Enabling Fine-Grained Channel Access in WLAN

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The Problem

How we can improve the access efficiency in high-speed wireless network?

IEEE 802.11n; 144.4Mbps
(20MHz channel; 2x2MIMO;
1500B frame size; aggregation disabled)
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IEEE 802.11n; 144.4Mbps (20MHz channel; 2x2MIMO; 1500B frame size; aggregation disabled)
Understanding the Overhead

CSMA MAC

Busy   DIFS   Backoff   Transmission   SIFS   ACK

Useful air time for data transmission

Coordination overhead

\[ \eta = \frac{t_{\text{data}}}{t_{\text{DIFS}} + t_{\text{slot}} \cdot W + t_{\text{data}} + t_{\text{SIFS}} + t_{\text{ACK}}} \]
Understanding the Overhead (cont.)

- When PHY data rate increases high, the useful air time ($t_{data}$) reduces, but
- Coordination overhead remains almost constant

\[
\eta = \frac{t_{data}}{t_{DIFS} + t_{slot} \cdot \bar{W} + t_{data} + t_{SIFS} + t_{ACK}}
\]

- $t_{DIFS} = t_{SIFS} + 2t_{slot}$
- $t_{SIFS} = t_{RFDelay} + t_{proc} + t_{TxRx}$
- $t_{slot} = t_{CCA} + t_{TxRx} + t_{prop}$

Ability to resolve collisions

- 10~16μs
- 9~20μs
- > 8
Understanding the Overhead (cont.)

- When PHY data rate increases high, the useful air time reduces, but coordination overhead remains almost constant.

![Graph showing efficiency vs. PHY data rate for different standards: 802.11b, 802.11a/g, 802.11n, 802.11ac/ad. Frame size 1500B.](image)
Existing MAC Limitations

• Always allocate whole channel to a single user at a time
  – Single carrier: too coarse when data rate is high and bandwidth is wide
  – Significant overhead with small data transmission

• Aggregation cannot solve the problem completely
  – Requires a large aggregation size (e.g. 23KB per frame for 80% efficiency at 300Mbps data rate
  – Increases latency - adversary interaction w/ RT, interactive, Web traffic, etc.
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*Calls for a fine-grained channel access model!*
Fine-Grained Channel Access

• Basic idea
  – Divide the spectrum band into small fine-grained slices
  – Allow different nodes to contend and transmit on different slices
  – Amortize the coordination overhead among multiple users

• Direct reduce the channel width does not work
  – Guard-band creates significant overhead
Our Approach: Using Orthogonal Subchannels

• Based on OFDM
  – Overlapped subchannels, but
  – Cross-subchannel interference is zero
• Remove the need of guard-band
Challenges

• Loss of orthogonality among asynchronous nodes

• How to coordinate transmissions in random access networks like WLAN

• How to handle contentions
  – Conventional time-domain backoff becomes very inefficient

Orthogonality lost; ICI is created
FICA Approach

• A new PHY architecture
  – Rely on carrier-sensing and broadcasting for synchronization
  – Adopt new symbol structure to accommodate the time misalignment

• A new MAC contention and backoff scheme
  – Frequency-domain contention and backoff
Overview

• Divide wide-band channel into orthogonal subchannels
• M-RTS/M-CTS/DATA/ACK access sequence
FICA PHY Architecture

• Analyze the timing misalignment in WLAN with carrier-sensing and broadcasting

Carrier-sensing $t_{mis} < 11\mu s$

Broadcasting $t_{mis} < 2\mu s$
FICA PHY Architecture (cont.)

- Design a proper cyclic-prefix to accommodate the timing misalignment

\[ t_{mis} \text{ Symbol} \]
FICA PHY Architecture (cont.)

• Design a proper cyclic-prefix to accommodate the timing misalignment

  – Enlarged CP size to be longer than the misalignment
    • Long CP for M-RTS - coordinated with carrier sensing
    • Short CP for M-CTS/DATA/ACK – synchronized by previous broadcasting signals
FICA PHY Architecture (cont.)

• Design a proper cyclic-prefix to accommodate the timing misalignment
  – Enlarged CP size to be longer than the misalignment
    • Long CP for M-RTS - coordinated with carrier sensing
    • Short CP for M-CTS/DATA/ACK – synchronized by previous broadcasting signals
  – Extend symbol time accordingly to offset the CP overhead
## PHY Design Details

### OFDM Symbol Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{fft_data}}$</td>
<td>256 points</td>
</tr>
<tr>
<td>$t_{\text{fft_data}}$</td>
<td>12.8 $\mu$s</td>
</tr>
<tr>
<td>$N_{\text{fft_mrts, \text{fft_mcts}}}$</td>
<td>512 points</td>
</tr>
<tr>
<td>$t_{\text{fft_mrts, \text{fft_mcts}}}$</td>
<td>25.6 $\mu$s</td>
</tr>
<tr>
<td>$t_{\text{long_cp}}$</td>
<td>11.8 $\mu$s</td>
</tr>
<tr>
<td>$t_{\text{short_cp}}$</td>
<td>2.8 $\mu$s</td>
</tr>
<tr>
<td>$t_{\text{data_sym}}$</td>
<td>15.6 $\mu$s</td>
</tr>
<tr>
<td>$t_{\text{mrts_sym}}$</td>
<td>37.4 $\mu$s</td>
</tr>
<tr>
<td>$t_{\text{mcts_sym}}$</td>
<td>28.4 $\mu$s</td>
</tr>
</tbody>
</table>

Data subcarrier width: 78KHz  
Subchannel width: 1.33MHz  
(17 subcarriers)

- 20 MHz channel: 14 subchannels
- 40 MHz channel: 29 subchannels

<table>
<thead>
<tr>
<th>Configuration</th>
<th>FICA (Mbps)</th>
<th>802.11n (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20MHz channel</td>
<td>71.8</td>
<td>72.2</td>
</tr>
<tr>
<td>40MHz channel</td>
<td>145</td>
<td>150</td>
</tr>
<tr>
<td>40MHz channel, 2xMIMO</td>
<td>290</td>
<td>300</td>
</tr>
<tr>
<td>40MHz channel, 4xMIMO</td>
<td>580</td>
<td>600</td>
</tr>
</tbody>
</table>

More details are explained in the paper
Contention and Resolution

• Time domain backoff is inefficient
  – Very large symbol, e.g. 37.4 us for M-RTS ➔ very large backoff slot

• Our solution: frequency-domain contention
  – Physical layer signaling: M-RTS/M-CTS
Frequency Domain Backoff

• Basic idea:
  – Reduce num. of subchannel to contend if collision
  – Increase num. of subchannel to contend if success
  – Analog to congestion control mechanisms

Update 1: Reset to max

if collision detected in any subchannel then
  \[ C_{\text{max}} = \max(C_{\text{max}}/2, 1); \]
else
  \[ C_{\text{max}} = C_{\text{total}}; \]
end if

Update 2: AIMD

if \( p\% \) subchannels have collisions and \( p > 0 \) then
  \[ C_{\text{max}} = \max(C_{\text{max}} \times (1 - p/100), 1); \]
else
  \[ C_{\text{max}} = \min(C_{\text{max}} + 1, C_{\text{total}}); \]
end if
Implementation and Evaluation

• Prototype using the Sora software radio platform
  – Based on SoftWiFi implementation

• Hybrid-evaluation strategy
  – Prototype $\rightarrow$ feasibility
    • How well timing synchronization can be done with CSMA?
    • How reliable to detect OOK in PHY signal symbols?
    • What is the decoding performance?
  – Simulation $\rightarrow$ performance gain in large scale networks
Results – Symbol Timing Misalignment

- Carrier sensing
  - Carrier Sense Probability
- Broadcasting
  - Symbol Timing Mismatch CDF

Relative Delay (μs)

Timing misalignment (μs)
Results – Signaling Reliability

![Graph showing error rates vs. threshold factor]

- False Positive (Rep 1)
- False Negative (Rep 1)
- False Positive (Rep 2)
- False Negative (Rep 2)
- False Positive (Rep 4)
- False Negative (Rep 4)
Results – Decoding Performance

![Graph](Image)

- BER vs SNR (dB)
- Different modulation schemes and decoding methods:
  - BPSK FICA
  - QPSK FICA
  - 16QAM FICA
  - 64QAM FICA
  - BPSK Single
  - QPSK Single
  - 16QAM Single
  - 64QAM Single
Simulation – Performance Gain

- Full aggregation
- Mixed traffic: 5 saturated with delay sensitive traffic

11n PHY: 600Mbps; FICA PHY: 580Mbps

More results are in the paper!
Related Work

• OFDMA in tight synchronized network
• FARA implements downlink OFDMA in WLAN
• SMACK uses OFDM signaling to send ACK
• MCBC uses OFDM signaling for multi-round contention
• Multi-channel MAC designs

• Voice over IP in WLAN
Conclusions

• MAC efficiency is critical
• Fine-grained channel access is the key
  – Aggregation among different nodes
• FICA: first cross-layer design to enable fine-grained channel random access
  – New PHY architecture based on OFDM
  – New frequency-domain contention and backoff
Thanks!
Take you questions!