Modelling and Analysis of Wi-Fi and LAA Coexistence with Priority Classes

Anand M. Baswade*, Luca Beltramelliγ, Antony Franklin A*, Mikael Gidlundγ, Bheemarjuna Reddy Tamma*, and Lakshmikanth Guntupalliγ

*Indian Institute Technology Hyderabad, India
γMid Sweden University, Sundsvall, Sweden

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Outline

1 Introduction

2 Wi-Fi EDCA and LAA AC Coexistence Analytical Model

3 Performance Evaluation

4 Conclusions

5 References
Abbreviations

- LAA: Licensed Assisted Access
- LTE-U: Long Term Evolution in Unlicensed Spectrum
- AP: Access Point
- QoS: Quality of Service
- EDT: Energy Detection Threshold
- LBT: Listen-Before-Talk
- EDCA: Enhanced Distributed Channel Access
- DTMC: Discrete Time Markov Chain
- AC: Access Categories
- CCA: Clear Channel Assessment
Introduction

- The phenomenal growth in mobile data demand
- Limited and costly license spectrum
- One promising solution is to use unlicensed spectrum (LAA/LTE-U)
- Major challenge in unlicensed is fair coexistence with Wi-Fi

Figure 1: Growth in Mobile Traffic

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Reference: Cisco VNI, Mobile 2017

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## LTE MAC Vs Wi-Fi MAC

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Multiple access</strong></td>
<td>Multiple users served simultaneously, occupying different frequencies in channel</td>
<td>only 1 user is served at a time, takes up entire channel spectrum</td>
<td></td>
</tr>
<tr>
<td><strong>Channel usage</strong></td>
<td>Frames are contiguous, so channels are approximately always on</td>
<td>Channel is occupied only when packets needs to be transmitted</td>
<td></td>
</tr>
<tr>
<td><strong>Channel access</strong></td>
<td>Centralized scheduling on DL and UL. LTE does not contend, it simply transmits</td>
<td>Distributed Coordination Function (DCF), contention-based</td>
<td></td>
</tr>
<tr>
<td><strong>Collision avoidance</strong></td>
<td>None, b/c channel access are centrally scheduled</td>
<td>CSMA/CA + RTS/CTS (In principle, LBT)</td>
<td></td>
</tr>
<tr>
<td><strong>Co-existence</strong></td>
<td>Has not had the need to be able to coexist with other technologies</td>
<td>Already coexists well with other technologies in unlicensed band, although with no common fairness mechanism</td>
<td></td>
</tr>
</tbody>
</table>
LTE in Unlicensed: Channel Access Approaches

1. **LTE-U (Without LBT)**

2. **CSAT\(^3\) (Carrier Sensing Adaptive Transmission):** In countries USA, Korea, India LBT is not mandatory. So mobile operator can deploy LTE in unlicensed based on 3GPP Rel. 10/11/12 (Carrier Aggregation) with CSAT like channel access scheme without LBT.

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\(^3\) Reference: LTE in Unlicensed Spectrum: Harmonious Coexistence with Wi-Fi, Qualcomm white paper, 2014

\(^4\) Reference: 3GPP TR 36.889 Release 13
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2. **LAA**
   - **With LBT**: In Europe and Japan LBT is mandatory. So mobile operator has to follow LBT channel access scheme to use unlicensed band. In Rel 13 LTE in unlicensed with LBT for channel access is explained which is called LAA.

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3. Reference: LTE in Unlicensed Spectrum: Harmonious Coexistence with Wi-Fi, Qualcomm white paper, 2014
4. Reference: 3GPP TR 36.889 Release 13
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- EDCA is an extension of DCF protocol to support QoS.

- To prioritize the traffic, four types of Access Categories (ACs) are introduced in EDCA.

- Similar to EDCA, in LAA also we have ACs to support QoS.
## Wi-Fi ACs Vs LAA ACs

### Table 1: Wi-Fi EDCA Parameters

<table>
<thead>
<tr>
<th>Class</th>
<th>CW&lt;sub&gt;MIN&lt;/sub&gt;</th>
<th>CW&lt;sub&gt;MAX&lt;/sub&gt;</th>
<th>AIFSN</th>
<th>Retry Limit (M)</th>
<th>TXOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC[3]</td>
<td>BK</td>
<td>15</td>
<td>1023</td>
<td>7</td>
<td>7/4</td>
</tr>
<tr>
<td>AC[2]</td>
<td>BE</td>
<td>15</td>
<td>1023</td>
<td>3</td>
<td>7/4</td>
</tr>
<tr>
<td>AC[1]</td>
<td>VI</td>
<td>7</td>
<td>31</td>
<td>2</td>
<td>7/4</td>
</tr>
<tr>
<td>AC[0]</td>
<td>VO</td>
<td>3</td>
<td>15</td>
<td>2</td>
<td>7/4</td>
</tr>
</tbody>
</table>

### Table 2: LAA Downlink Channel Access Parameters

<table>
<thead>
<tr>
<th>Priority Class</th>
<th>CW&lt;sub&gt;MIN&lt;/sub&gt;</th>
<th>CW&lt;sub&gt;MAX&lt;/sub&gt;</th>
<th>m</th>
<th>Retry Limit at CW&lt;sub&gt;MAX&lt;/sub&gt;</th>
<th>Transmission Duration γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>15</td>
<td>1023</td>
<td>7</td>
<td>4</td>
<td>8 ms</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>63</td>
<td>3</td>
<td>4</td>
<td>8 ms</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>31</td>
<td>1</td>
<td>4</td>
<td>3 ms</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>15</td>
<td>1</td>
<td>4</td>
<td>2 ms</td>
</tr>
</tbody>
</table>
• It can be noted that there are few differences between LAA and Wi-Fi parameters.
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• Hence, we focus on the performance evaluation of EDCA and LAA priority classes.

• We propose a new mathematical model for LAA and Wi-Fi coexistence capable of describing the performance of eight priority classes in EDCA and LAA.
Contributions

- We provide an analytical framework to evaluate the throughput of coexisting LAA and Wi-Fi networks with traffic of different priority classes.
- The model captures the effects of transmission durations and message structure of LAA and Wi-Fi systems on the network throughput.
- We show that LAA is unfair with Wi-Fi in terms of throughput.
- We show that Wi-Fi throughput decreases when RTS/CTS is enabled for Wi-Fi, while LAA classes increase their throughput.
- Finally, to improve the fairness between Wi-Fi and LAA systems, we propose to reduce the LAA transmission opportunity.
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### Table 3: Notation used in the analytical model

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CW_{i,r}$</td>
<td>Contention window size</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Slot duration</td>
</tr>
<tr>
<td>$M_i$</td>
<td>Maximum retransmission attempts</td>
</tr>
<tr>
<td>$PC_i$</td>
<td>Collision probability</td>
</tr>
<tr>
<td>$PB_i$</td>
<td>Backoff countdown blocking probability</td>
</tr>
<tr>
<td>$b_{i,r,z}$</td>
<td>Steady state probability of $(i,r,z)$</td>
</tr>
<tr>
<td>$\tau_i$</td>
<td>Transmission Probability</td>
</tr>
</tbody>
</table>

**EDCA**
- AIFSN$_i$: Adaptive inter frame space number
- SIFS: Short inter frame space
- $n_w$: Number of Wi-Fi devices
- $N_i$: Number of Wi-Fi packets in a TXOP
- $T_{phy}$: Phy overhead transmission time
- $D_{mac}$: Size of MAC overhead
- $D_{ack}$: Size of ACK frame
- $D_{data}$: Size of data payload
- $BR$: Base transmission rate
- $DR$: Data transmission rate

**LAA**
- $n_l$: Number of LAA devices
- $\Gamma_i$: Duration of an LAA Class $i$ transmission
- $T_l$: Half of a LTE slot duration
- $T_{sframe}$: Duration of a LTE sub-frame
Assumptions

- Only downlink traffic from the eNB to the LAA users is present in the network;
- The channel is assumed to be ideal, i.e., packet loss is only caused by collisions;
- No frame capture effect at the receivers;
- All nodes (LAA eNB and Wi-Fi AP) are within the carrier sense range, i.e., there are no hidden nodes;
- Saturated traffic condition at all nodes;
- LAA and EDCA use the same slot time $\sigma$. 
Wi-Fi EDCA and LAA AC Coexistence Analytical Model

DTMC Model for Wi-Fi EDCA and LAA

Figure 2: DTMC model for Wi-Fi EDCA and LAA LBT.
We jointly solved the DTMC model for Wi-Fi and LAA to find the transmission probabilities of each ACs in Wi-Fi ($\tau_i^w$) and LAA ($\tau_i^l$).
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The transmission probabilities ($\tau_i^w$ and $\tau_i^l$) are function of backoff parameters, probabilities of collision ($PC$), probabilities of successful transmission ($PS$), and probability of an idle slot ($P_{idle}$).
Possible Events in a Slot

- **Idle Slot:**
  \[
P_{\text{idle}} = \left( 1 - \sum_{i=0}^{3} \tau_{i}^{w} \right)^{n_{w}} \left( 1 - \sum_{i=0}^{3} \tau_{i}^{l} \right)^{n_{l}}. \tag{1}
\]

- **Successful Transmission:**
  \[
  PS_{i}^{x} = n_{x} \tau_{i}^{x} \left( 1 - \sum_{k=0}^{3} \tau_{k}^{x} \right)^{n_{x}} \prod_{j \geq i} \left( 1 - \tau_{j}^{x} \right)^{n_{x}-1} \prod_{s<i} \left( 1 - \tau_{s}^{x} \right)^{n_{x}}. \tag{2}
  \]

- **Collision:** We identified four types of collisions each with different channel time duration. \( PC^{ww}, PC^{wl}, PC^{l_{i},l_{j}}, PC^{l_{i},l_{j}}. \)

- The transmission probabilities and the event probabilities form a non-linear system of equations which we solved using numerical methods.
The average duration of a contention slot $T_{cs}$ is calculated by multiplying the probability of each event by their channel occupancy as given below.

\[
T_{cs} = \sum_{i=0}^{3} PS_i^w \left( \min [AIFS_i] + T_s^w \cdot N_i - SIFS \right) \\
+ \sum_{k=0}^{3} \left( PS_k^l + PC_{wlk}^l + PC_{lk,lk}^l \right) \cdot (\Gamma_k + T_l) \\
+ \sum_{j=0}^{2} PC_{l3,lj} \cdot (\Gamma_3 + T_l) + \sum_{s=0}^{1} PC_{l2,ls} \cdot (\Gamma_2 + T_l) \\
+ PC_{l1,l0} \cdot (\Gamma_1 + T_l) + PC_{ww} \cdot T_{c,ww} + P_{idle} \sigma, \tag{3}
\]

where, $N_i$ is the number of Wi-Fi frames transmitted in the TXOP of traffic Class $i$; $T_s^w$ and $T_{c,ww}$ are respectively the time durations of a successful and colliding Wi-Fi transmissions, given by
\[ T_s^w = T_{phy} + \frac{D_{mac}}{BR} + \frac{D_{data}}{DR} + 2 \cdot \text{SIFS} + \frac{D_{ack}}{BR}; \]  
\[ T_{cw}^w = \min [\text{SIFS} + \sigma \text{AIFSN}_i] + T_{phy} + \frac{D_{mac}}{BR} \]
\[ \quad + \frac{D_{data}}{DR} + \text{ACK}_{\text{Timeout}}; \]

where \( T_{phy} \) is the physical layer overhead; \( D_{mac}, D_{data} \) and \( D_{ack} \) are respectively the size of the mac header, data payload, and ack frame; \( DR \) and \( BR \) are the data and base transmission rates.
Throughput of Wi-Fi and LAA in coexistence scenario

The throughput of Class $i$ of Wi-Fi is given by

$$T_{th_i}^w = \frac{PS_i^w N_i D_{data}}{T_{cs}}. \quad (6)$$

The throughput of LAA for Class $i$ is given by

$$T_{th_i}^l = \frac{13}{14} \frac{1}{T_{cs}} \left[ PS_i^l \Gamma_i + PC_i^{wl} (\Gamma_i - P_{fc} \cdot T_{sframe}) \right. \right.$$  

$$\left. + \sum_{k<i} PC_i^{li/k} (\Gamma_i - \Gamma_k) \right], \quad (7)$$

where $T_{sframe}$ is the duration of an LTE sub-frame, and $P_{fc}$ is the probability that a Wi-Fi transmission causes the first sub-frame to be lost.
For this, the following aspects of the model need to be modified:

1. The maximum number of retransmissions ($M_i$) for all Wi-Fi classes is increased to 7;
2. $P_{fc}$, the probability that a collision between Wi-Fi and LAA occurs before the beginning of an LAA slot is equal to the ratio of a RTS frame transmission time and an LTE slot time (0.5 ms).
3. The expressions for $T_{ww}^C$ and $T_E$ are given by (8) and (9);
\[ T_{c_{ww}} = \min \left[ \text{SIFS} + \sigma AIFS N_i \right] + T_{\text{phy}} + \frac{D_{\text{rts}}}{BR} + \text{RTS}_{\text{Timeout}}. \quad (8) \]

\[ T_E = \sum_{i=0}^{3} PS^w_i \cdot \left( \min \left[ \text{SIFS} + \sigma AIFS N_i \right] + T_{\text{phy}} + \frac{D_{\text{rts}}}{BR} + \text{SIFS} + T_{\text{phy}} + \frac{D_{\text{cts}}}{BR} + T^w_s \cdot N_i - \text{SIFS} \right) \]

\[ + \sum_{k=0}^{3} \left( PS^l_k + PC^{wl_k} + PC^{l_k l_k} \right) \cdot (\Gamma_k + T_l) \]

\[ + \sum_{j=0}^{2} PC^{l_3 l_j} (\Gamma_3 + T_l) + \sum_{r=0}^{1} PC^{l_2 l_r} \cdot (\Gamma_2 + T_l) \]

\[ + PC^{l_1 l_0} (\Gamma_1 + T_l) + PC^{ww} \cdot T^c_{ww} + P_{\text{idle}} \sigma. \quad (9) \]
## Performance Evaluation

### Table 4: Wi-Fi & LAA Parameters

<table>
<thead>
<tr>
<th>Wi-Fi parameters</th>
<th>Value</th>
<th>LAA Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>$DR, BR$</td>
<td>54 Mbps, 6 Mbps</td>
<td>Data Rate</td>
<td>70.2 Mbps</td>
</tr>
<tr>
<td>$\sigma, SIFS$</td>
<td>9 $\mu$s, 16 $\mu$s</td>
<td>$\sigma$</td>
<td>9 $\mu$s</td>
</tr>
<tr>
<td>$D_{ack}, D_{mac}$</td>
<td>112, 272 bits</td>
<td>$T_f$</td>
<td>16 $\mu$s</td>
</tr>
<tr>
<td>$T_{phy}, ACK_{Timeout}$</td>
<td>20 $\mu$s, 50 $\mu$s</td>
<td>$T_{sframe}$</td>
<td>1 ms</td>
</tr>
<tr>
<td>$D_{data}$</td>
<td>1470 bytes</td>
<td>$T_l$</td>
<td>0.25 ms</td>
</tr>
</tbody>
</table>
(a) Collision probability of LAA and Wi-Fi.

(b) Throughput for Each Priority Class.

**Figure 3**: LAA and Wi-Fi coexistence performance with priority classes, $n_w = n_l = N/2$, where $N$ is the total number of nodes in the network.
Figure 4: LAA and Wi-Fi coexistence performance with RTS/CTS enabled, \( n_w = n_l = N/2 \), where \( N \) is the total number of nodes in the network.

(a) Collision prob. of LAA and Wi-Fi.  
(b) Throughput for each priority class.
Performance Evaluation with Reduced TXOP

(a) Throughput without RTS/CTS.

(b) Throughput with RTS/CTS.

Figure 5: Wi-Fi and Total Throughput (i.e., Wi-Fi + LAA) in Wi-Fi only scenario (WW) and coexistence scenario (LW).
Figure 6: Wi-Fi and LAA Fairness.
Conclusions

- We have proposed a mathematical model to study the coexistence between Wi-Fi and LAA.
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- The model allows to calculate throughput of each of the four priority classes defined in LAA and Wi-Fi.
- The results show that though the backoff parameters are similar, LAA is unfair with Wi-Fi.
- The major reason behind this is the different channel access durations of LAA and Wi-Fi. Further, the collisions can still allow LAA to successfully deliver part of the transmitted frame but Wi-Fi transmission would fail completely.
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- In future, the proposed model can be easily extended to hidden terminal case, unsaturated traffic case.
References

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Performance analysis of the IEEE 802.11 distributed coordination function

A simple but accurate throughput model for IEEE 802.11 EDCA in saturation and non-saturation conditions

On the Fairness of Wi-Fi and LTE-LAA Coexistence

Performance evaluation of LAA-LBT based LTE and WLANs co-existence in unlicensed spectrum

Downlink performance analysis of LTE and WiFi coexistence in unlicensed bands with a simple listen-before-talk scheme
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Queries

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<thead>
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<th>Website</th>
</tr>
</thead>
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<td>+91 8788988269</td>
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Thank you!