Deterministic Channel Aggregation for LTE in Unlicensed Spectrum

Weiwei Zhou, Gordon J. Sutton, Ren Ping Liu, J. Andrew Zhang, and Su Pan

***Abstract*—We propose Deterministic Channel Aggregation (DCA) for LTE-Unlicensed, where the LTE eNodeB aggregates a predetermined number of channels in the unlicensed spectrum to achieve high data-rate communications. We introduce the MAC layer design, and analyze the collision probability and channel occupation ratio for DCA. Simulation results validate the effectiveness of DCA and our analytical results, when the eNB coexists with multiple WiFi systems under a range of traffic load conditions. DCA is particularly useful for applications that require high bandwidth and enables efficient access control of mobile broadband applications in the LTE-Unlicensed.**

***Index Terms*—Channel Aggregation (CA), LTE-Unlicensed (LTE-U), access control.**

I. INTRODUCTION

Long-term-evolution (LTE) unlicensed technology (LTE-U) is promising for enhanced mobile broadband (eMBB) services [1]. In LTE-U, the LTE eNodeB (eNB) shares unlicensed spectrum with WiFi stations (STAs) by adopting the listen before talk (LBT) mechanism. Most existing research on LTE-U considers an eNB sharing resources with WiFi STAs on one unlicensed channel. The LTE-U devices in [2] aggregate the licensed channel and one unlicensed channel to transmit the control signals and information data signals respectively. An unlicensed component carrier selection algorithm is proposed in [3] to select component carriers for newly arrived LTE-U users. Both of them only aggregate a single unlicensed channel for the LTE-U data transmission at any time, thus may not provide enough bandwidth for LTE-U.

In reality, multiple unlicensed channels can be utilized. Channel aggregation (CA), which aggregates multiple spare channels and transmits data across them for LTE-U users, can potentially achieve higher data rates and more effective usage of the unlicensed spectrum. However, the works closely related to channel aggregation in LTE-U are limited. In [4], the authors investigated several aggregation schemes for LTE-U. One multi-channel access scheme allows the LTE users to sense all available unlicensed channels and independently transmit data on each channel. A similar multi-channel scheme is studied in [5], where the LTE eNB can use unlicensed channels from different WiFi APs. However, for some applications with more stringent bandwidth requirements, the aggregated channels under the multi-channel scheme may result in unpredictable user experience due to the throughput fluctuations.

In this paper, we propose a Deterministic Channel Aggregation (DCA) for LTE-U, trying to explore an alternative way to avoid such fluctuation for LTE-U. We introduce the MAC layer mechanism and characterize the performance of the DCA mechanism. In DCA, multiple channels in the unlicensed spectrum are aggregated and the LTE frames are simultaneously transmitted on the aggregated channels. This is particularly useful for high bandwidth applications requiring high peak data rates. We study the DCA mechanism that enables the LTE eNB to transmit data on multiple channels simultaneously, and analyze its performance. In the DCA mechanism, the eNB senses all the channels it intends to aggregate, conducts the backoff process only when all the channels are sensed idle, and transmits the data frames on aggregated channels simultaneously when the counter reaches zero. The challenge for such an aggregation is mainly associated with the independent operations of different WiFi networks and the random access of the LTE eNB to multiple unlicensed channels at the same time. Therefore, the mechanism on the MAC layer needs to be carefully designed.The MAC design inherits the CSMA protocol of 802.11 and extends the protocol to the multi-channel scenario, which provides the eNB a fair competition with the incumbent WiFi systems. To understand the impact of DCA on system performance, we analyze the optimal number of channels the eNB should aggregate, under a range of traffic loads of the coexisting WiFi systems. We also calculate the Channel Occupation Ratio (COR) of the eNB and WiFi STAs to evaluate the performance of coexisting systems. Monte Carlo simulation results are provided afterwards, and are shown to match well with our analytical results on the eNB performance. The results could provide guidelines for access control of mobile broadband applications in the LTE-Unlicensed.

II. AGGREGATION MECHANISM ON THE MAC LAYER

In this section, we present the MAC layer design of DCA mechanism in the unlicensed spectrum, where the eNB is able to aggregate multiple spare unlicensed channels to transmit data simultaneously, as shown in Fig. 1. Under DCA, the eNB adopts LBT to compete for transmission opportunities with multiple WiFi networks operating independently in different channels. The eNB senses all the channels it intends to aggregate and conducts the backoff process only when all the channels are idle. Once the backoff counter reaches zero, the LTE eNB transmits a frame consisting of both uplink and downlink subframes on all the aggregated channels simultaneously.

In DCA, the eNB listens to all the channels that it intends to aggregate. The number of channels can be as small as one. In the coexisting systems, there are WiFi slots and eNB slots, and each of them could be busy or idle. Both idle

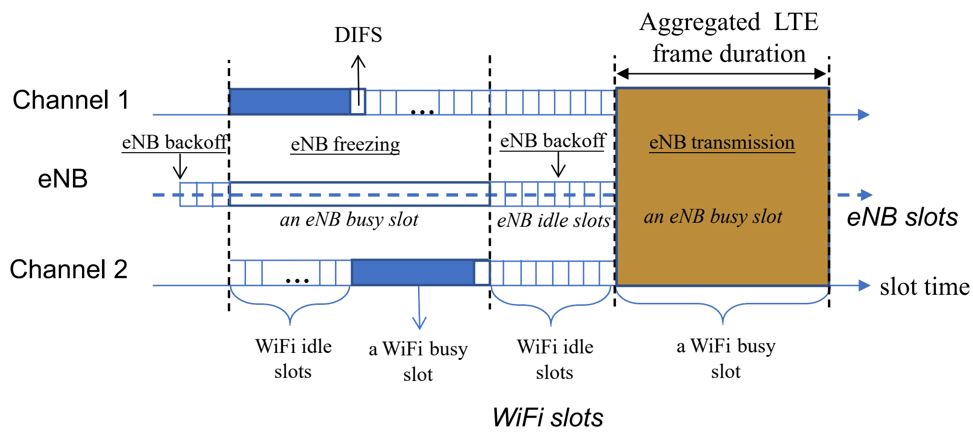

Fig. 1: Illustration of the DCA concept.

slots equate to a sensing slot. We define the idle slot time as the duration of a sensing slot σ unless stated otherwise. A station is allowed to sense the channel or transmit only at the beginning of each slot. The eNB counter decreases by one for each eNB slot from the eNB's perspective, freezes if any channel is busy, and resumes after a Distributed InterFrame Space (DIFS) duration when all the channels are idle. The eNB transmits data simultaneously on all the channels, after the counter reaches zero and all channels are sensed idle for a duration of a DIFS. The eNB slots are similar to the WiFi slots, being either short idle slots, or long busy slots (inclusive of a DIFS).

Below, we elaborate the backoff operations of the LTE eNB, referring to the aggregation of two channels under various situations of WiFi transmission, as shown in Fig. 2. STAs of WiFi 1 and 2 can only transmit on channel 1 and 2, respectively, while the eNB can transmit on both channels simultaneously.

1) The eNB counter counts down when one channel finishes a transmission and other channels are idle, as shown in Fig. 2a. After channel 1 finishes a transmission, the eNB senses the availability of all channels and its counter is decreased by one when all channels are empty.
2) The eNB counter counts down when one channel finishes a transmission with a DIFS duration and the other channel just begins to transmit, as shown in Fig. 2b. Note that we have included the DIFS duration at the end of a transmission. The eNB senses all channels at the end of channel 1 transmission, and decreases its counter by one if there is no other ongoing transmission in any channels. The eNB freezes the counter after channel 2 begins transmission.
3) The eNB keeps its counter frozen until channel 2 finishes its transmission, as shown in Fig. 2c. The eNB freezes its counter until channel 2 finishes its transmission. In this case, the eNB slot is a busy one where multiple WiFi transmissions can overlap without a gap.

The eNB performs energy detection to sense the channel state when transmissions happen in any of the channels. When channels are idle, the eNB and WiFi STAs repeatedly sense the channels during each time slot, σ, to determine whether the channel is still idle and whether to decrement their backoff counters.

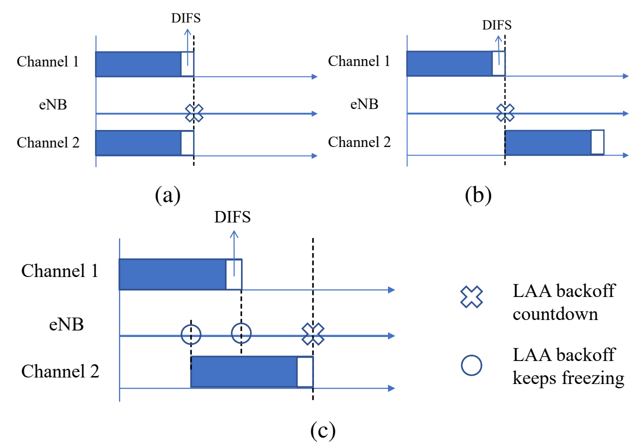

Fig. 2: The backoff operations of the eNB under various WiFi transmission scenarios.

Compared with the multi-carrier access LAA option in 3GPP [6], our proposed DCA uses a different strategy for channel aggregation and has a different backoff procedure. In the DCA, the backoff procedure on all aggregated channels is different from the channel bonding scheme in 802.11ac, as channel bonding only performs backoff on its primary channel, and clear channel assessment (CCA) is used for other secondary channels immediately before transmitting on them.

The eNB needs to obtain the information of WiFi traffic load under our DCA. Wireless/WLAN Termination (WT) nodes in [7] are introduced to provide the communication between the eNB and the WiFi AP through Software-Defined Networking (SDN), such that the eNB could know WiFi information to determine the optimal number of aggregated channels.

III. System Performance Analysis

We consider the coexisting system with one eNB and K WiFi networks, where each WiFi network independently occupies a unique channel. The eNB can share N unlicensed channels with any of N out of the K WiFi networks. If multiple eNBs co-locate, they will independently compete for the resource according to the LBT scheme under DCA. For simplicity, we assume that each WiFi network comprises the same number of STAs, n, so that we do not need to distinguish different channels during performance analysis. The eNB adopts the load-based Listen-Before-Talk (LBT) mechanism and WiFi STAs adopt Carrier Sensing Multiple Access (CSMA) mechanism. We assume that the traffic of eNB is saturated, and the WiFi traffic is unsaturated.

A. Probabilities of Transmission

We denote the number of slots per second perceived by the eNB and WiFi STAs, within a channel, as S_0 and S_w, respectively, and the number of the eNB transmission attempts per second as A_0. The slots include both empty and busy slots, and a transmission attempt occurs when the backoff counter reaches zero. Let τ_0^w be the eNB transmission probability from a WiFi STA's perspective and τ_0 be the eNB transmission probability from the eNB's perspective. They are given by

$$\tau_0^w \triangleq A_0/S_w, \text{ and } \tau_0 \triangleq A_0/S_0. \quad (1)$$

Thus, for each WiFi channel,we can write τ_0^w as

$$\tau_0^w = \frac{S_0}{S_w}\tau_0 = \eta\tau_0, \quad (2)$$

where $\eta \triangleq S_0/S_w$. In practice, η equals the ratio of the average number of eNB slots to the number of WiFi slots for each channel. It also represents the ratio of the WiFi slot expected duration to the eNB slot expected duration.

The values of these probabilities are obtained via Monte Carlo simulation in Section IV under different WiFi traffic load situations.

B. Performance Analysis

The number of aggregated predetermined channels is denoted as N, and therefore the eNB shares the unlicensed spectrum with N WiFi networks. We assume the N WiFi networks, each with n WiFi STAs, have the same load for simplicity. The model can also be applied to a system with different number of stations in each WiFi network, by changing n to n_w for the w-th channel.

The eNB in this paper uses the LBT scheme with an exponential backoff process, where there are m_0 maximum backoff stages and s_0 retransmission limits. The eNB starts the backoff counter randomly from $[0, W_0^L - 1]$, where W_0^L is the initial contention window size of the eNB.

Referring to the work in [8] and [9], we can obtain the transmission probability and the collision probability of the LTE eNB as

$$\tau_0 = \frac{2(1-p_0^{s_0+1})}{(1-p_0)\sum_{i=0}^{s_0}(W_{0,i}^L+1)p_0^i} \text{ and} \quad (3)$$

$$p_0 = 1 - \prod_{w=1}^{N}(1-\tau_w)^n, \quad (4)$$

respectively, where $W_{0,i}^L = 2^{\min(i,m_0)}W_0^L$ is the window size of the LTE eNB at the backoff stage i; τ_w is the transmission probability of a tagged STA during each WiFi slot in the w-th channel; and τ_0 is the transmission probability within each eNB slot. The availability of eNB slots depends on whether all the aggregated channels are simultaneously free or not, as shown in Fig. 2. From the WiFi perspective, the number of WiFi slots during each eNB busy slot can be quite different. These WiFi slots are not synchronized across the different WiFi networks. This is why we transform the slots when computing the transmission probabilities in III-A.

For WiFi systems, we consider the scenario where n STAs have the same traffic load and denote the probability as q that each STA has packets to send. In this case, referring to [10] we can obtain that they have the same transmission probability τ_w and collision probability p_w as

$$\tau_w = \frac{2q(1-p_w^{s_w+1})}{(1-p_w)\left(\sum_{i=0}^{s_w}q(W_{0,i}^w+1)p_w^i + 2(1-q)\right)}, \quad (5)$$

$$p_w = 1-(1-\tau_0^w)(1-\tau_w)^{n_w-1}, \quad (6)$$

where $W_{0,i}^w = 2^{\min(i,m_w)}W_0^w$ is the window size of WiFi at the stage i, m_w is the maximum backoff stage and s_w is the maximum number of retransmission. The model can also be extended to accommodate different traffic loads on each channel, by changing q to q_w for the w-th channel. In (6), τ_0^w denotes the eNB transmission probability from the WiFi's perspective. We can obtain $\tau_0^w = \eta\tau_0$ according to (2) and τ_w is the probability of a tagged STA in the w-th channel transmitting during each WiFi channel slot. These slots are synchronized among the n STAs in the w-th channel , but they are not synchronized with the slots in other WiFi channels nor the eNB's.

The parameters can be obtained as follows.

- Set an initial candidate p_0;
- Calculate the τ_0 with the given p_0 from (3);
  Solve the $\{\tau_w, p_w\}$-pair for $w = 1, 2, \ldots, N$ of Markov Chain model from (5) and (6);
- Solve p_0 from (4) under the given $\{\tau_w, p_w\}$, $w = 1, 2, \ldots, N$. Compare p_0 to the candidate p_0;
- Stop, if the discrepancy is acceptable;
- otherwise, decide the next candidate p_0 based on the search method and loop.

C. Channel Occupation Ratio

We use the Channel Occupation Ratio (COR), denoted as R, to characterize the performance of LTE eNB and WiFi systems [8]. The COR is defined as the ratio between the average duration per WiFi slot occupied by a successful frame, and the average WiFi slot duration, that is,

$$R = \frac{\text{E[successful frame duration per WiFi slot]}}{\text{E[WiFi slot duration]}}, \quad (7)$$

where E[·] denotes the expectation operator. Here the successful frame duration includes the preceding DIFS, which is part of the protocol.

For each WiFi system, the average duration of one WiFi slot, which is the denominator in (7), is given by

$$E_s^w = P_{Idle}\sigma + P_s^w T_w + P_c^w T_w + P_s^L T_L + P_c^L T_L, \quad (8)$$

whre P_{Idle} is the per-slot probability that the w-th WiFi channel is empty during each WiFi slot and σ is the channel slot time duration; P_s^w and P_c^w are the probabilities of successful WiFi transmission and collision among WiFi STAs during each slot of duration T_w, respectively; P_s^L and P_c^L are the successful transmission probability of eNB and the collision probability between the eNB and WiFi STAs, respectively, during each slot of the eNB with duration T_L.

These probabilities can be computed as

$$\begin{aligned} P_{Idle} &= (1-\tau_0^w)P_{Idle,w}, \\ P_s^w &= (1-\tau_0^w)P_{s,w}, \\ P_c^w &= (1-\tau_0^w)P_{c,w}, \\ P_s^L &= \tau_0^w P_{Idle,w}^N, \\ P_c^L &= \tau_0^w(1-P_{Idle,w}^N), \end{aligned}$$

where $P_{Idle,w}$, $P_{s,w}$ and $P_{c,w}$ are the conditional probabilities that the channel is empty, there is a successful WiFi transmission, and there is a collision, respectively, given that the eNB is not transmitting during each slot in a single channel.

These conditional probabilities can be represented as

$$\begin{aligned} P_{Idle,w} &= (1-\tau_w)^n, \\ P_{s,w} &= n\tau_w(1-\tau_w)^{n-1}, \\ P_{c,w} &= 1-P_{Idle,w}-P_{s,w}. \end{aligned}$$

The value of the numerator in (7) can be readily obtained as P_s^L. The COR of the eNB for one channel is thus given by

$$R_L^w = P_s^L T_L / E_s^w, \quad (9)$$

Similarly, the COR of each WiFi network, within one channel, is

$$R_W = P_s^w T_w / E_s^w. \quad (10)$$

Since the traffic of the WiFi systems is summed to be the same, the aggregated COR of the eNB R_L for N channels can be obtained as N times of R_L^w

$$R_L = NR_L^w = NP_s^L T_L / E_s^w. \quad (11)$$

We denote the bandwidth of one single unlicensed channel as B_0, then the aggregated bandwidth of our DCA could be used by one application is $B = B_0 R_L$. DCA's deterministic bandwidth provides certainty for LTE applications that require high bandwidth in the unlicensed spectrum, such that the application is assured that the high bandwidth is available for the successful slot. Such assurance enables development for future high performance applications.

IV. Simulation Results

We provide simulation results to verify the analytical results and validate the effectiveness of the aggregation mechanism here. In the simulation, the frame lengths of WiFi STAs and the eNB are slightly adjusted to be integral multiples of the slot time σ, so that WiFi STAs and the eNB can sense the channel in each slot time. Otherwise, they might need to sense in a more delicate time scale. The LTE frame duration is 8 ms when there is WiFi traffic [6], and the idle slot time is $\sigma = 9$ μs. We adjust the LTE frame length to $T_l = 889 \times \sigma = 8001 \mu s$, and the frame length of WiFi STAs to $T_w = 30 \times \sigma = 270 \mu s$. Therefore, the devices only need to sense channels every slot time instead of every μs. We consider $K = 4$ WiFi networks, and $n = 3$ STAs for each WiFi network. Then the eNB can aggregate $N = 1, 2, 3, 4$ channels, where the case of $N = 1$ corresponds to the single channel transmission scheme in [2]. The bandwidth of one unlicensed channel B_0 is 20 MHz or 40 MHz in the 802.11n protocol.

Fig. 3 and Fig. 4 show the COR and the collision probability of the LTE eNB, respectively, when it aggregates multiple unlicensed channels under various traffic loads for each WiFi STA. In both figures, curves are not shown for the whole range of q, as either the collision probability becomes too large or the COR becomes too small, which is impractical for real applications of the eNB. When the eNB aggregates more channels, the CORs decreases more rapidly and the collision probability increases faster with increasing WiFi traffic load, as can be seen from Figs. 3 and 4, respectively. Both figures also show an excellent matching between the analytical and simulation results.

The efficiency of aggregation is closely related to the WiFi traffic load q, as expected, and the two figures provide important guidance for the eNB's access control. Fig. 3 indicates that the eNB can effectively aggregate $N = 4$ channels and achieve a large COR when q is less than 0.02. This implies that a minimum bandwidth of $B = 2.25B_0$ can be accessed by the eNB, while the collision probability of the eNB is smaller than 0.2 under this WiFi traffic range, according to Fig. 4. When q is between 0.02 and 0.04, the eNB would get better performance by aggregating $N = 3$ channels, which gives access to applications with a total bandwidth between $B = 1.5B_0$ and $2.25B_0$, while keeping the collision probability below 0.25. Furthermore, when q is between 0.04 and 0.12, aggregating $N = 2$ channels would be the better option, allowing access to the LTE applications with a minimum bandwidth of $B = 1.1B_0$.

The multi-channel scheme in [4] may achieve the better performance of channel access than our proposed DCA in terms of the eNB system throughput. The eNB COR of the multi-channel scheme is N times of the COR when $N = 1$ due to the independent transmission of each user on each channel. Many current applications, e.g. video streaming, are able to tolerate the short-term throughput fluctuations. However, some applications with more stringent bandwidth requirements may not be able to adapt to the multi-channel scheme, as such fluctuations may result in unpredictable user experience. Comparatively, our proposed DCA is able to deliver a channel with large aggregated bandwidth to the application layer and provide a certainty for high bandwidth applications in LTE-U.

The COR of the WiFi systems is presented in Fig. 5. The overall trend for the COR of one WiFi system is that it increases with the WiFi traffic load and increases faster when the eNB aggregates more channels. This is because the eNB needs to wait a longer time to aggregate multiple channels, allowing the WiFi STAs more transmission opportunities. The analytical and simulation results again match well. The results provide guidelines on the feasibility for DCA to be effective

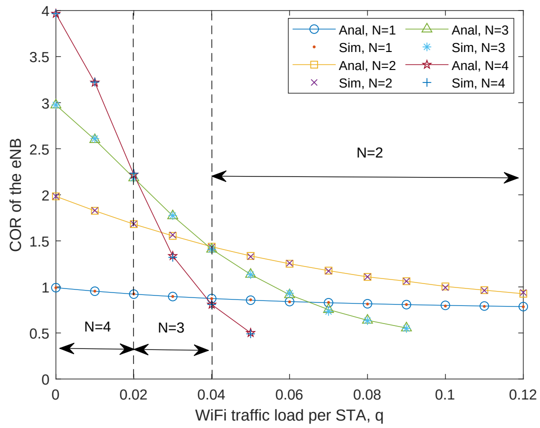

Fig. 3: COR of the eNB versus WiFi traffic load per STA for different numbers of aggregated channels.

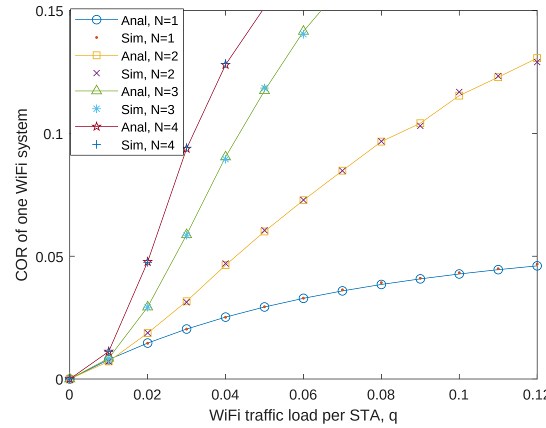

Fig. 5: COR of one WiFi system versus WiFi traffic load per STA for different numbers of aggregated channels.

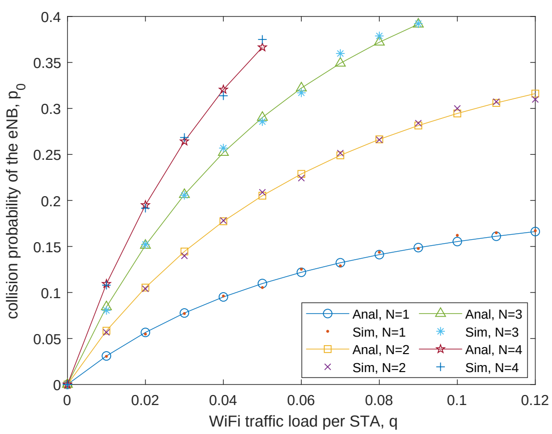

Fig. 4: Collision probability of the eNB versus WiFi traffic load per STA for different numbers of aggregated channels.

in aggregating various number of channels, so that the eNB can make informed decision of its offloading to unlicensed spectrum.

V. Conclusion

We propose the Deterministic Channel Aggregation (DCA) mechanism for LTE in the unlicensed spectrum. Our DCA aggregates multiple channels into a deterministic high bandwidth channel, and thus provides certainty for broadband applications with a high data rate requirement. We provided a MAC design where the eNB senses all the predetermined channels with only one backoff counter and starts the backoff process when all the channels are idle. Our design enables the eNB to share unlicensed channels with multiple WiFi systems, and to aggregate multiple channels to transmit data simultaneously. We provided analytical analysis for the collision probability and channel occupation ratio, and the accuracy of our analytical results is validated by simulation results under a range of WiFi traffic conditions. Our work can be effectively applied to resource allocation and access control of mobile broadband applications in the unlicensed spectrum.

Our work also shows that the DCA mechanism will mostly be effective for aggregating a small number of channels. It will hence be more promising to combine the DCA mechanism with other dynamic channel aggregation schemes, based on the insights obtained in this work.

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