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

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Outline

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

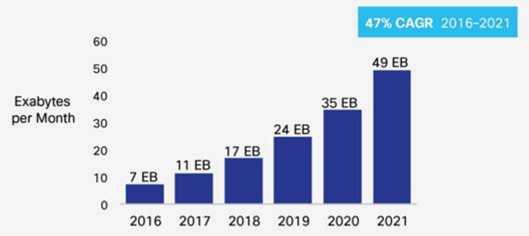

Figure 1 : Growth in Mobile Traffic[1]

[1] Reference: Cisco VNI, Mobile 2017

LTE MAC Vs Wi-Fi MAC

	LTE	Wi-Fi
Multiple access[2]	Multiple users served simultaneously, occupying different frequencies in channel	only 1 user is served at a time, takes up entire channel spectrum
Channel usage	Frames are contiguous, so channels are approximately always on	Channel is occupied only when packets needs to be transmitted
Channel access	Centralized scheduling on DL and UL. LTE does not contend, it simply transmits	Distributed Coordination Function (DCF), contention-based
Collision avoidance	None, b/c channel access are centrally scheduled	CSMA/CA + RTS/CTS (In principle, LBT)
Co-existence	Has not had the need to be able to coexist with other technologies	Already coexists well with other technologies in unlicensed band, although with no common fairness mechanism

[2] Reference: On the Impact of LTE-U on Wi-Fi Performance, International Journal of Wireless Information Networks, 2015

LTE in Unlicensed: Channel Access Approaches

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

[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
   1. **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[4].

[3] Reference: LTE in Unlicensed Spectrum:Harmonious Coexistence with Wi-Fi, Qualcomm white paper,2014

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- EDCA is a extension of DCF protocol to support QoS.
- To priorities the traffic four type 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

	Class	CW^{MIN}	CW^{MAX}	AIFSN	Retry Limit (M)	TXOP
AC[3]	BK	15	1023	7	7/4	1 frame
AC[2]	BE	15	1023	3	7/4	1 frame
AC[1]	VI	7	31	2	7/4	3.008 ms
AC[0]	VO	3	15	2	7/4	1.504 ms

Table 2 : LAA Downlink Channel Access Parameters

Priority Class	CW^{MIN}	CW^{MAX}	m	Retry Limit at CW^{MAX}	Transmission Duration Γ
4	15	1023	7	4	8 ms
3	15	63	3	4	8 ms
2	7	31	1	4	3 ms
1	3	15	1	4	2 ms

Cont..

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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

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- We show that Wi-Fi throughput decreases when RTS/CTS is enabled for Wi-Fi, while LAA classes increase their throughput.

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- 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.

Wi-Fi EDCA and LAA AC Coexistence Analytical Model

Table 3 : Notation used in the analytical model

Notation	Description
$CW_{i,r}$	Contention window size
σ	Slot duration
M_i	Maximum retransmission attempts
PC_i	Collision probability
PB_i	Backoff countdown blocking probability
$b_{i,r,z}$	Steady state probability of (i,r,z)
τ_i	Transmission Probability
	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
Γ_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 σ.

DTMC Model for Wi-Fi EDCA and LAA

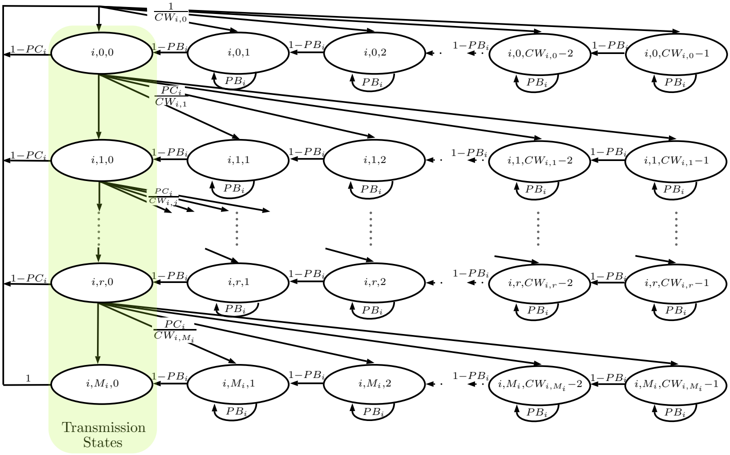

Figure 2 : DTMC model for Wi-Fi EDCA and LAA LBT.

Cont..

- We jointly solved the DTMC model for Wi-Fi and LAA to find the transmission probabilities of each ACs in Wi-Fi (τ_i^w) and LAA (τ_i^l).

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- The transmission probabilities (τ_i^w and τ_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:

$$P_{\text{idle}} = \left(1 - \sum_{i=0}^{3} \tau_i^w\right)^{n_w} \left(1 - \sum_{i=0}^{3} \tau_i^l\right)^{n_l}. \quad (1)$$

- Successful Transmission:

$$PS_i^x = n_x \tau_i^x \left(1 - \sum_{k=0}^{3} \tau_k^{\overline{x}}\right)^{n_{\overline{x}}} \prod_{j \geq i} \left(1 - \tau_j^x\right)^{n_x - 1} \prod_{s<i} \left(1 - \tau_s^x\right)^{n_x}. \quad (2)$$

- Collision: We identified four type of collisions each with different channel time duration. PC^{ww}, PC^{wl}, PC^{l_i,l_i}, 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.

Average Duration of Contention Slot

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.

$$\begin{aligned} T_{cs} = & \sum_{i=0}^{3} PS_i^w \left(min\left[\text{AIFS}_i\right] + T_s^w \cdot N_i - SIFS \right) \\ & + \sum_{k=0}^{3} \left(PS_k^l + PC^{wl_k} + PC^{l_k l_k} \right) \cdot (\Gamma_k + T_l) \\ & + \sum_{j=0}^{2} PC^{l_3 l_j} \cdot (\Gamma_3 + T_l) + \sum_{s=0}^{1} PC^{l_2 l_s} \cdot (\Gamma_2 + T_l) \\ & + PC^{l_1 l_0} \cdot (\Gamma_1 + T_l) + PC^{ww} \cdot T_c^{ww} + P_{\text{idle}}\sigma, \end{aligned} \quad (3)$$

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

Cont..

$$T_s^w = T_{phy} + \frac{D_{\text{mac}}}{BR} + \frac{D_{\text{data}}}{DR} + 2 \cdot \text{SIFS} + \frac{D_{\text{ack}}}{BR}; \quad (4)$$

$$T_c^{ww} = min\left[\text{SIFS} + \sigma \text{AIFSN}_i\right] + T_{phy} + \frac{D_{\text{mac}}}{BR} + \frac{D_{\text{data}}}{DR} + \text{ACK}_{\text{Timeout}}; \quad (5)$$

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

$$Th_i^w = \frac{PS_i^w N_i \frac{D_{\text{data}}}{DR}}{T_{\text{cs}}}. \tag{6}$$

The throughput of LAA for Class i is given by

$$\begin{aligned} Th_i^l \quad = \quad & \frac{13}{14}\frac{1}{T_{\text{cs}}}\Bigg[PS_i^l \Gamma_i + PC_i^{wl}(\Gamma_i - P_{\text{fc}} \cdot T_{\text{sframe}}) \\ & + \sum_{k<i} PC^{l_i l_k}(\Gamma_i - \Gamma_k)\Bigg], \end{aligned} \tag{7}$$

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.

Extension to Wi-Fi with RTS/CTS

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_c^{ww} and T_E are given by (8) and (9);

Cont..

$$T_c^{ww} = min\left[\text{SIFS} + \sigma \text{AIFSN}_i\right] + T_{phy} + \frac{D_{\text{rts}}}{BR} + \text{RTS}_{\text{Timeout}}. \quad (8)$$

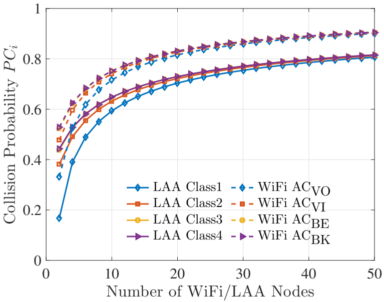
$$\begin{aligned} T_E = & \sum_{i=0}^{3} PS_i^w \cdot \Big(min\left[\text{SIFS} + \sigma \text{AIFSN}_i\right] + T_{phy} \\ & + \frac{D_{rts}}{BR} + \text{SIFS} + T_{phy} + \frac{D_{cts}}{BR} + T_s^w \cdot N_i - \text{SIFS} \Big) \\ & + \sum_{k=0}^{3} \left(PS_k^l + PC^{wl_k} + PC^{l_k l_k} \right) \cdot (\Gamma_k + T_l) \\ & + \sum_{j=0}^{2} PC^{l_3 l_j} (\Gamma_3 + T_l) + \sum_{r=0}^{1} PC^{l_2 l_r} \cdot (\Gamma_2 + T_l) \\ & + PC^{l_1 l_0} (\Gamma_1 + T_l) + PC^{ww} \cdot T_c^{ww} + P_{idle}\sigma. \end{aligned} \quad (9)$$

Performance Evaluation

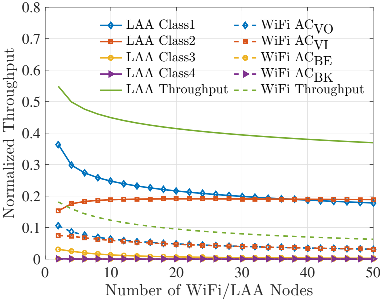
Table 4 : Wi-Fi & LAA Parameters

Wi-Fi parameters		**LAA Parameters**	
Parameter	**Value**	**Parameter**	**Value**
DR, BR	54 Mbps, 6 Mbps	Data Rate	70.2 Mbps
σ, SIFS	9 μs, 16 μs	σ	9 μs
D_{ack}, D_{mac}	112, 272 bits	T_f	16 μs
T_{phy}, $\text{ACK}_{\text{Timeout}}$	20 μs, 50 μs	T_{sframe}	1 ms
D_{data}	1470 bytes	T_l	0.25 ms

Performance Evaluation



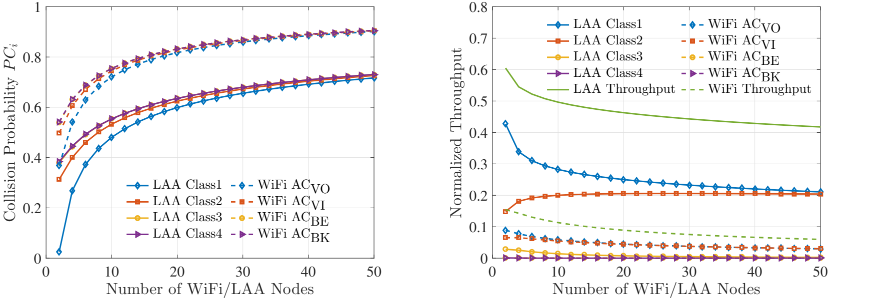
(a) Collision probability of LAA and Wi-Fi.



(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.

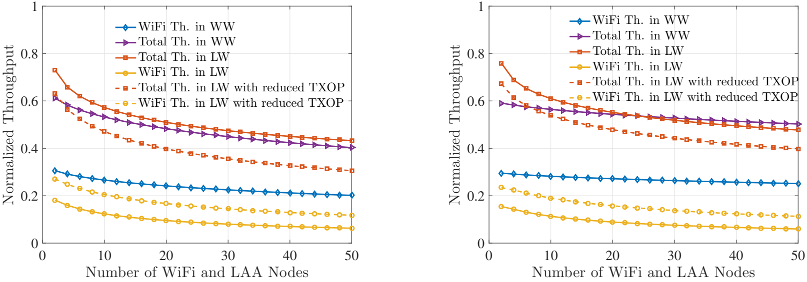
Performance Evaluation with RTS/CTS



(a) Collision prob. of LAA and Wi-Fi. (b) Throughput for each priority class.

Figure 4 : LAA and Wi-Fi coexistence performance with RTS/CTS enabled, $n_w = n_l = \mathrm{N}/2$, where N is the total number of nodes in the network.

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).

Performance Evaluation (Fairness)

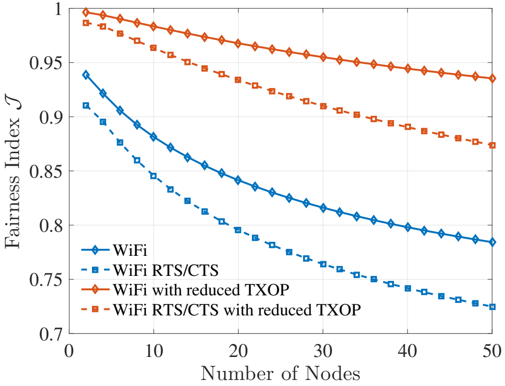


Figure 6 : Wi-Fi and LAA Fairness.

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- In future, the proposed model can be easily extended to hidden terminal case, unsaturated traffic case.

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Thank you!