Fine-grained Channel Access in Wireless LAN

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Physical-layer data rate

- **PHY layer data rate in WLANs is increasing rapidly**
  - Wider channel widths and MIMO increases data rate
  - Latest ratified 802.11n standard has data rates up to 600Mbps
  - Data rates for future standards like 802.11ac & 802.11ad are expected to be > 1Gbps

- **However, throughput efficiency in WLANs is degrading**
  - senders with small amount of data still contend for whole channel
  - entire channel (single resource) allocated to a single sender
Inefficiency of 802.11 MAC

- DIFS: the minimum time a sender has to sense the channel idle before trying to transmit
- SIFS: the time for the sender to receive the ACK from the receiver
- Contention Window: used for the back-off mechanism
- Contention slot: useful time during which data is transmitted
- RTS/CTS are used for trying to solve the hidden terminal problem (optional and generally disabled)
Inefficiency of 802.11 MAC

- $t_{\text{slot}}$: sending time
- $t_{\text{sifs}}$: SIFS time
- $t_{\text{cca}}$: time to reliably sense a channel
- $t_{\text{TxRx}}$: time needed to change from rcv/snd mode & vice-versa
- $t_{\text{prop}}$: signal propagation time
- $t_{\text{preamble}}$: time for sending training symbols (channel estimation)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{\text{slot}}$</td>
<td>9$\mu$s</td>
</tr>
<tr>
<td>$t_{\text{sifs}}$</td>
<td>10–16$\mu$s</td>
</tr>
<tr>
<td>$t_{\text{cca}}$</td>
<td>4$\mu$s</td>
</tr>
<tr>
<td>$t_{\text{TxRx}}$</td>
<td>$\leq$ 5$\mu$s</td>
</tr>
<tr>
<td>$t_{\text{prop}}$</td>
<td>$\leq$ 1$\mu$s</td>
</tr>
<tr>
<td>$t_{\text{preamble}}$</td>
<td>20–56$\mu$s</td>
</tr>
</tbody>
</table>

Timing parameters of 802.11.
Inefficiency of 802.11 MAC

Efficiency formula (\( \eta \)) :

\[
\eta = \frac{t_{\text{data}}}{t_{\text{slot}} \cdot W + t_{\text{difs}} + t_{\text{preamble}} + t_{\text{sifs}} + t_{\text{ack}} + t_{\text{data}}} \]

- Only \( t_{\text{data}} \) is used for transmitting application data, the others times are overhead

- As PHY data rate increases, only \( t_{\text{data}} \) decreases proportionally while the overhead remains the same
Inefficiency of 802.11 MAC
Solving MAC inefficiency

- Frame aggregation: Transmitting larger frames decreases the inefficiency
  - What about low latency applications?
- Divide the channel in multiple subchannels
  - Senders can transmit simultaneously
  - One sender can transmit on more channels than the others
Solving MAC inefficiency

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OFDM

- Divide the available spectrum into many partially overlapping narrowband subcarriers
- Choose subcarrier frequencies so that they are orthogonal to one another, thereby cancelling cross-talk
- Thus, eliminating the need for guard bands
- Used in 802.11a/g/n, WiMax and other future standards
OFDM using iFFT/FFT

Transform from the frequency to the time domain and adding the cyclic prefix.

http://www.iet.unipi.it/f.giannetti/documenti/powerlines/Pow erLineCom/Bibliografia/Rif48.pdf
OFDM using iFFT/FFT

- Fast Fourier Transform
  - The sender applies Inverse FFT
    - $N$ number of subcarriers
    - $B$ is the width of the channel
    - Each subcarrier’s channel width = $B/N$
    - $f_c$ central frequency of the channel
    - Choose subcarriers central frequency:
      \[
      f_c + \frac{2\pi n B}{N}, \quad n = -\frac{N}{2} \ldots \left(\frac{N}{2} - 1\right)
      \]
  - The receiver applies FFT
Multiple-access using OFDM

- Time synchronisation is critical
- If nodes misalign, orthogonality will be lost and interference will occur
- Add a Cyclic-Prefix (CP) to guard against symbol misalignment
- In 802.11 the Cp-to-symbol length ratio is 1:4
- OFDMA is used in multiple-access cellular networks like WiMax and LTE but it requires tight timing synchronization with the cellular base station (order of nanoseconds)
- OFDMA is not suitable for WiFi
  - coordination in WLAN is distributed and decentralised
  - would require new hardware functionality beyond current 802.11
  - would add too much system complexity
Fine-grained Channel Access in WLAN

- OFDMA does not support random access
- Design a system OFDM like that allows random access
  - Split channel width into multiple subcarriers
  - A number of subcarriers form a sub-channel
  - Each subcarrier can use a different modulation scheme
  - Assign each sender a number of sub-channels according to their sending demands
  - Use a larger CP field to allow looser time constraints
  - Lengthen the OFDM symbol to maintain the 1:4 CP to Symbol ratio
  - Roughly synchronise senders by using the current 802.11 coordination mechanism
  - Apply OFDM on the whole channel to eliminate the need of guard bands
  - Revise the MAC contention mechanism used in 802.11
FICA – Basic Idea for uplink using 20-MHz channel

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- ACK for the packets are sent
FICA – PHY Architecture

- Handle the symbol timing misalignment
  - Use a long CP for M-RTS
  - Use a short CP for M-CTS, DATA, ACK
- Reduce the short CP overhead (keep 1:4 ratio)
  - Use longer OFDM symbol by applying a larger FFT size \( N \) (number of subcarriers)
  - \( N \) is constrained
    - By computational power
    - A large \( N \) will mean a larger number of subcarriers making it more sensitive to the frequency offset of different nodes
- \( N = 256 \) for 20 MHz channel
Frequency Domain Contention

- The entire channel is split into multiple subcarriers
- 16 data subcarriers + 1 pilot subcarrier form a sub-channel
- Each node contents for one or more channels by means of M-RTS/M-CTS
- M-RTS/M-CTS use simple binary amplitude modulation (BAM)
  - Receivers can simply detect BAM symbol by checking energy level (zero amplitude = 0 else 1)
- K subcarriers from each sub-channel form a contention band
Frequency Domain Contention

- Contending nodes randomly pick a subcarrier within the subchannel’s contention band and send a signal “1” using BAM
- The AP chooses a winner based on a predefined rule (eg. The subcarrier with highest center frequency wins) and sends an M-CTS back on the same subcarrier
- Receiving nodes know which subcarrier they used for contending and if a M-CTS is returned on the same subcarrier it means they won
- Winners wait SIFS and then start transmitting
Possible problems

- What if the nodes randomly pick the same subcarrier to send M-RTS?
- How many subcarriers should be used for contention purposes?
- Who is responsible for returning the M-CTS?
  - Single broadcast domain -> any node can do it
  - Reasonable for the receiver to do it
    - Hash(receiverID) between 0 and (m-1) to represent receiver information in M-RTS
Frequency domain backoff

- In a heavily-contended network, multiple senders can contend on the same subcarrier -> collisions
- We could limit the number of channels a sender can contend for
  - Pick up to \( n \) subchannels to contend for
    - \( n = \min(C_{\text{max}}, L_{\text{queue}}) \)
    - \( C_{\text{max}} \) decreases when collisions are detected
    - \( L_{\text{queue}} \) – the number of fragments in node’s sending queue
    - Mechanism similar to binary-exponential-backoff and additive increase/multiplicative decrease
Downlink access

- Uses the same M-RTS/M-CTS mechanism only this time the AP sends M-RTS
- The id of the receiver is encoded in the M-RTS
- Receiving clients return M-CTS to AP
- What if AP and node A have frames to exchange both ways
  - They could send the M-RTS simultaneously and this might cause a failure
Downlink Access

- Pick different DIFS for stations and AP
- The AP can use a shorter or longer DIFS compared to the stations DIFS
- Shorter DIFS gives priority because they cause sending the M-RTS earlier
- To ensure fairness between uplink & downlink
  - AP chooses a long DIFS after a short DIFS access of the channel
  - After an M-RTS is received, it will use a short DIFS for its next access
- AP has more chances to transmit (fairness?)
Discussion

- Hidden terminals problem
  - Carrier sensing is not useful thus M-RTS can collide
  - A sender can receive a mixture of two M-CTS
  - However, M-RTS/M-CTS are small therefore the collision chances are slim
- Backwards compatibility
  - FICA is still based on CSMA
Simulation

- Only collisions can cause frame reception failures
- Focus only on the uplink transmissions
- Apply various traffic patterns in a wide 40MHz channel with high data rates
- For 802.11n also simulate aggregation method
- For FICA, they used the same values for SIFS and DIFS as in 802.11
No aggregation

Efficiency ratio of 802.11 and FICA with different PHY data rates. No frame aggregation is enabled.
Full aggregation case. For 802.11, the maximal aggregated frame size is 28KB. All nodes are saturated.
Mixed traffic

Mixed traffic. Five nodes are fully saturated. All other nodes have delay-sensitive traffic with a uniform distribution between 800Kbps to 5Mbps.
Related Work

- FARA implements a OFDMA like system as well but there is only one transmitter (the AP) therefore the symbol alignment is not an issue.

- There is extensive work to improve 802.11 by fine-tuning the back-off scheme, however most of these approaches still consider the channel as one resource unit.
Future Work

- The fairness between nodes and APs
- Multi-user diversity in multi-channel
- Choosing the optimal frequency domain back-off strategy
- Ad-hoc network
Conclusion

- Current 802.11 MAC protocol are inefficient for high PHY data-rates
- Current MAC protocol allocates the whole channel as a single resource
- FICA addresses this problem by using fine-grained channel access
- An OFDM like approach eliminates the need of guard bands
- FICA employs a novel contention mechanism that uses physical layer RTS/CTS signalling
- In detailed simulation FICA outperformed 802.11n