Robust and Energy Efficient MAC/PHY Strategies of Wi-Fi

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Introduction

- Wi-Fi has become an indispensable part of our daily lives!
  - 8 billion global Wi-Fi shipments expected in 2015

Source: IDC & HIS Research
Introduction

- New features of the emerging Wi-Fi
  - PHY rate
    - Multiple antenna system: up to 8 antennas
    - Wider bandwidth: up to 160 MHz
    - Higher order modulation: up to 256 QAM → Require robustness and energy efficiency
  - MAC efficiency
    - Frame aggregation: Aggregate MPDU (A-MPDU)
Contents

- Robust Wi-Fi in mobile environments
  - MoFA: Mobility-Aware Frame Aggregation in Wi-Fi
  - ChASER: Channel-Aware Symbol Error Reduction

- Energy efficient Wi-Fi
  - Power consumption of Wi-Fi
  - WiZizz: Energy Efficient Bandwidth Management
Robust Wi-Fi in Mobile Environment
Introduction

- Paradigm shift of Wi-Fi
  - Now, people hold their Wi-Fi devices and move
  - Performance degradation due to mobility (user and/or environment)
    - Faster PHY rate (higher modulation, multiple streams, and wide bandwidth)
    - Longer frame duration (Aggregate MPDU, A-MPDU)
Introduction

- **Aggregate MAC protocol data unit (A-MPDU)**
  - **Core technology** of IEEE 802.11n/ac
  - Packing several MPDUs into a single A-MPDU
  - **Amortizing protocol overhead** over multiple frames
  - Positive/negative acknowledgement for individual MPDUs (subframes) using **BlockAck**
    - Aggregating more subframes results in much higher throughput!
Introduction

- Channel estimation and compensation in Wi-Fi
  - Obtaining channel state information (CSI) using **training symbols** in PLCP preamble
    - Conducted only at the beginning of a frame reception
    - OFDM pilot symbols designed only to track the difference of the local oscillators
    - No way to catch up with **CSI variations during a frame reception**
Channel Estimation and Compensation in Wi-Fi

- Limitation of channel estimation and compensation

Testbed experiment 1. Error Vector Magnitude (EVM) and IQ constellation

- Microsoft Sora SDR platform (Rx) and Qualcomm Atheros AR9380 (Tx)
  - As mobility increases, EVM increases!

Rx symbol dispersion at the latter part of AMPDU is much larger than that at the front part of A-MPDU
Channel Estimation and Compensation in Wi-Fi

- Limitation of channel estimation and compensation

Testbed experiment 2. Throughput measurement

- Programmable **802.11n commercial device**
  - Qualcomm Atheros AR9380 / Intel IWL5300
  - Using **hostAP** to build an AP on linux machine
  - Controlling device drivers (**ath9k/iwlwifi**)
Two Proposed Approaches

- **MoFA: Mobility-Aware Frame Aggregation in Wi-Fi**
  - A-MPDU length (aggregation bound) adaptation with ease of implementation
  - **Simple modification of device driver** (using commercial programmable 802.11n NIC)

- **ChASER: Channel-Aware Symbol Error Reduction**
  - Chasing channel variation without overhead
  - **Receiving process modification** (using SDR platform)
MoFA: Mobility-Aware Frame Aggregation in Wi-Fi

MoFA: Mobility-Aware Frame Aggregation in Wi-Fi

![Diagram showing MoFA](image)

11111101101101110010000000

\[ T_{D_{o,new}} \]

\[ SFER_f \leftrightarrow SFER_l \]

\[ SFER_l - SFER_f = M > M_{th} ? \]
MoFA: Mobility-Aware Frame Aggregation in Wi-Fi

- Implementation issues
  1) Standard-compliant algorithm (with ease of implementation)
  2) Prototype in commercial 802.11n devices (AR9380) with ath9k driver
  3) Need to modify transmitter-side only

A-RTS: Adaptive use of RTS/CTS in order to overcome hidden interference
MoFA: Mobility-Aware Frame Aggregation in Wi-Fi

- Performance of MoFA in time-varying mobile environments
  - One-to-one scenario: Stays and moves half-and-half with a regular pattern
  - Divided into two regions (dashed line in the left figure)

  ➔ Performance of MoFA reaches up to the most outer curve which is obtained by the optimal fixed time bound in each region

(CDF vs. Throughput (Mb/s) and Throughput (Mb/s) vs. Time (sec))
Performance of MoFA in time-varying mobile environments

- Multiple node scenario: Three mobile nodes and two stationary nodes

- 127%, 109%, and 35% higher network throughput than no aggregation, 802.11n default setting, and optimal bound for 1 m/s

- STA4 (stationary and close to AP) gets the biggest benefit
ChASER: Channel-Aware Symbol Error Reduction

ChASER: Channel-Aware Symbol Error Reduction

- Channel estimation using unknown data symbols
  - Exploit unknown data symbols using
    \[ H_i = \frac{Y_i}{X_i} \]
  - Exponential weighted moving average filter
    \[ \tilde{H}_i = (1 - \mu)\tilde{H}_{i-1} + \mu \frac{Y_i}{\tilde{X}_i} \]
  - CRC-assisted error correction

- Evaluation methodologies
  - Microsoft Sora SDR platform
  - SDK version 1.6
ChASER: Channel-Aware Symbol Error Reduction

- Implementation issues (Microsoft Sora SDR platform)
  - High complexity and difficult to implement
  - Feasibility verification
    - We cannot control the commercial 802.11 device’s Rx process (hardware-level)
  - Real-time rx processing?
    - Processing latency due to multiple thread ➔ update CSI every 4 OFDM symbols
    - Sora does not provide real-time AGC at RF front-end ➔ Offline gain control

- Testbed experiments
  - Baseline 802.11n vs. ChASER
  - Fixed MCS 3, good channel condition
ChASER: Channel-Aware Symbol Error Reduction

- ChASER chases the wireless channel variation with high fidelity

- Eliminate caudal losses by tracking channel variation
- Standard compliant, but high performance gain (up to 56%)
Energy Efficient Wi-Fi
Introduction

- IEEE 802.11ac standard offers data rate as high as 6933 Mb/s
  
  - Higher order modulation: up to 256QAM
  - The number of spatial streams and antennas: up to 8
  - Channel bonding: up to 160 MHz

- WiFi is a primary energy consumer in battery-powered mobile devices
  
  - IEEE 802.11n 3x3 MIMO receiver consumes more energy than IEEE 802.11a receiver [1]
    
    - 2x in active mode
    - 1.5x in idle/listening (IL) mode.
    - More energy consumption in IEEE 802.11ac

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Background

- Time and energy spent in IDLE/CCA mode [2]
  - Real-world Wi-Fi traces
  - IDLE/CCA is the dominant source of energy consumption in Wi-Fi

Background

- IDLE/CCA mode power consumption in IEEE 802.11 [3, 4]

\[
P_{idle} = P_{mix} + P_{LNA} + P_{fil} + P_{amp} + P_{ADC}
\]

\[
P_{ADC} \propto \text{Bandwidth} \times N_{ANT}
\]

Measurement Environment

- **Network Interface Card (NIC)**
  - Qualcomm Atheros 9880 (QCA 9880)
  - IEEE 802.11ac
  - 3 x 3, 80 MHz, 256QAM

- **Device driver**
  - ath10k
  - 3.18.0 Linux kernel

- **Measurement tools**
  - NI USB-6218 Data Acquisition (DAQ)
  - PEX1-MINI-E Adaptor
  - Current sense resistors (40 mΩ)
  - External power source (Power Monitor)
  - LabVIEW
Measurement Result

- Power consumption of QCA 9880 in Idle mode
  - The power consumption highly depends on BW and $N_{\text{ANT}}$
  - Power consumption of 160 MHz is obtained from our model
Measurement Result

- Power consumption of QCA 9880 in RX mode
  - The power consumption highly depends on BW, MCS, and N\textsubscript{ANT}
WiZizz: Energy Efficient Bandwidth Management

WiZizz: Energy Efficient Bandwidth Management

- WiFi in Zizz (WiZizz)
  - Save the power consumption of STAs
  - More suited to portable devices than SMPS (e.g., Smartphone)
  - Key idea
    - Listen with the narrowest bandwidth (e.g., 20 MHz)
    - Transmit/receive data frames with a larger bandwidth (e.g., 160 MHz)
**WiZizz: Energy Efficient Bandwidth Management**

- **PHY-level Filtering**
  - WiZizz STAs can ignore 40/80/160 MHz PPDUs addressed to others
    - Bandwidth information in the preamble
    - Reduce RX mode power consumption

![Diagram showing energy saving and processes](image)
WiZizz: Energy Efficient Bandwidth Management

- Dynamic WiZizz
  - Switching delay \((D_{up}, D_{down}) < SIFS\)
  - Use RTS/CTS sequence to announce bandwidth switching and to set Network Allocation Vector (NAV)
  - 20 MHz duplicate frame
  - Upward switching condition
    - If switching overhead is relatively small compared to the frame duration
      \[ T_{RTS} + T_{CTS} + T_{data} (r_{80}) + T_{ack} + 3SIFS < T_{data} (r_{20}) + T_{ack} + SIFS \]
  - Downward switching condition
    - End of data packet reception

\[ T_{RTS} + T_{CTS} + T_{data} (r_{80}) + T_{ack} + 3SIFS < T_{data} (r_{20}) + T_{ack} + SIFS \]
WiZizz: Energy Efficient Bandwidth Management

- Dynamic WiZizz example

Upward switching condition

Network Allocation Vector (NAV)

Downward switching condition

BW of STA

Bandwidth

<table>
<thead>
<tr>
<th>RTS</th>
<th>RTS</th>
<th>RTS</th>
<th>RTS</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>20 MHz</th>
<th>Switch to 80 MHz</th>
<th>Switch to 20 MHz</th>
</tr>
</thead>
</table>

Time
WiZizz: Energy Efficient Bandwidth Management

- Delay in switching bandwidth
  - QCA 9880
  - Average over 15 runs

<table>
<thead>
<tr>
<th>BW</th>
<th>N\text{ANT}</th>
<th>Upward (D_{up})</th>
<th>Downward (D_{down})</th>
</tr>
</thead>
<tbody>
<tr>
<td>20→80</td>
<td>3</td>
<td>73.6 \mu s</td>
<td>48.53 \mu s</td>
</tr>
<tr>
<td>20→80</td>
<td>1</td>
<td>73.04 \mu s</td>
<td>45.07 \mu s</td>
</tr>
<tr>
<td>20→40</td>
<td>3</td>
<td>40.53 \mu s</td>
<td>22.67 \mu s</td>
</tr>
</tbody>
</table>
WiZizz: Energy Efficient Bandwidth Management

- **Pseudo-Dynamic WiZizz**
  - Can be readily implemented with current hardware
  - **Switching delay** \((D_{up}, D_{down}) > SIFS\)
  - Use action frame to announce bandwidth switching and to set NAV
  - Upward switching condition
    - If switching overhead is relatively small compared to the frame duration
      \[
      T_{action} + SIFS + T_{ack} + T_{data}(r_{80}) + D_{up} + D_{down} < T_{data}(r_{20})
      \]
  - Downward switching condition
    - Receives the WiZizz action frame addressed to it
    - Receives a frame addressed to others, its duration is longer than the switching delay
    - Receives a frame with the more data bit in the frame control field set to 0
WiZizz: Energy Efficient Bandwidth Management

- Pseudo-Dynamic WiZizz example

**Upward switching condition**

- Action
- Action
- Action
- Action

**DATA**

More Data = 0

**Downward switching condition**

- ACK

**Switch to 20 MHz**

- ACK
- ACK
- ACK

**Switch to 80 MHz**

- ACK
- ACK
- ACK

**Switch to 20 MHz**

- ACK

BW of STA

Time

Bandwidth

20 MHz
WiZizz: Energy Efficient Bandwidth Management

- Prototype and testbed experiments (QCA 9880)
  - Pseudo-dynamic WiZizz
  - Single node with various source rates
  - Multiple node environment
    * Saturated downlink traffic

![Graphs showing energy saving comparison between Baseline and WiZizz]

- Single node (80 MHz)
  - 25% energy saving

- Multiple node (80 MHz)
  - 55% energy saving
WiZizz: Energy Efficient Bandwidth Management

- **Simulation (ns-3)**
  - Dynamic WiZizz
  - Using measurement-based power model
    - Performance of 160 MHz bandwidth can be obtained
  - Saturated downlink traffic

**80 MHz**

- **57% energy saving**

**160 MHz**

- **73% energy saving**
Conclusion (1/2)

- Robust Wi-Fi in mobile environments
  - **MoFA**: Mobility-Aware Frame Aggregation in Wi-Fi
    - Standard-compliant adaptive frame aggregation control at transmitter
    - Prototyping using programmable **802.11n commercial device**
    - Open-source linux device driver: Ath9k / iwlwifi
  
  - **ChASER**: Channel-Aware Symbol Error Reduction
    - Eliminate caudal losses by tracking channel variation at receiver
    - Receiver architecture modification
    - Prototyping using Microsoft **Sora SDR platform**
Conclusion (2/2)

- Energy efficient Wi-Fi
  - Power consumption of Wi-Fi
    - IEEE 802.11n/ac consume more energy than IEEE 802.11a/b/g
    - Impact of wider channel bandwidth on the power consumption is significant

- **WiZizz**: Energy Efficient Bandwidth Management
  - Practical, standard-congenial bandwidth management
  - Achieve significant performance gain over the baseline 802.11ac
Do You Have any Questions?
Thank you for your attention!
References


Back-up slides
Impact of Mobility (1/2)

- Impact of modulation

  • MCS 4 / MCS 7 (using **amplitude modulation**) are highly susceptible to mobility

- Impact of 11n features

  • Spatial multiplexing (MCS 15) and channel bonding (BW 40) are highly affected by the mobility

  • STBC (2 X 1) does not alleviate the performance degradation
Impact of Mobility (2/2)

- Rate adaptation: *Minstrel*
  - Window-based rate adaptation algorithm
  
  - Achieving the maximum throughput at 2 ms aggregation time bound
  
  - **Malfunction** for large aggregation time bound due to high SFER for currently selected PHY rate
    - Undesirably using too high MCS index
    - Unnecessarily frequent MCS changes

> A-MPDU length adaptation will increase the accuracy of *Minstrel* rate selection
Measurement Result

- Power consumption of QCA 9880 in TX mode
  - The power consumption highly depends on $N_{\text{ANT}}$
  - $P_{\text{DAC}} \ll P_{\text{ADC}}$
Measurement Result

- Power consumption of QCA 9880 in TX mode
  - W.R.T TX power
Related Work

- **Spatial Multiplexing Power Save (SMPS)**
  - Save the power consumption of STAs
    - Static
      - Use a single antenna
    - Dynamic
      - Use a single antenna in IDLE/CCA mode
      - STA enables its additional antennas when it receives the start of a frame sequence (e.g., RTS) addressed to it

![Baseline SMPS Diagram](image)
Power Consumption Modeling

- RX/IDLE listening mode power consumption in 802.11ac [1]

\[ P_{rx} = (\alpha_1 N_{rx} + f(N_{ss}))BW + \alpha_2 N_{rx} + \alpha_3 r + P_f \]

\[ P_{idle} = i_1 N_{rx}BW + i_2 N_{rx} + P_f \]

\(BW\) : Bandwidth (MHz)

\(r\) : Data rate (Mb/s)

<table>
<thead>
<tr>
<th>OURS</th>
<th>(\alpha_1)</th>
<th>(\alpha_2)</th>
<th>(\alpha_3)</th>
<th>(f(N_{ss}))</th>
<th>(P_f)</th>
<th>(i_1)</th>
<th>(i_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IWL5300 (11n)</td>
<td>2.5</td>
<td>354</td>
<td>0.2</td>
<td>3.34</td>
<td>493.1</td>
<td>4.117</td>
<td>241.4</td>
</tr>
<tr>
<td>AR9380 (11n)</td>
<td>2.31</td>
<td>19.8</td>
<td>0.3</td>
<td>0.6</td>
<td>414.7</td>
<td>1.654</td>
<td>34.62</td>
</tr>
<tr>
<td>QCA9880 (11ac)</td>
<td>2.22</td>
<td>54.36</td>
<td>0.472</td>
<td>1.08</td>
<td>11.93</td>
<td>472.1</td>
<td>79.88</td>
</tr>
</tbody>
</table>

- Non-linear regression analysis in SPSS

- Average error rate is 0.329%