2019 IEEE 4th International Conference on Signal and Image Processing

Markov Chain Based Performance Analysis of LAA and WiFi Coexistence in Dual Carrier Aggregation

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***Abstract*—License Assisted Access (LAA) is a feature in 3GPP Rel-13 which is the global standard for LTE deployment in the unlicensed band. While the availability of large amount of extra spectrum in unlicensed band is always desirable, the coexistence of LAA and WiFi with an acceptable fairness is a primary challenge. This paper extends the Markov Chain based performance analysis of LTE-WiFi coexistence for a single-carrier contention to a dual-carrier contention for WiFi-Only, LAA-Only and finally WiFi-LAA coexistence. A dual-carrier aggregation allows us to aggregate the secondary channel onto the primary channel when the secondary channel is free before transmission. In this paper, throughput and airtime performance in this dual-carrier aggregation is studied and compared with single-carrier case for different number of WiFi and LTE stations.**

Keywords-license-assisted access; throughput; channel occupancy time; coexistence; dual-carrier aggregation

I. Introduction

Approaches to increase spectrum resources in cellular networks are always needed to fulfill the exponentially ever increasing data traffic growth. However, the reliable licensed spectrum is a limited resource and therefore the opportunity to utilize available unlicensed spectrum should be further explored. LTE-LAA (LTE-Licensed Assisted Access) is a feature of Rel-13 in 3GPP [1] which uses carrier aggregation in the downlink to combine LTE in unlicensed spectrum (5 GHz) with LTE in the licensed band.

WiFi, an established system currently operating in unlicensed band, uses contention-based Carrier Sensing Multiple Access (CSMA) protocol. Listen Before Talk (LBT) scheme with category (Cat)2, 3, 4 [2] are the global standard for LTE-LAA channel sensing and have been mandated in many parts of the world. LAA-Cat4 LBT mechanisms is very similar to the distributed coordination function (DCF) of WiFi for channel access.

There exist many studies of coexistence effects on WiFi performance based on simulations [3], test-beds [4] and stochastic geometry frameworks [5]. In addition to these works the analytical framework based on Markov-chain steady-state analysis provides a complete mathematical description of access mechanism and is an important tool to calculate throughput achieved by each system. The analysis is based on [6]. Extension of such analysis for LAA and WiFi has been done in [7]. However, the analysis done in previous studies are all based on availability of a single channel for contention. Even though a multi-carrier channel access for WiFi IEEE 802.11ac for a hierarchical channel bonding scheme [8] exists, there is not much work done for the case of contention in multiple channels. It is necessary to understand the performance in throughput and the airtime when multiple channels are utilized.

In this paper, we analyze the performance in terms of throughput and airtime (fraction of successful transmission period with respect to total period of no transmission, successful transmission and collision) using single and dual-carrier in a WiFi-Only, LAA-Only and WiFi-LAA coexistence system. Thus the main purpose of the paper is to extend Markov Chain model based performance analysis on a single-carrier [9] to a dual-carrier case for WiFi-Only, LAA-Only and finally WiFi-LAA coexistence scenario. The paper investigates the performance of throughput and airtime when systems use secondary channel whenever possible in addition to the primary channel. This is achieved by analyzing the coupling of LAA and WiFi Markov Chains to evaluate the channel access probabilities, and combining the channel time duration obtained from the standard specifications.

This paper is organized as follows. The Markov Chain based system models for a single-carrier for WiFi-Only, LAA-Only and WiFi-LAA systems are introduced in Section II with the analysis of throughput and airtime of the systems. The Markov Chain model and the analysis for the dual-carrier case for all the systems are addressed in Section III. Numerical results of comparison between the single and dual-carrier cases are summarized in Section IV and finally the conclusion is provided in Section V.

II. System Model: Single Carrier Case

Table I lists the symbols used in the Markov Chain model for a single-carrier WiFi and LAA. In the table, the probabilities for idle, successful and collision events will be obtained from the steady-state analysis of the Markov Chain model and time duration for those events will be determined by the specifications of system parameters presented in Table II. From these two types of information, throughput and airtime will be finally calculated.

A. Markov Chain and Steady State Analysis

A scenario where W number of WiFi Access Points (APs) share a channel in unlicensed bands is considered. WiFi single-carrier Markov Chain model as shown in Fig. 1 is studied in [9]. The transmission probability that an AP transmits in a randomly chosen slot time, P_t^w is given by (1).

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TABLE I. NOTATION DEFINITIONS: SINGLE CARRIERSYSTEM PARAMETERS

q	Probability of packet availability for transmission
W_0^l (or W_0^w)	Initial contention window length of LAA (or WiFi)
$m = m^l = m^w$	Contention stages of LAA, WiFi
W_m^l(or W_m^w)	Max contention window length of LAA (or WiFi)
p_f^l (or p_f^w)	Channel failure probability for LAA (or WiFi)
P_t^l (or P_t^w)	Probability an eNB (or WiFi) transmits in a randomly chosen slot time
P_I	Probability the channel is idle
P_s^l (or P_s^w)	Probability an eNB (or WiFi) successfully transmits
P_c^l (or P_c^w)	Probability of collision within eNBs (or WiFis)
P_c^{wl}	Probability of collision between eNB and WiFi
T_s^l (or T_s^w)	Average time for successful transmission
T_c^l (or T_c^w)	Average time for collision within eNBs (or WiFis)
T_c^{wl}	Average time for collision between eNB and WiFi
σ	Average time for no transmission in a slot time
S^l (or S^w)	Throughput of LAA (or WiFi)
A^l (or A^w)	Airtime of LAA (or WiFi)

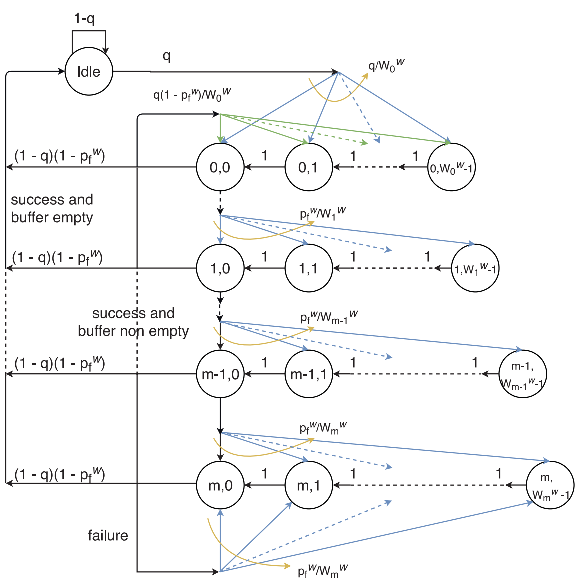

Figure1: WiFi-DCF Markov Chain single-carrier

$$P_t^w = \sum_{k=0}^{m} \pi_{k,0} = \frac{2q(1-2P_f^w)}{D_1 + D_2} \tag{1}$$

where

$$D_1 = 2(1-q)(1-P_f^w)(1-2P_f^w)$$

$$D_2 = q[(W_0^w + 1)(1-2P_f^w) + W_0^w P_f^w (1-(2P_f^w)^m)]$$

Assuming there is no hidden node problem, the transmission failure probability for WiFi p_f^w is calculated as

$$p_f^w = 1 - (1 - P_t^w)^{W-1} \tag{2}$$

Once the transmission probability of WiFi P_t^w is obtained, the corresponding probability for single-carrier channel being in Idle P_I, successful transmission P_s^w, collision within WiFi P_c^w can be calculated from (3).

$$\begin{cases} P_I = (1-P_t^w)^W \\ P_s^w = W \cdot P_t^w (1-P_t^w)^{W-1} \\ P_c^w = 1 - P_I - P_s^w \end{cases} \tag{3}$$

B. Performance Analysis of WiFi-Only

The total average event time duration considering all the possible events of no transmission i.e. idle, successful transmission and collision is calculated as

$$\begin{cases} E[T] = P_I\sigma + P_s^w T_s^w + P_c^w T_c^w \\ T_s^w = (H + E[Z^w])/R^w + \delta + SIFS + ACK/R^w + DIFS + \delta \\ T_c^w = (H + E[Z^w])/R^w + \delta + DIFS \end{cases} \tag{4}$$

where, SIFS is the short inter-frame space, DIFS is the DCF inter-frame space, H is the size of the MAC + PHY header, $E[Z^w]$ is the packet size and ACK is the size of acknowledgment frame. Even though a bonding scheme for carrier aggregation is based on 802.11ac, specifications from 802.11n are used for fair comparison between equivalent systems. The highest possible data rates of 144.4 Mbps for 2x2 MIMO 20 MHz (single-carrier) and 300 Mbps for 2x2 MIMO 40 MHz (dual-carrier) are considered under best channel conditions.

TABLE II. SYSTEM PARAMETERS

Packet Size, $E[Z^w] = E[Z^l]$	12800 bits
MAC header	272 bits
PHY header	128 bits
ACK	112 bits + PHY header
WiFi Mode	802.11n (Single Carrier: 2x2 20 MHz) (Dual Carrier: 2x2 40 MHz)
Wi-Fi Bit Rate, R^{w1}	144.4 Mbps, one channel
Wi-Fi Bit Rate, R^{w12}	300 Mbps, two channels
LAA Mode	(Single Carrier: Class-4 20 MHz) (Dual Carrier: Class-7 40 MHz)
LAA Bit Rate, R^{l1}, R^{l12}	150, 300 Mbps
Slot Time σ	9 μs
SIFS	16 μs
DIFS	34 μs
Propagation Delay, δ	1 μs
Initial CW size Wi-Fi W_0	16
CW Stages Wi-Fi, LAA m	5

System throughput and airtime for WiFi single-carrier is calculated from (5) with fully saturated traffic ($q = 1$), where $E[Z^w]$ denotes the average packet size for WiFi. The effects of various q on WiFi performance is similar to that of LTE and is studied in [9].

$$S^w = \frac{P_s^w E[Z^w])}{E[T]} \quad , \quad A^w = \frac{P_s^w T_s^w}{E[T]} \tag{5}$$

C. LAA-Only and WiFi-LAA System

LBT-Cat4 is a channel access mechanism for LAA very similar to DCF of WiFi. Like WiFi, LBT-Cat4 enforces the exponential backoff with various contention stages. For LAA-Only, the Markov Chain model and state equations are similar to that of WiFi-Only [7], therefore the throughput and airtime can be calculated similarly. The only difference is that the time duration are different due to change in the system parameters for LAA.

For WiFi-LAA, individual Markov Chain models for WiFi and LAA do not change but further coupling between LAA and WiFi systems have to be taken into consideration. A scenario where L number of LAAs and W number of WiFi

APs coexisting in a single channel is considered. For a single-carrier contention, the channel probabilities similar to (3) are modified to (6) and channel failure probabilities similar to (2) are modified to (7) to incorporating LAA and WiFi.

$$\begin{cases} P_I = (1-P_t^w)^W(1-P_t^l)^L \\ P_s^w = W \cdot P_t^w(1-P_t^w)^{W-1}(1-P_t^l)^L \\ P_s^l = L \cdot P_t^l(1-P_t^l)^{L-1}(1-P_t^w)^W \\ P_c^w = (1-P_t^l)^L(1-(1-P_t^w)^W - W \cdot P_t^w(1-P_t^w)^{W-1}) \\ P_c^l = (1-P_t^w)^W(1-(1-P_t^l)^L - L \cdot P_t^l(1-P_t^l)^{L-1}) \\ P_c^{wl} = 1 - P_I - P_s^w - P_s^l - P_c^w - P_c^l \end{cases} \tag{6}$$

$$\begin{cases} p_f^l = 1-(1-P_t^l)^{L-1}(1-P_t^w)^W \\ p_f^w = 1-(1-P_t^w)^{W-1}(1-P_t^l)^L \end{cases} \tag{7}$$

The throughput and airtime can then be calculated from (8)

$$S^w = \frac{P_s^w E[Z^w]}{E[T]},\ S^l = \frac{P_s^l E[Z^l]}{E[T]},\ A^w = \frac{P_s^w T_s^w}{E[T]},\ A^l = \frac{P_s^l T_s^l}{E[T]} \tag{8}$$

where the total average time period $E[T]$ is calculated as

$$E[T] = P_I\sigma + P_s^w T_s^w + P_s^l T_s^l + P_c^w T_c^w + P_c^l T_c^l + P_c^{wl} T_c^{wl}$$

with $T_c^{wl} = max(T_c^w, T_c^l)$.

III. System Model: Dual Carrier Case

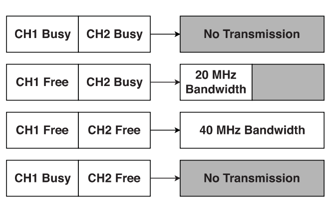

Figure2: Carrier Aggregation Mechanism

The multi-carrier channel access for WiFi IEEE 802.11ac for a hierarchical channel bonding scheme [8] enables a channel aggregation mechanism for WiFi system and hence provides a motivation for extending a single-carrier to a dual-carrier Markov Chain model. In this mechanism, only lower adjacent channel is used as a secondary channel. As shown in Fig. 2, no transmission occurs when primary channel is busy. The WiFi system cannot use only secondary channel to transmit the data. However when the primary channel is free, the system senses the secondary channel and if it is busy, system transmits only in the primary channel at 20 MHz bandwidth. If the secondary channel is also free, the system aggregates both primary and secondary channel into a single 40 MHz channel and transmits in the aggregated channel.

Table III lists the symbols used in the Markov Chain model for a dual-carrier WiFi. The process of performance evaluation is similar to that of the single-carrier.

TABLE III. Notation Definitions: Dual Carrier

p_{f1}^l (or p_{f1}^w), p_{f2}^l (or p_{f2}^w)	Channel failure probability for LAA (or WiFi) in primary, secondary channel
P_t^l (or P_t^w)	Probability an eNB (or WiFi) transmits in a randomly chosen slot time in primary channel
P_{I1}, P_{I12}	Probability only one, both channels are idle
P_s^{l1} (or P_s^{w1}), P_s^{l12} (or P_s^{w12}	Probability an eNB (or WiFi) successfully transmits in one, both channels
P_c^{l1} (or P_c^{w1}), P_c^{l12} (or P_c^{w12})	Probability of collision within eNBs (or WiFis) in one, both channels
P_c^{wl1}, P_c^{wl12}	Probability of collision between eNB and WiFi in one, both channels
T_s^{l1} (or T_s^{w1}), T_s^{l12} (or T_s^{w12})	Average time duration for successful transmission in one, both channels
T_c^{l1} (or T_c^{w1}), T_c^{l12} (or T_c^{w12})	Average time duration for collision within eNBs (or WiFis) in one, both channels
T_c^{wl1}, T_c^{wl12}	Average time duration for collision between eNB and WiFi in one, both channels
σ	Average time duration for no tx in a slot time
S_a^l (or S_a^w)	Aggregated Throughput of LAA (or WiFi)
A_a^l (or A_a^w)	Airtime of LAA (or WiFi)

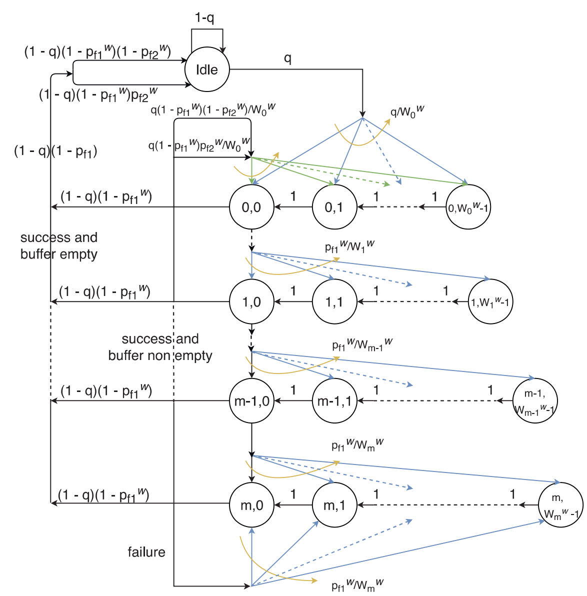

Figure3: WiFi-DCF Markov Chain for dual carrier

A. Markov Chain and Steady State Analysis

Similar as before, Markov Chain model for WiFi-Only is discussed for dual-carrier and then extended for other systems. A scenario is considered where W number of WiFi APs contend on primary channel and different W number of WiFi APs on secondary channel in unlicensed bands. The Markov Chain model for WiFi dual-channel is shown in Fig. 3. This Markov Chain is for the primary channel. In this model, the success branch both in buffer empty and non-empty case is split into two components: one that uses only single-carrier at 20 MHz bandwidth and the other that uses both channels at 40 MHz aggregated bandwidth. Usually this can be merged into a single probability but the two components are explicitly shown for proper understanding single and dual-carrier case. The steady state equations do not change since we assume channel access probability in both channels are independent. Once the transmission probability of WiFi is obtained, the corresponding channel probabilities are calculated from (9).

$$\begin{cases} P_{I1} = P_I, \quad P_{I12} = (P_I)^2 \\ P_s^{w1} = P_s^w, \quad P_s^{w12} = (P_s^w)^2 \\ P_c^{w1} = P_c^w, \quad P_c^{w12} = 1 - P_{I12} - P_s^{w12} \end{cases} \tag{9}$$

Assuming there is no hidden node problem, for W number of WiFi APs contending in primary and another W number contending in secondary channel, the failure probabilities for WiFi are calculated as

$$\begin{cases} p_{f1}^w = p_{f2}^w = 1 - (1 - P_t^w)^{W-1} \end{cases} \tag{10}$$

B. Performance Analysis of WiFi-Only

Considering all the possible events, the total average event time duration can be calculated from (11). The average event time duration $E[T_{12}]$ is approximately half of $E[T_1]$ because of nearly double data rate for dual-carrier. This is because the time duration are calculated based on data-rate. System throughput and airtime for dual-carrier are calculated from (12) with fully saturated traffic ($q = 1$). Effect of probability of traffic availability q on system performance is similar to that studied in [9].

$$\begin{cases} E[T_1] & = P_{I1}\sigma + P_s^{w1}T_s^{w1} + P_c^{w1}T_c^{w1} \\ E[T_{12}] & = P_{I12}\sigma + P_s^{w12}T_s^{w12} + P_c^{w12}T_c^{w12} \end{cases} \tag{11}$$

$$S^w = \left(\frac{P_s^{w1}}{E[T_1]} + \frac{P_s^{w12}}{E[T_{12}]}\right)E[Z^w],\ A^w = \left(\frac{P_s^{w1}T_s^{w1}}{E[T_1]} + \frac{P_s^{w12}T_s^{w12}}{E[T_{12}]}\right) \tag{12}$$

C. LAA-Only and WiFi-LAA System

For LAA-Only, the Markov Chain model and state equations for dual-carrier are similar to those of WiFi-Only, therefore the throughput and airtime can be calculated similarly as in (12).

For WiFi-LAA, the Markov Chain for dual-carrier is similar to that of WiFi-Only thus the channel probabilities similar to (9) is used to calculate the event probabilities for dual-carrier. Hence the aggregated throughput and the airtime can be calculated using (14) with average time duration for single and dual-channel as

$$\begin{cases} E[T_1] & = P_{I1}\sigma + P_s^{w1}T_s^{w1} + P_s^{l1}T_s^{l1} + P_c^{w1}T_c^{w1} + P_c^{l1}T_c^{l1} \\ & +P_c^{wl1}T_c^{wl1} \\ E[T_{12}] & = P_{I12}\sigma + P_s^{w12}T_s^{w12} + P_s^{l12}T_s^{l12} + P_c^{w12}T_c^{w12} \\ & +P_c^{l12}T_c^{l12} + P_c^{wl12}T_c^{wl12} \end{cases} \tag{13}$$

$$\begin{cases} S^w = \left(\frac{P_s^{w1}}{E[T_1]} + \frac{P_s^{w12}}{E[T_{12}]}\right)E[Z^w],\ S^l = \left(\frac{P_s^{l1}}{E[T_1]} + \frac{P_s^{l12}}{E[T_{12}]}\right)E[Z^l] \\ A^w = \left(\frac{P_s^{w1}T_s^{w1}}{E[T_1]} + \frac{P_s^{w12}T_s^{w12}}{E[T_{12}]}\right),\ A^l = \left(\frac{P_s^{l1}T_s^{l1}}{E[T_1]} + \frac{P_s^{l12}T_s^{l12}}{E[T_{12}]}\right) \end{cases} \tag{14}$$

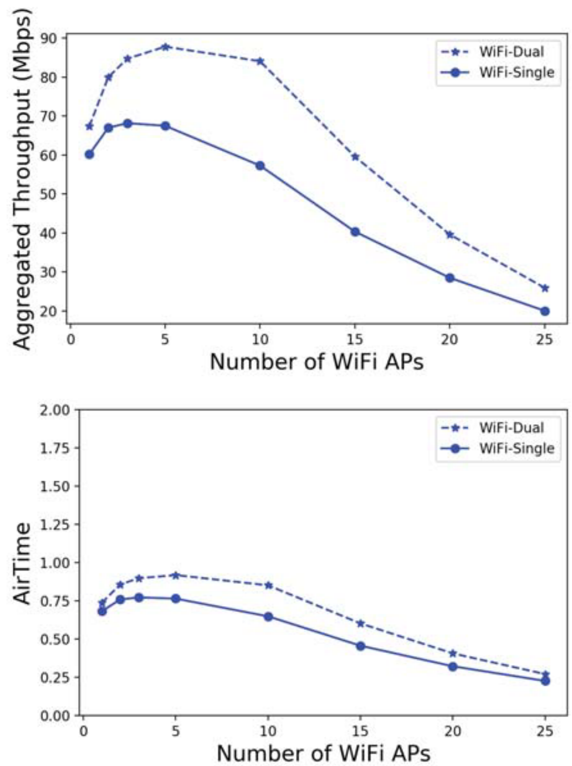

Figure4: Throughput and Airtime performance: WiFi-Only

IV. Results and Discussion

Fig. 4 illustrates the aggregated throughput and airtime of WiFi-Only system for both single and dual-carrier cases. As expected in each of single or dual-carrier case, the throughput initially rises with number of WiFi APs since the channel is under-utilized during backoff procedure. But after the channel utilization is saturated the throughput slowly decreases with increase in the WiFi APs because of high contention between numerous APs. Also the airtime initially rises with number of WiFi APs because of the same reason and then decreases further in full channel utilization for higher number of WiFi APs. In comparison to a single-carrier, the aggregated throughput and airtime is higher but not double. It is due to the fact that secondary channel can only be aggregated when primary channel is free. It is to be noted that the guard-band between primary and secondary can be utilized in dual-carrier aggregation and not in single-carrier case, and the throughput is aggregated over W number of WiFi APs.

Similar behavior in throughput and airtime performance can be seen for LAA-Only system in Fig. 5. This similarity is seen because the LAA uses LBT-Cat4 channel access mechanism that is much similar to WiFi's CSMA. It is also observed that LAA-Only achieves higher aggregated throughput than WiFi-Only for similar airtime usage. This actually depends on the system parameters chosen for each system.

In the coexistence case of LAA and WiFi, as in Fig. 6, 1W-1L denotes that one WiFi AP contends in primary

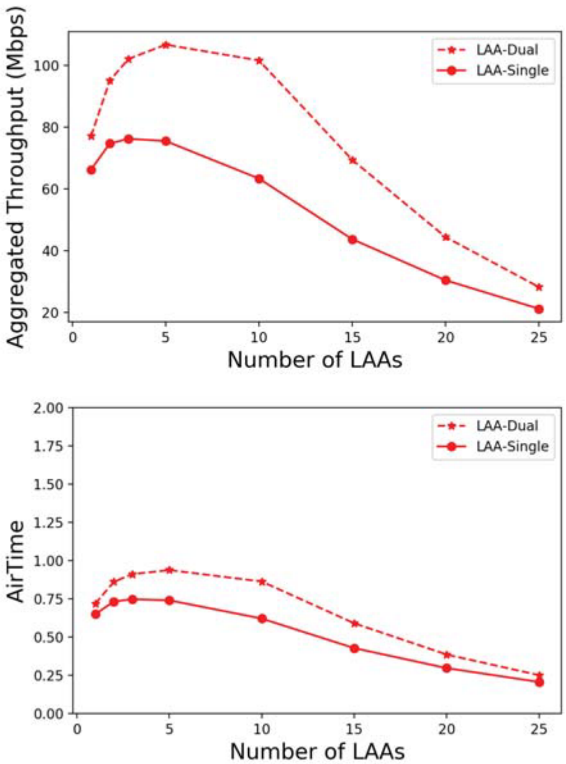

Figure5: Throughput and Airtime performance: LAA-Only

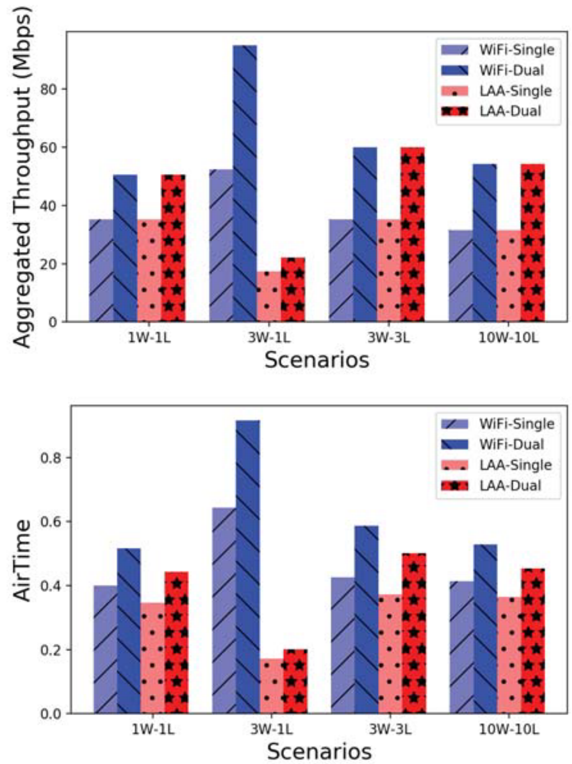

Figure6: Throughput and Airtime performance: WiFi-LAA

and another WiFi AP contends in secondary and similarly for one LAA. It can be clearly seen in the figure that the aggregated throughput is increased for both WiFi and LAA systems in dual-carrier than in the single carrier because of the availability of secondary channel. For equal numbers of LAAs and WiFis in cases 1W-1L, 3W-3L and 10W-10L, the fair coexistence of LAA and WiFi in terms of throughput and airtime can also be seen for the chosen system parameters. In 3W-1L where we have higher number of WiFi APs than LAAs and is normally the case, the LAAs coexist fairly and give equal opportunity to all WiFi APs.

V. Conclusion

In this paper, we investigated the throughput and airtime of WiFi-Only, LAA-Only and WiFi-LAA systems in single and dual-carrier scenario. Numerical results indicate that throughput is maximum at a medium number of stations. With few stations, the channel is under-utilized and with large number of stations, the channel is saturated. In comparison to a single-carrier, the aggregated throughput airtime usage is higher in dual-carrier for WiFi and LAA due to aggregation mechanism of utilizing the secondary channel when both channels are free. The throughput gains for both WiFi and LAA are same and are obtained for different scenarios as follows {'1W-1L': 1.43, '3W-1L': 1.81 , '3W-3L': 1.70 , '10W-10L': 1.72}.

Acknowledgment

This work has been supported by the NSF I/UCRC Grant 1539990 and by the C Spire Corporation.

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