of a station $S_1$ to successfully decode the transmissions received from station $S_2$ while transmitting to station $S_2$ or an other station $S_3$ on the same frequency resource.

Requirements to support In-Band STR in WLAN:
- Sufficient suppression of the Tx signal at STR node (referred here as self-interference cancellation (SIC)).
- Protocol (MAC) support for STR
- Co-existence considerations
Motivation for considering In-Band STR

Present: Either Tx or RX

Wireless devices either transmit or receive, but not both

Inefficient Spectral Utilization!

What if: Simultaneous Tx & Rx

On the same time and frequency resource

Up to 2x throughput improvements!

First, hardware must be capable of providing sufficient Self-Interference cancellation!
Status of BB/RF self-interference Cancellation technologies to enable STR
Self-Interference Cancellation Approach

Tx

Modulator → DAC → PA → Tx Antenna

D-Cancellation

Rx

Demodulator → ADC → LNA → Rx Antenna

A-Cancellation

Active/Passive Antenna Cancellation
Advances in Self-Interference Cancellation

Stanford approaches

60 dB  73 dB
2010  2011

Rice

~80 dB

Single Antenna Design

110 dB! Cancellation

Stanford
## Self Interference Cancellation Designs

<table>
<thead>
<tr>
<th>Reference</th>
<th>Band</th>
<th>Bandwidth</th>
<th># Antenna</th>
<th># RF</th>
<th>Cancellation Antenna</th>
<th>Analog</th>
<th>Digital</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSR [8]</td>
<td>530MHz</td>
<td></td>
<td>2</td>
<td>2</td>
<td>25~30 dB</td>
<td>30 dB</td>
<td></td>
<td>55~60 dB</td>
</tr>
<tr>
<td>Rice [9]</td>
<td>2.4GHz</td>
<td>625KHz</td>
<td>2</td>
<td>3</td>
<td>39~45 dB</td>
<td>31~33 dB</td>
<td></td>
<td>78~80 dB</td>
</tr>
<tr>
<td>Stanford [10]</td>
<td>2.4GHz</td>
<td>5MHz 802.15.4</td>
<td>3</td>
<td>2</td>
<td>30 dB</td>
<td>20 dB</td>
<td>10 dB</td>
<td>60 dB</td>
</tr>
<tr>
<td>Stanford [10]</td>
<td>2.4GHz</td>
<td>10MHz 802.11n</td>
<td>2</td>
<td>2</td>
<td>45 dB</td>
<td>28 dB</td>
<td></td>
<td>73 dB</td>
</tr>
<tr>
<td>Stanford [7]</td>
<td>2.4GHz</td>
<td>80MHz 802.11ac</td>
<td>1</td>
<td>2</td>
<td>60 dB</td>
<td>50 dB</td>
<td></td>
<td>110 dB</td>
</tr>
<tr>
<td>NEC [11]</td>
<td>5GHz</td>
<td>10MHz WiMAX</td>
<td>4</td>
<td>2</td>
<td>10(polar)+45 dB</td>
<td></td>
<td>20 dB</td>
<td>75 dB</td>
</tr>
<tr>
<td>Princeton [12]</td>
<td>2.4GHz</td>
<td>625KHz</td>
<td>2M + 2N</td>
<td>M + N</td>
<td>37 dB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NYU [13]</td>
<td>914MHz</td>
<td>26MHz</td>
<td>1</td>
<td>2</td>
<td>40~45 dB</td>
<td>14 dB</td>
<td></td>
<td>59 dB</td>
</tr>
</tbody>
</table>
Cancellation Requirements and Tech Status

Digital Cancellation

Analog Cancellation (Antenna + RF)

In-Band Simultaneous Transmit and Receive

Requires about 110 dB self-interference cancellation for WLAN operation.

SIC Requirements

SIC Feasibility

State of the art (Stanford Design 2013):
- 110 dB self-cancellation for
- 80MHz signal bandwidth
- 20dBm Tx Power
- 2.4 GHz band

How to utilize advances in SIC technology to improve WLAN MAC efficiency?
MAC Issues in In-band STR
Scenarios for STR in WLAN

Two Basic Constructs for STR in WLAN

- Pair-Wise STR:
  - Example: AP Transmits to $S_1$; $S_1$ transmits to AP
  - AP/$S_1$ cancel own outgoing transmissions while receiving the transmissions from $S_1$/AP.
- Unrestricted STR
  - Example: AP Transmits to Station $S_1$; AP receives from Station $S_2$
  - $S_1$ needs to cancel the transmission from $S_2$ to decode the AP transmission correctly
STR MAC Issues: Basic Overhearing Issues

\[ G_{S_1 \setminus S_2} = \{ \text{nodes hear } S_1 \text{ only} \} \]

\[ G_{S_1 \cap S_2} = \{ \text{nodes hear both } S_1 \text{ and } S_2 \} \]

\[ G_{S_2 \setminus S_1} = \{ \text{nodes hear } S_2 \text{ only} \} \]

- During \( T_{B \setminus A} \), the nodes in \( G_{S_1 \setminus S_2} \) may send packets to \( S_1 \) as they sense the completion of transmission from \( S_1 \), and that may result in corrupted reception of packet \( B \) at \( S_1 \).
- During \( T_{A \cap \bar{B}} \), the nodes in \( G_{S_1 \cap S_2} \) always receive corrupted packets even if the transmissions succeed.
- During \( T_{A \setminus B} \), the nodes in \( G_{S_2 \setminus S_1} \) might send packets to \( S_2 \) since they cannot overhear packet \( A \) which is sent by \( S_1 \), and hence corrupt packet \( A \) (hidden terminal problem).
STR MAC issues: ACK mechanism

- In a 2-node scenario (node $S_1$ and node $S_2$) with pair-wise symmetric STR:
  - $S_1$ sends packet A to $S_2$ and $S_2$ sends packet B to $S_1$ with overlapping TX duration.
  - Both A and B request/expect ACK.
- Waiting for ACK after transmission is the highest priority in current 802.11ac MAC
  - $S_2$ cannot send ACK to $S_1$ even after it has received packet A correctly because $S_2$ is still transmitting packet B to $S_1$.
  - How long should $S_1$ wait for ACK before resending packet A and when should $S_1$ transmit an ACK for successfully receiving packet B
  - $S_1$ and $S_2$ may get stuck in retransmissions and ACK timeouts.
STR MAC issues: Contention Fairness

Contestation fairness for the overhearing nodes

- Suppose node $S_0$ is in the radio ranges of all the nodes involved in STR transmission.
  - $S_1$ receives packet B successfully and $S_2$ receives packet A successfully.
  - $S_0$ receives a corrupted packet.
- Upon corrupted packet reception, $S_0$ waits for EIFS for next contention while $S_1$ and $S_2$ wait for DIFS for next contention. Unfair Contention!

![Diagram showing STR MAC issues](image)
... + several backward compatibility issues

Coexistence will pose several challenges

- Should STR be a separate mode or a feature with sufficient co-existence built-in?
- In case of Co-existence
  - How to set/broadcast NAVs correctly?
  - How to avoid/alleviate the interference from Primary Transmitter ($S_0$ in the right figure) to Secondary Receiver ($S_2$ in the right figure) in unrestricted STR?
- Are we willing to even consider the option that legacy stations performance may degrade?

Node $S_0$ has problems setting NAV$_1$ and/or NAV$_2$

Node $S_2$ has problems decoding packet B due to interference

Corrupted!
## Summary of STR MAC issues

<table>
<thead>
<tr>
<th>STR Scenarios</th>
<th>• Two Scenarios: <strong>Pair-Wise and Unrestricted STR.</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>ACK mechanism</td>
<td>• Modifications necessary to the <strong>ACK mechanism</strong></td>
</tr>
<tr>
<td>Overhearing behavior</td>
<td>• Behavior of the overhearing nodes need to be taken into account when defining/incorporating the STR MAC protocol.</td>
</tr>
</tbody>
</table>
| Backward compatibility | • How to **co-exist with** legacy 802.11 devices?  
• How to minimize **throughput degradation** of legacy devices? |

### Diagrams
- **Corrupted!**
  - Both A and B request ACK
  - No ACK?
- **Interference**
  - A
  - B
  - Both A and B request ACK
  - No ACK?

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Rakesh Taori et. al., - Samsung
A Summary of Published Approaches
ContraFlow[1]

**Algorithm**
- CSMA/CA-based algorithm;
- Supports pair-wise and unrestricted STR scenarios.

**Changes to Specification**
- **Requires Modification** of current ACK:
  - Specify the order of sending ACKs after full duplex transmission.
- **Adds a new feature** – Secondary Transmission:
  - Determine the destination of secondary transmission based on history-based interfering table.
- **Adds a new feature** – Primary Collision mechanism:
  - Use Secondary Transmission as an implicit ACK.

**Backward Compatibility**
- Require all nodes to be STR-aware.
- Cannot support legacy 802.11 devices.

**Performance**
- Claim 30%-50% throughput improvement over CSMA/CA for
  - 3 network topologies with 5-6 stations
  - Random traffic with fixed arrival rate.
FD MAC[2]

Algorithm

- Support existing 802.11 devices;
- Focus only on pair-wise STR scenario

Changes to Specification

- Requires Modification of current ACK:
  - Modify the priority of sending ACKs to be higher than waiting for ACKs.

- Requires modification of current overhearing behavior:
  - After one successful full-duplex transmission, every node waits for EIFS to start next contention.

- Adds a new feature – Pairwise secondary transmission:
  - Embed the initiation of secondary transmission in RTS-CTS exchange.

Backward Compatibility

- Compatible with existing 802.11 devices with higher contention overhead (EIFS).

Performance

- Claims 45%-72% throughput improvement over CSMA/CA under
  - 3 network topologies with 2 to 8 stations;
  - Saturated arrival traffic.
Janus[3]

Algorithm
- AP-centralized algorithm;
- Supports pair-wise and unrestricted STR scenarios.

Backward Compatibility
- Require all nodes to be STR-aware.
- Cannot support legacy 802.11 devices.

Changes to Specification
- Requires a new centralized medium access mechanism.
  - Controlled by AP and operated in a 3-step cycle;
  - AP collects information about data-length and interference relationship from STAs;
  - AP broadcasts the scheduling decision packet and initiates data transmissions;
  - Send ACKs in the predefined order embedded in the scheduling decision packet.

Performance
- Claim maximum 150% throughput improvement over CSMA/CA under
  - 3 interfering topologies with 1 AP; 3 STAs;
  - 3 traffic types with varying packet sizes.
# Summary of other STR MAC approaches

<table>
<thead>
<tr>
<th>Other References</th>
<th>Attributes</th>
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<tbody>
<tr>
<td></td>
<td>1) Primary Receiver initiates the secondary transmission (restricted to pairwise STR);</td>
</tr>
<tr>
<td></td>
<td>2) Primary Receiver sends busy tone whenever there is no packet for secondary transmission.</td>
</tr>
<tr>
<td></td>
<td>1) Primary Receiver initiates the secondary transmission (can be unrestricted STR);</td>
</tr>
<tr>
<td></td>
<td>2) Remove ACK mechanism;</td>
</tr>
<tr>
<td></td>
<td>3) Remove contention window.</td>
</tr>
<tr>
<td></td>
<td>1) Primary Receiver initiates the secondary transmission (restricted to pairwise STR);</td>
</tr>
<tr>
<td></td>
<td>2) AP adopts dynamic contention window size to balance the uplink/downlink load.</td>
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Concluding remarks
Concluding Remarks

Summarized the status of technologies needed for supporting In-Band STR

- It is well understood that introducing STR will result in increased MAC efficiency.
- Inadequate and insufficient suppression of self-interference was a major obstacle to STR adoption.
- Self-Interference techniques have advanced significantly and initial results claiming sufficient SIC are beginning to emerge ➔ Time to consider system/protocol aspects to accommodate STR
- We also surveyed the System/Protocol changes to accommodate In-Band STR operation and summarized it in this presentation.

It is very likely that changes to the existing MAC mechanisms will be needed to accommodate In-band STR

Is this group willing to consider those changes in HEW?
HEW SG Straw poll
Straw Poll

In-band simultaneous transmit and receive (STR) feature should be considered for inclusion in HEW even if fundamental changes to the MAC are incurred

In Favour: 44
Opposed: 20
Abstain: 48

Acknowledgment: Many thanks to Sean Coffey (Realtek) and Brian Hart (Cisco) for their comments and contributions to the wordings of this straw poll
Thank you!
References


References


