COTA: Channel Occupancy Time Adaptation for LTE in Unlicensed Spectrum

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Growth of Mobile Data Traffic

2016: 7 EB/Month
2021: 49 EB/Month

Needs for Spectrum

Mobile Data Traffic

Licensed spectrum
Licensed spectrum
Unlicensed spectrum
Needs for Spectrum

3GPP Rel. 12 Carrier Aggregation

Licensed spectrum

Licensed spectrum

Unlicensed spectrum

3GPP Rel. 13 LAA (Licensed-Assisted-Access)
"Don’t worry! I’ll be a good neighbor!"
Definition of Good Neighbor \[1\]

- Not to impact Wi-Fi networks
  more than additional Wi-Fi network

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\[1\] 3GPP TR 36.889, “Study on licensed-assisted access to unlicensed spectrum (Release 13),” version 13.0.0, June 2015.
Definition of Good Neighbor [1]

- Not to impact Wi-Fi networks
  more than additional Wi-Fi network

To Be a Good Neighbor

- To guarantee fair airtime to Wi-Fi
  - Similar channel access mechanism
  - Similar continuous transmission time

<table>
<thead>
<tr>
<th></th>
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<th>LAA</th>
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<tr>
<td>1. Channel access mechanism</td>
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  - Similar channel access mechanism
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Similar Channel Access Mechanism

- **CSMA/CA of Wi-Fi**
  - Initial defer duration: 43 us
  - Slot duration: 9 us
  - Random backoff

- **Listen-Before-Talk (LBT) of LAA**
  - Initial defer duration: 43 us
  - Slot duration: 9 us
  - Random backoff
  - Reservation signal

![Diagram showing channel access mechanisms](image-url)
Different Continuous TX Time

- Wi-Fi A-MPDU aggregation limits

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- If the additional aggregation is limited by at least one of three limits  → Stop aggregation
## Different Continuous TX Time

### Wi-Fi A-MPDU aggregation limits

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### Data rate:

- **Data rate:** 6.5 Mb/s

### PLCP preamble:

- **1500 B**

### Timing:

- **9.3 ms**
- **7,500 bytes**
- **5 MPDUs**
Different Continuous TX Time

- **Wi-Fi A-MPDU aggregation limits**

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**PLCP preamble**

- 1500 B
- 1500 B
- 1500 B
- 1500 B

(Data rate: **130 Mb/s**)

- **4.0 ms**
- **64,500 bytes**
- **43 MPDUs**
Different Continuous TX Time

Channel occupancy time (COT) of LAA

- Maximum COT: 8 ms
- Longer COT $\rightarrow$ Smaller reservation signal (RS) overhead

- Not affected by transmission rate
<table>
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<th>LAA COT</th>
<th>Wi-Fi A-MPDU</th>
<th>LAA COT</th>
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<tr>
<td>4 ms</td>
<td>4 ms</td>
<td>4 ms</td>
<td>8 ms</td>
<td>8 ms</td>
<td>8 ms</td>
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- **Fair airtime**: Graphics showing equal share of airtime.
- **Unfair airtime**: Graphics showing unequal share of airtime.
- **Fair airtime**: Graphics showing equal share of airtime.
## COT Adaptation (COTA) Algorithm

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<td>4 ms</td>
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<td>8 ms</td>
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*Fair airtime*
COTA Utilizes Co-located Wi-Fi Module

- **Expected to include Wi-Fi module in practice**
  - Broadcom’s patent assumes to embed a Wi-Fi AP in an unlicensed LTE eNB [2]
  - According to recent demo, Qualcomm will do the same
  - Advantages
    - Carrier sensing instead of energy detection
    - Virtual carrier sensing

- **COTA observes A-MPDU frame info.**
  - Frame duration, byte length, MAC addr., etc.

Reservation Signal Overhead

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Up to 25%  
Up to 12.5%  
Up to 6.25%
COTA Detects Wi-Fi Saturation

- COTA decides to adapt COT to A-MPDU duration only if
  - Wi-Fi has more data to send (we call this by *saturation*)

- Fully aggregated A-MPDU → *Saturation detected* → Adjust COT
COTA Detects Wi-Fi Saturation

- COTA decides to adapt COT to A-MPDU duration only if
  - Wi-Fi has more data to send (we call this by saturation)

- Fully aggregated A-MPDU $\rightarrow$ **Saturation detected $\rightarrow$ Adjust COT**

- Not fully aggregated A-MPDU $\rightarrow$ **Saturation not detected** $\rightarrow$ Do not adjust COT
Saturation Detection

- Compare with 3 limits of A-MPDU frame aggregation

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- Maximum A-MPDU duration limit can be different by devices

- COTA can detect actual value of “maximum frame duration” limit of coexisting Wi-Fi devices (details in my paper)
  - Based on observed frame duration pattern
  - Without explicit signaling (no overhead, no Wi-Fi modification)
COT Adaptation (COTA) Algorithm

1. Observe Wi-Fi packets (# MPDUs, size, duration)

2. Saturation detection (SD):
   Fully aggregated A-MPDU → Wi-Fi TX node has more data to send → Saturation detected!

3. If SD = false → COT = 8 ms

4. If SD = true → COT = A-MPDU duration
ns-3 Simulation Settings

<table>
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<tr>
<th>Simulation settings</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Data Traffic</td>
<td>Full pumping UDP</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Wi-Fi PHY</td>
<td>802.11n, 2x2 MIMO</td>
</tr>
<tr>
<td>Wi-Fi rate adaptation</td>
<td>Minstrel HT</td>
</tr>
</tbody>
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- **LAA performance of unlicensed spectrum only**
  - For fair comparison with Wi-Fi
  - Both LAA and Wi-Fi use 20 MHz unlicensed spectrum
Simulation Result: Airtime

- **Coexist with LAA**
  - Short A-MPDU duration $\rightarrow$ Wi-Fi gets smaller airtime

- **Coexist with COTA**
  - Wi-Fi gets almost $\frac{1}{2}$ airtime regardless of A-MPDU duration

![Graph showing the fractional airtime ratio vs. Wi-Fi A-MPDU duration (ms)](image)
Simulation Result: Throughput

❖ Coexist with LAA
  - Short A-MPDU duration → Wi-Fi throughput decreases

❖ Coexist with COTA
  - Wi-Fi gets almost same throughput regardless of A-MPDU duration
Conclusion and Future Work

- Standard LAA cannot be a good neighbor
- COTA guarantees fair airtime to coexisting Wi-Fi by adjusting COT

Future work:
- Evaluation with multiple Wi-Fi TX nodes
- Hidden node problem
- Delay sensitive traffic (voice, video)
Thank you
To Be a Good Neighbor

- Unfair examples

1. Unfair channel access mechanism

2. Unfair continuous transmission time
Unfair Continuous TX Time

- Wi-Fi A-MPDU duration
  - Impacted by
    - TX rate (channel condition)
    - Maximum PPDU duration setting

- LAA Maximum Channel Occupancy Time (MCOT)
  - Fixed 8 ms
3GPP’s definition of Fairness [1]

- Fairness is the capability of an LAA network not to impact Wi-Fi networks active on a carrier more than an additional Wi-Fi network operating on the same carrier, in terms of both throughput and latency.

Similar Channel Access Mechanism

Listen-Before-Talk (LBT) of LAA

- Similar to Wi-Fi, except:
  1. Contention window ($CW$): {15, 31, 63}
  2. HARQ-ACK feedback based $CW$ adaptation
  3. -72 dBm energy detection threshold
  4. Maximum channel occupancy time: 8 ms
  5. Reservation signal
## Unfair Continuous TX Time

**Wi-Fi A-MPDU aggregation limits**

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<th>AR9380 NIC (802.11n device)</th>
<th>802.11ac Std.</th>
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<tbody>
<tr>
<td>Maximum PPDU duration (adjustable)</td>
<td>10 ms</td>
<td>4 ms</td>
<td>5.484 ms</td>
</tr>
<tr>
<td>Maximum PSDU length</td>
<td>65,535 bytes</td>
<td>65,535 bytes</td>
<td>4,692,480 bytes</td>
</tr>
<tr>
<td>BlockAck bitmap size</td>
<td>64</td>
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<td>64</td>
</tr>
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**LAA Maximum Channel Occupancy Time (MCOT)**

- 8 ms
- 10 ms (If the absence of other technology sharing the carrier can be guaranteed)
Maximum PPDU Duration Limit Detection

- Utilize PPDU duration patterns

- If PPDU duration is not limited by threshold
  - Longest PPDU duration cannot be consistent (even in CBR traffic case)
  - Other devices’ intermittent channel occupancy
  - Beacon transmission

- Only if longest PPDU duration is consistent
  - Longest PPDU duration \( \approx \) maximum PPDU duration
## Airtime Unfairness btw. LAA and Wi-Fi

### ns-3 simulation settings

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<td>2 s</td>
</tr>
<tr>
<td>Number of iterations</td>
<td>10</td>
</tr>
<tr>
<td>File size</td>
<td>0.5 MB</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Wi-Fi PHY</td>
<td>802.11n, 2×2 MIMO</td>
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<tr>
<td>Wi-Fi guard interval</td>
<td>800 ns</td>
</tr>
<tr>
<td>Wi-Fi maximum A-MPDU bound</td>
<td>2–10 ms, 65,535 bytes</td>
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<td>Wi-Fi rate adaptation</td>
<td>Minstrel HT</td>
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<tr>
<td>AP/eNodeB transmission power</td>
<td>23 dBm</td>
</tr>
<tr>
<td>STA/UE transmission power</td>
<td>18 dBm</td>
</tr>
<tr>
<td>Wi-Fi CS/CCA threshold</td>
<td>–82 dBm</td>
</tr>
<tr>
<td>Wi-Fi CCA-ED threshold</td>
<td>–62 dBm</td>
</tr>
<tr>
<td>LAA CCA-ED threshold</td>
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Shorter A-MPDU $\Rightarrow$ Poorer Wi-Fi thpt.

- Standard LAA is not a good neighbor!
Flowchart of COTA

Wi-Fi network interface

Wi-Fi frame

Saturation detection

LAA network interface

Use channel up to $COT_{next}$

COT decision

COTA algorithm
Unsaturated Wi-Fi Traffic Environment

![Graph showing throughput vs. Wi-Fi source rate for different scenarios.]
Bursty Wi-Fi Traffic Environment

(a) Instantaneous throughput trace.

(b) COT trace.