A QoS-Oriented Scheduler Design for License Assisted Access (LAA)

Chi-Tao Chiang, You-En Lin and Chang-Kuo Yeh

Abstract—**Listen-Before-Talk (LBT) has been adopted by LTE to access unlicensed spectrum. Related contributions deal with the misalignment of LTE and WiFi slots by using reservation signal or additional channel sensing before transmissions. However, they do not consider some practical issues, such as the processing time of MAC and PHY layers due to the limit computation power of an eNodeB. Consequently, a Quality of Service (QoS) oriented scheduler for License Assisted Access (LAA) is designed in this paper with the consideration of MAC/PHY processing time. The proposed QoS oriented scheduler is divided into two sub-schedulers: Quality of Service (QoS) Scheduler (QSCH) and Resource Blocks Scheduler (RSCH). QSCH maintains the long-term QoS of each radio bearer of UEs, while RSCH deals with the real-time events, such as retransmission because of channel busy/collision on the unlicensed band. The proposed architecture of the QoS-oriented scheduler considers practical implementation issues and strikes an excellent balance between complexity and performance.**

Index Terms — **Listen Before Talk (LBT), Licensed-Assisted Access (LAA), Clear Channel Assessment (CCA).**

I. Introduction

LICENSE Assisted Access (LAA) is a technique proposed by the 3rd Generation Partnership Project's (3GPP) for the Long Term Evolution (LTE) devices in order to increase the throughput by the carrier aggregation of unlicensed bands and licensed bands. Similar with the WiFi channel access, LTE devices coexist with other devices on the same band by using a contention protocol known as Listen-Before-Talk (LBT). LBT is a procedure that the eNodeB first senses the channel and transmits only if the channel is sensed to be idle for the collision avoidance. Accordingly, LBT is also called Clear Channel Assessment (CCA) and the term, CCA will be used in the contexts of this paper for the consistency considerations.

CCA procedure applied in the LTE system can be divided into two parts, Initial Clear Channel Assessment (ICCA) and Extended Clear Channel Assessment (ECCA). Before the eNodeB transmits downlink data to UEs, the eNodeB shall senses the channel idle for a defer duration T_d. If the channel is occupied by other devices during T_d, ECCA procedure is applied by the eNodeB before this transmission; otherwise, the eNodeB gets a transmission opportunity (TxOP) for the downlink data transmission. Fig. 1 illustrates an example of ICCA procedure.

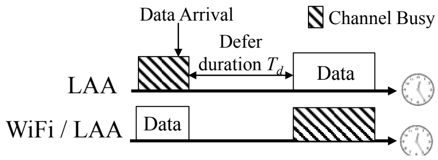

Fig. 1 An example of ICCA procedure.

Compared with ICCA procedure, the sensing duration in the ECCA procedure is much longer than that in ICCA procedure. Besides the channel sensed by the eNodeB is not occupied for an additional defer duration T_d, as the same with ICCA, the eNodeB then keeps sensing channel for N WiFi slots, which N is a random counter uniformly distributed between 0 and the contention window (CW). If the channel sensed by the eNodeB is free for one WiFi slot, the eNodeB decreases the random counter by one until $N = 0$. If N is counted to 0, the eNodeB gets a TxOP and may access the channel for the downlink data transmission. Fig. 2 shows an example of ECCA procedure.

Once the eNodeB gets a TxOP for one downlink data transmission after CCA procedures (ICCA or ECCA), the eNodeB is allowed to transmit data to UEs for several continuous subframes and the duration occupied by the eNodeB for one downlink data transmission is termed Channel Occupancy Time (COT), which the length of COT is limited by the Max Channel Occupancy Time (MCOT) for the fair channel access consideration. The length of MCOT is determined by the channel access priority of each service type. For supporting the Quality of Service (QoS) guarantee, the specification provides a mapping between the channel access priority and QoS Class Identifier (QCI). The higher channel access priority the service type is, the shorter duration one downlink data for this service type is deferred.

Due to the unpredicted state of the unlicensed band, the time when the eNodeB gets a TxOP for one downlink data transmission is not determined. Moreover, downlink data transmissions shall start at the LTE subframe/slot boundary of the expected subframe. The misalignment gap between the LTE subframe/slot boundary of one subframe and the time when the eNodeB gets a TxOP for a downlink data transmission often occurs. Therefore, the eNodeB uses a dummy signal for the channel reservation, as shown in Fig. 3. Using the reservation signal will lead to low bandwidth efficiency. Without using channel reservation signal, the eNodeB keeps sensing the channel free for one WiFi slot duration at least for the collision avoidance until the LTE subframe/slot boundary, illustrated in

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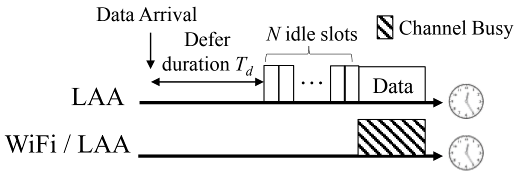

Fig. 2 An example of ECCA procedure that the channel is detected as free for N WiFi slots.

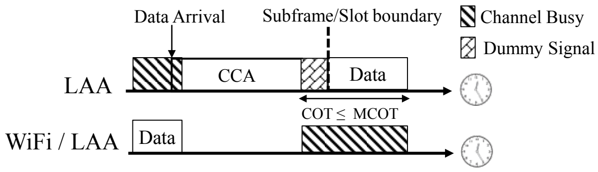

Fig. 3 An example that the eNodeB uses a dummy signal for the channel reservation until the LTE subframe/slot boundary of one subframe.

Fig. 4. However, other devices may occupy the channel during this duration and the downlink data transmission by the eNodeB is postponed to the next subframe. Although the eNodeB starts a downlink data transmission at the LTE subframe/slot boundary of one subframe, the encoded MAC PDUs for the expected LTE subframe/slot boundary allocation may be different from the current one. Consequently, the downlink data will not be transmitted by the eNodeB and the downlink transmission delay will increase. If the eNodeB encodes two types MAC PDUs for the LTE subframe/slot boundary allocation in advance, this downlink transmission can be adjusted with the time of getting a TxOP. However, the computing load becomes heavy because the time used by the eNodeB to encode MAC PDUs is time-exhausted. A tradeoff exists between the downlink transmission delay and the additional time-consuming operation for the MAC PDU encoding in the eNodeB and this tradeoff should be considered in a well-designed scheduler. Based on the above mentions, this paper proposes a LBT-based scheduler for the reduction of downlink transmission delay, the improvement of the downlink bandwidth utilization and QoS in the eNodeB. This paper is the first contribution to take the MAC and PHY processing time into considerations for the design of the LBT-based scheduler. In addition, this LBT-based scheduler is under implementation based on the LTE R13 specification.

The rest of the paper is organized as follows. Section II summarizes the contribution of the related work. Section III introduces an implementation architecture of a LBT-based scheduler for LAA. Section IV and V demonstrate the design of a QoS Scheduler (QSCH) and a Resource-block Scheduler (RSCH), respectively. Section III to V are the main contributions of this paper. Finally, the future work and the expected result are presented in Section VI.

II. Relate Work

For the discussions of unlicensed band access, much related work [2][3][4][5][7][8][9][10][11] has been contributed and the LTE R13 specification [1] is under modifications until now.

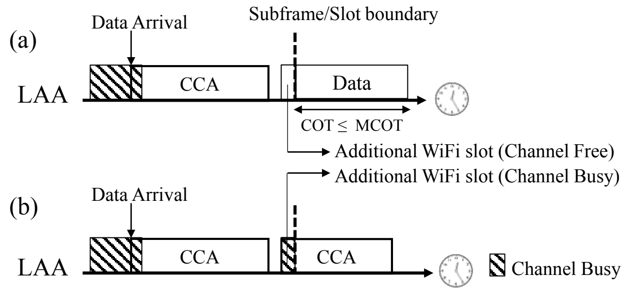

Fig. 4 An example that the eNodeB senses channel for one additional WiFi slot at least before LTE subframe/slot boundary of one subframe. (a) If the eNodeB senses the channel free at the additional WiFi slot, the eNodeB transmits data. (b) If the eNodeB senses the channel busy at the additional WiFi slot, the eNodeB needs to perform CCA (i.e. ICCA or ECCA).

An eNodeB shall perform CCA before unlicensed spectrum access. If the time when the eNodeB completes CCA procedures is earlier than the LTE subframe or slot boundary of the subframe when a downlink transmission starts, the eNodeB must keep to sense channel free for one slot duration at least or use a dummy signal to reserve the idle channel until the LTE subframe or slot boundary of the subframe. In [2][4][5][6], these contributions claims that using the dummy signal to reserve the idle channel until LTE subframe/slot boundary of one subframe. In addition, Mediatek and Qualcom also provide the design of the dummy signal for the LAA channel reservation [2][5]. However, using a downlink reservation signal shorts the downlink transmission duration for UEs' data. Besides using the dummy signal for the channel reservation, related contributions [1][3] claim that the eNodeB keeps sensing the channel state for one slot duration at least. In spite that MCOT can be fully used, the channel may be occupied by other devices during this additional channel sensing duration.

Above related mentioned contributions are focus on the misaligned duration between the time when the eNodeB gets a TxOP and the LTE subframe/slot boundary of one subframe. Some related work has focus on the design of MAC scheduler for the improvement of the downlink bandwidth utilization and fairness access with WiFi systems. In [7], the authors provide a dynamic CW adjustment algorithm for LAA based on channel state. In [8], the authors formulate the constraints of LAA-LTE transmission time to fairly maintain WiFi services and to maximize the network throughput. In [9], the authors provide a Q-learning mechanism for the advanced learning of the unlicensed band activity resulting in the efficient coexistence. In [10], the authors proposed three methods to enhance downlink hybrid automatic repeat request (HARQ) based TDD LAA-LTE for the reduction of the retransmission probability and the improvement of the bandwidth utilization. In [11], the authors proposed an enhanced LBT-based mechanism with cross-correlated information by utilizing assistant measurement report from UEs.

From the above related work, the MAC and PHY processing time of the eNodeB are not taken into consideration and should not be ignored when a well-designed LBT-based scheduler from the aspect of the implementation.

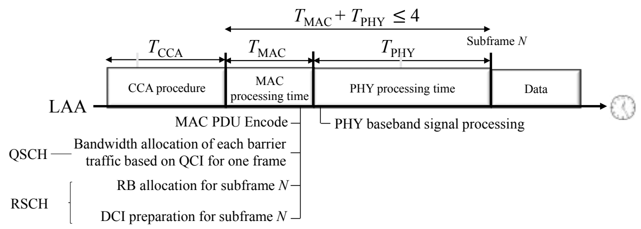

Fig. 5. An example to demonstrate the MAC and PHY processing of the eNodeB after CCA procedure.

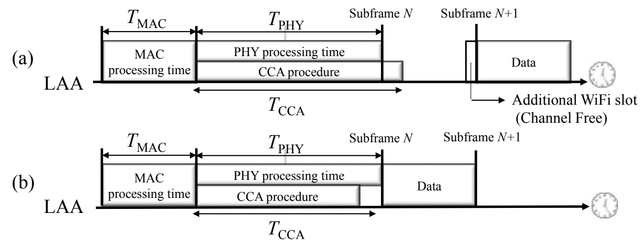

Fig. 6. Examples for cases when $T_{PHY} > T_{CCA}$ and $T_{PHY} < T_{CCA}$

III. An Architecture of a LBT-based Scheduler

From the implementation aspect, the eNodeB is composed of two main functional modules, Media Access Control (MAC) module and Physical (PHY) module. The main task of the MAC module in the eNodeB is to build the MAC PDUs of UEs, allocate downlink resource blocks with a well-designed scheduler, prepare the downlink control information (DCI) and inquire the PHY module for a TxOP before a downlink transmission. Based on the functionality of the scheduler and real-time requirements, the implemented in the MAC module, the MAC module is further divided into two parts, QSCH and RSCH. Both QSCH and RSCH are contributions of this paper.

QSCH is a frame-based bandwidth scheduler to ensure that each bearer traffic is allocated in a well-designed allocation priority based on the LAA channel access priority associated with the QoS Class Identifier (QCI) of each bearer traffic. In the meanwhile, the transmission queue of each bearer traffic is also taken into consideration for the downlink bandwidth allocation. Since the QCI of each bearer traffic does not varies frequently, the operation of QSCH is triggered for each frame. Therefore, QSCH belongs to a frame-based bandwidth scheduler.

Different from QSCH, RSCH is a subframe-based bandwidth scheduler. Since the RB allocation and channel condition for each UE for each subframe is different, the operation of RSCH is triggered for every subframe. RSCH is designed to allocate RB for each UE based on the scheduling result of QSCH, prepare DCI for each UE. Then, MAC module builds the MAC PDUs for UEs based on the RB allocation results. After that, MAC module notifies the PHY module to sense the channel with a set of CCA parameters associated with the LAA channel access type for a TxOP before a downlink transmission. After receiving the request from RSCH in the MAC module, the PHY module in the eNodeB is to generate PHY baseband signal carrying MAC PDUs and to detect the channel state for unlicensed band access.

Let T_{MAC} and T_{PHY} be the MAC and PHY processing time, respectively. Suppose that T_{CCA} is the time duration when the eNodeB detects the channel state. Both T_{MAC} and T_{PHY} are at least 1 subframe respectively in practice but $T_{MAC} + T_{PHY}$ is not longer than 4 subframes due to the Hybrid Automatic Repeat reQuest (HARQ) mechanism. T_{CCA} is determined by the results of the channel state detection. Take Fig. 5 as an example. Assume that the MAC processing time (i.e. T_{MAC}) is 1 subframe and the PHY processing time (i.e. T_{PHY}) is 2 subframes. If the eNodeB performs the MAC and PHY operations after the eNodeB get a TxOP for a downlink data transmission, a downlink data transmission starts after at least 3 subframe (i.e. $T_{MAC} + T_{PHY} = 3$). During the MAC and PHY processing duration, the channel may be occupied by other WiFi devices and the eNodeB needs to perform CCA procedure. Consequently, it is a practical implementation to make that the eNodeB detects the channel state and generates a PHY baseband signal in a parallel manner. That is to say that T_{PHY} and T_{CCA} are overlapped. The time when the eNodeB gets a TxOP for starting a downlink transmission is after T_{MAC} + max ($T_{PHY} + T_{CCA}$) and aligned with a LTE subframe/slot boundary of a subframe. Fig. 6 (a) and Fig. 6 (b) show the cases when $T_{PHY} > T_{CCA}$ and $T_{PHY} < T_{CCA}$, respectively.

Table I.
Mapping between 4 LAA channel access priority classes and 13 QCIs

QCI (q)	LAA Channel Access Priority Class (c)	Examples for the barriers
1	1	Conversational Voice
2	2	Conversational Video (Live Streaming)
3	1	Real Time Gaming
4	3	Non-Conversational Video
65	1	Mission Critical user plane Push To Talk voice (MCPTT)
66	1	Non-Mission-Critical user plane Push To Talk voice
5	1	IMS Signalling
6	3	Video (Buffered Streaming)
7	2	Voice, Video (Live Streaming), Interactive Gaming
8	3	Video (Buffered Streaming)
9	3	Video (Buffered Streaming)
69	1	Mission Critical delay sensitive signaling
70	3	Mission Critical Data

IV. A Quality of Service (QoS) Scheduler (QSCH)

QSCH provides QoS guarantee function for each barrier traffic with a two levels downlink bandwidth allocation priority for each barrier traffic. QSCH is composed of 2 main functional components, radio barrier management controller and LAA downlink bandwidth allocator. In order to support downlink transmissions with multiple QoS on the unlicensed band, LTE R13 specification provides the mapping relationships between 4 LAA channel access priority classes and 13 QCIs, as shown in Table I.

A. Radio Barrier Management Controller

From the barrier traffic establishment procedure, one radio barrier of one UE is associated with one QCI and LAA channel access priority classes based on the mapping relationship in Table II. Since the QoS requirement for each QCI is different, the radio barrier management controller in QSCH will assign one QCI-based bandwidth allocation priority to each QCI. The mapping relationship between the 13 QCI-based bandwidth

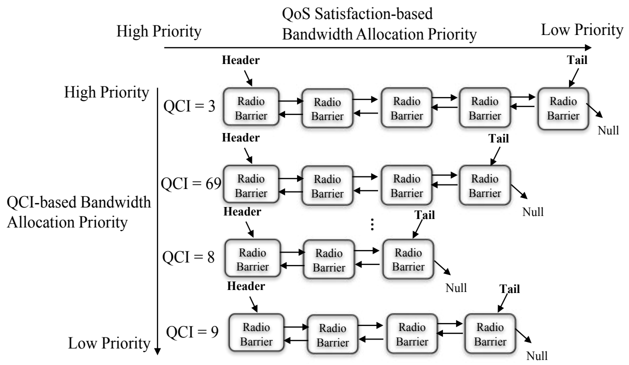

Fig. 7. An example of 13 link lists maintained by the radio barrier management controller in the QSCH.

allocation priorities, 13 QCIs and 4 LAA channel access priority classes are shown in Table II. Therefore, for each radio barrier, only one QCI-based bandwidth allocation priority is mapped and this is the first level priority for each radio barrier. Since each QCI may contains multiple radio barriers, the case that multiple radio barriers with the same QCI-based bandwidth allocation priority is allowed.

With the 13 first level bandwidth allocation priorities, the radio barrier management controller maintains 13 link lists. Nodes in each link list stand for radio barriers, which are linked each other with the second level bandwidth allocation priority. Fig. 7 shows an example of 13 link lists maintained by the radio barrier management controller in the QSCH. In other words, the eNodeB allocates bandwidth to radio barriers in the order with the first level bandwidth allocation priority and then with the QoS satisfaction-based bandwidth allocation priority, which is the secondary level bandwidth allocation priority if the radio barriers are with the same first level bandwidth allocation priority. The QoS satisfaction-based bandwidth allocation priority is determined by the QoS satisfaction ratio, which are defined the ratio between the allocated downlink bandwidth per second and the QoS parameters of traffic types, separately. The QoS parameters for radio barriers are defined as maximal guaranteed bit rate (GBR) for GBR traffic and UE maximal aggregate bit rate for the Non-GBR traffic. Initially, the second level bandwidth allocation priority of the radio barrier is set to 1 and sorted by the established order. Then, the eNodeB updates the second level bandwidth allocation priority of each radio barrier based on the downlink bandwidth results and QoS satisfaction ratio every observation duration. The lower QoS satisfaction ratio the radio bearer has, the higher priority the eNodeB allocates downlink bandwidth to the radio barrier.

B. LAA Downlink Bandwidth Allocator

After assigning the first and second level bandwidth allocation priorities for radio barriers, the eNodeB allocates the downlink bandwidth to each radio barrier in the priority order. The eNodeB allocates downlink bandwidth to each radio barrier based on the bandwidth requirement of packets in the transmission queue status and QoS parameters of GBR or Non-GBR.

(a) GBR Traffic

Table II.
Mapping between the 13 QCI-based bandwidth allocation priorities, 13 QCIs and 4 LAA channel access priority classes.

QCI-based Bandwidth Allocation Priority (p)	QCI (q)	LAA Channel Access priority Class (c)
1	3	1
2	69	1
3	65	1
4	5	1
5	1	1
6	66	1
7	7	2
8	2	2
9	70	3
10	4	3
11	6	3
12	8	3
13	9	3

For the GBR traffic, the allocated bandwidth for each radio barrier per second is limited between the minimal guarantee bit rate and maximal guarantee bit rate. Since QSCH is a frame-based scheduler, QSCH will take 100 frames approximating to 1 second as the observation duration. First, the eNodeB sets the remaining allocated bandwidth as the maximal guarantee bit rate every 100 frames. Then, the eNodeB checks the required bandwidth for the downlink packets in the transmission queue and the remaining allocated bandwidth for this observation duration. If the remaining allocated bandwidth is larger than the requirement and the current frame is not the 99-th frame, the allocated downlink bandwidth of the radio barrier is set to the required bandwidth for the downlink packets in the transmission queue. If the remaining allocated bandwidth is larger than the required bandwidth for the downlink packets in the transmission queue at the 99-th frame and the total amount allocated bandwidth for the radio barrier until now is less than the minimal guarantee bit rate of the radio barrier, the allocated downlink bandwidth of the radio barrier is set to the difference between the minimal guarantee bit rate and the total amount allocated bandwidth for the radio barrier for providing the QoS throughput guarantee. If the remaining allocated bandwidth is less than the requirements, the eNodeB allocates the remaining bandwidth to the radio barrier. After allocating the bandwidth to the radio barrier, the eNodeB deducts the allocated bandwidth at the current frame from the remaining bandwidth and takes the results as the basis of the bandwidth allocation at the next frame. Considering the case that the remaining allocated bandwidth is less than the requirements, the bandwidth will not be allocated at the next frame.

(b) Non-GBR Traffic

Apart from the GBR traffic, the allocated bandwidth of each Non-GBR radio barrier is only limited to the UE maximal aggregate bit rate. In addition, the QoS parameter is UE level. In other word, the total allocated bandwidth for all Non-GBR radio barriers per second is equal to or less than the UE maximal aggregate bit rate.

As the same with GBR, the observation duration is set to 100 frames. The eNodeB sets the remaining allocated bandwidth of

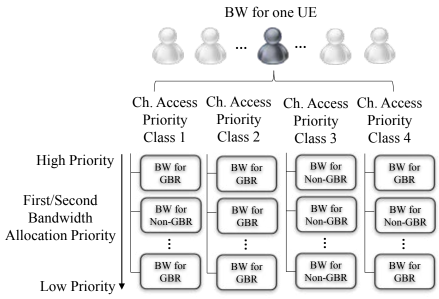

Fig. 8. An example of the downlink bandwidth of one UE.

the UE as the UE maximal aggregate bit rate every 100 frame. Then, the eNodeB checks the required bandwidth for the downlink packets in the transmission queue and the remaining allocated bandwidth of a UE for each frame in the observation duration. If the remaining allocated bandwidth is larger than the requirement no matter that the current frame is the last frame of the observation or not, the allocated bandwidth of the radio barrier is set to the required bandwidth of the packets in the transmission queue. If the remaining allocated bandwidth is equal to or less than the requirements, the allocated bandwidth of the radio barrier is set to the remaining allocated bandwidth of the UE. After allocating the bandwidth to the radio barrier, the eNodeB deducts the allocated bandwidth at the current frame from the remaining bandwidth and takes the results as the basis of the bandwidth allocation at the next frame. Considering the case that the remaining allocated bandwidth is less than the requirements, the bandwidth will not be allocated to the radio barrier at the next frame until the end of the observation duration.

After the operations of the radio barrier management controller and LAA downlink bandwidth allocator, QSCH summarizes the bandwidth results of the radio barriers into each UE for the compatibility with RSCH. For the bandwidth of one UE, it contains 4 bandwidth allocation types corresponding to 4 LAA channel access priority classes. For each LAA channel access priority classes, the bandwidth of each radio barrier is sorted with the first and second level bandwidth allocation priority in the decreasing order, which is shown in Fig. 9. Let C_f be a set of LAA channel access priority classes. Each element c_i in C_f is the highest LAA channel access priority class of UE i, which the eNodeB transmits data to at subframe f. Therefore, the LAA channel access parameters for CCA procedure used by the eNodeB at subframe f is termed as c_f^{min}, which is formulated in Eq. (1).

$$c_f^{min} = \min \{c_i \mid c_i \in C_f\} \quad (1)$$

From Eq(1), the MAC module of the eNodeB gets a set of LAA channel access parameters for ICCA or ECCA and notifies QSCH for the determination of MAC PDU encode, which is described in the introduction of QSCH. In the meanwhile, QSCH also deliveries the UEs' bandwidth requirements, which is the summation of the allocated bandwidth requirements for all radio barriers, to RSCH for a downlink bandwidth allocation.

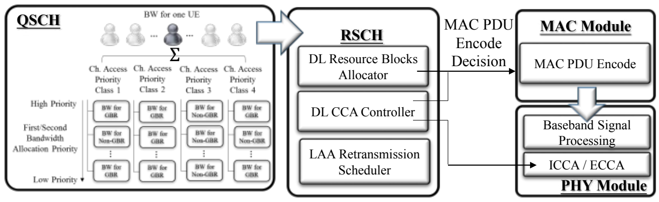

Fig. 9. The main functional components of RSCH and the communications between RSCH and MAC.

V. A Resource Blocks Scheduler (RSCH)

RSCH is a subframe-based scheduler to allocate downlink resource blocks for each downlink transmission. Then, RSCH notifies the MAC module to build MAC PDUs based on the downlink resource allocation results for each subframe. Fig. 9 illustrates the main functional components of RSCH and communications with MAC module. After receiving the decision of channel access priority and UEs' bandwidth requirements to RSCH from QSCH, RSCH needs to allocate resource blocks for each UE to meet the UEs' bandwidth requirements and trigger PHY module to get a TxOP for a downlink data transmission. Then QSCH also determines the trigger operation for MAC PDU encode. RSCH is composed of 3 main functional components, a downlink resource block allocator, a downlink CCA Controller and a downlink retransmission scheduler. Since much related work has contributed in the design of downlink resource block allocation for LTE, this paper will focus on the design of a CCA controller and a downlink retransmission scheduler.

A. Downlink CCA Controller

Considering the example shown in Fig. 10, the eNodeB cannot transmit data to UEs at subframe f because the random counter is not zero at the subframe boundary of subframe f. Therefore, the time consumed by the operation of MAC PDU encode is wasted. To avoid the situation, a downlink CCA controller is developed to determine if RSCH indicates the MAC module to build MAC PDUs based CCA states after receiving the LAA channel access priority of each subframe from the MAC module.

Fig. 11 shows the control flow chart of the decision that the eNodeB informs the MAC module to build MAC PDUs. Let T_{PHY} be the baseband processing time and t_f be the Wifi slot of the subframe/slot boundary of subframe f when a downlink transmission is expected to occur. When a downlink packet arrives at the WiFi slot t_a and the eNodeB senses the channel state at the WiFi slot t_s, where $t_a \le t_s$, the eNodeB generates a random counter N in ECCA procedure based on the LAA channel access priority class c from the MAC module. In ECCA procedure, the duration of channel state detection can be divided into two parts, which are termed T_c and N. If the eNodeB transmits data right after $t_a + T_{PHY}$, Eq. (2) must be satisfied.

$$\max (t_s + T_c + N, t_f) \le t_a + T_{PHY} \quad (2)$$

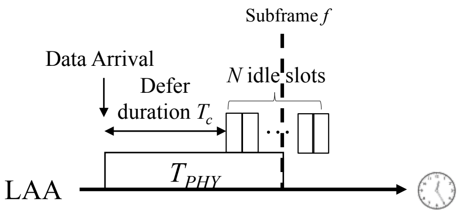

Fig. 10. An example that the eNodeB cannot transmit data to UEs at subframe *f*.

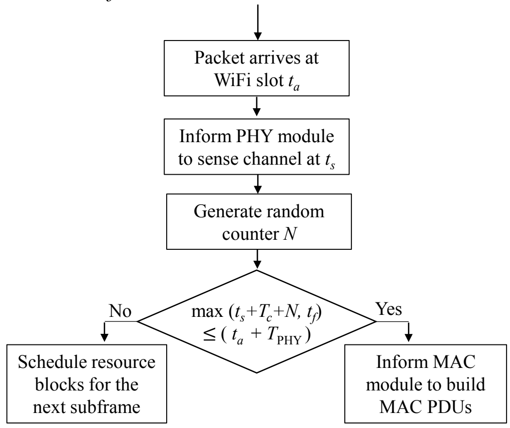

Fig. 11. A control flow chart that RSCH informs the MAC module to build MAC PDUs.

Let the conditions that $t_f \le (t_s + T_c + N)$ and $t_a = t_s$ be satisfied. That is to say that the time when eNodeB starts to detect channel state is immediate after the packet arrival time t_a. N can be derived as Eq(3).

$$N \le (t_{PHY} - T_c) \tag{3}$$

Give an example to show the operation of a downlink CCA controller. Suppose that T_{PHY} = 2 subframes and $t_f \le (t_s + T_c + N)$. In LTE R13 specification, the range of T_c and N are specified, which are summarized as Table III. If the eNodeB will transmit data at the LTE subframe/slot boundary of one subframe, the range of N can be summarized as Table IV.

In other words, the eNodeB generates a random counter N and then looks up the available maximal random counter defined Table IV. If N is larger than the available maximal random counter, a downlink CCA controller does not requests the MAC module to build MAC PDUs. Otherwise, a downlink CCA controller requests the MAC module to build MAC PDUs. Besides, the determination of MAC PDU encode is provided in a downlink CCA controller of RSCH. RSCH needs to maintain the CCA states and notify the PHY module to perform ICCA or ECCA procedure based on parameters of CCA Procedures for 4 LAA channel access priority classes.

B. Downlink Retransmission Scheduler

Since the state of unlicensed band is not determined, the eNodeB may not get a TxOP at the expected subframe. If these transmissions are ignored, the overall downlink bandwidth utilization will degrade. Therefore, a downlink retransmission scheduler of RSCH is developed to re-schedule the downlink transmissions due to the unpredicted channel state.

Table III.
Parameters of CCA Procedures for 4 LAA Channel Access Priority Classes

LAA Channel Access Priority Class (*c*)	T_c (ms)	Maximal random counter
1	25	{3, 7}
2	25	{7, 15}
3	43	{15, 31, 63}
4	79	{15, 31, 63, 127, 255, 511, 1023}

Table IV.
Available Maximal Random Counters for 4 LAA Channel Access Priority Classes

LAA Channel Access Priority Class (*c*)	Available Maximal random counter (Subframe / Slot Boundary)
1	7/7
2	15/15
3	63/63
4	213/269

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Let T_f^{COT} be the COT of a downlink transmission starting at subframe *f*. Let T_{PHY} and T_{MAC} be the PHY baseband signal processing time and MAC processing time, respectively. Let a downlink transmission that $T_3^{COT} = 10$ start from subframe 3. Assume that the PHY baseband processing time T_{PHY} is equal to 2 subframes and the MAC processing time T_{MAC} is equal to 1 subframe. Based on the assumption, the normal and expected case of this downlink transmission is illustrated as Fig. 12.

However, the normal and expected case of this downlink transmission is infrequent due to the unpredicted channel state. Fig. 13 shows a retransmission example that the eNodeB detects the channel busy at subframe 3 at which the channel detected by the eNodeB is busy, the MAC PDUs for the subframe 3 will be buffered in the MAC module and waits for a new transmission with the same HARQ process scheduled by the downlink retransmission scheduler of RSCH. In the meanwhile, the PHY baseband signal is also buffered in the PHY module. Since the MAC PDUs for the subframe 4 and subframe 5 have been built in the MAC module and the PHY module has been notified to generate the PHY baseband signal for subframe 4 and subframe 5, a downlink retransmission scheduler will notify the PHY module to re-generate the PHY baseband signal containing the data of subframe 3 and this downlink retransmission for the subframe 3 will be re-scheduled with the same HARQ process after the subframe 5, which is equal to the expected subframe after (T_{PHY} + T_{MAC}) subframes. Since the transmission starts at the subframe 4, the COT for this transmission also keeps 10 continuous subframes, which are equal to or less than MCOT. From the above example, the subframe f_r when the eNodeB retransmits data of the subframe *f* can be formulated as Eq (4) and the control flow chart of the decision when RSCH retransmits for subframe *f* is shown in Fig 14.

$$f_r = f + T_{PHY} + T_{MAC} \tag{4}$$

Based on design of the downlink retransmission scheduler, the MAC module only buffers data for 3 (T_{PHY} + T_{MAC}) subframes at most. It does not take much memory for the MAC module to buffer the MAC PDU for a data retransmission since each data will be re-scheduled after (T_{PHY} + T_{MAC}) subframes if the data has not been transmitted at the expected subframe.

Subframe N

Subframe Index	0	1	2	3	4	5	6	7	8	9
MAC processing	(N, 3)	(N, 4)	(N, 5)	(N, 6)	(N, 7)	(N, 8)	(N, 9)	(N+1, 0)	(N+1, 1)	(N+1, 2)
PHY basband signal processing		(N, 3)	(N, 3) (N,4)	(N, 4) (N, 5)	(N, 5) (N, 6)	(N, 6) (N, 7)	(N, 7) (N, 8)	(N, 8) (N, 9)	(N, 9) (N+1, 0)	(N+1, 0) (N+1, 1)
Data Transmission				(N, 3)	(N,4)	(N, 5)	(N, 6)	(N, 7)	(N, 8)	(N, 9)
Channel Sate (I: Idle, B: Busy)				I	I	I	I	I	I	I

Subframe N+1

Subframe Index	0	1	2	3	4	5	6	7	8	9
MAC processing										
PHY baseband signal processing	(N+1, 1) (N+1, 2)	(N+1, 2)								
Data Transmission	(N+1, 0)	(N+1, 1)	(N+1, 2)							
Channel Sate (I: Idle, B: Busy)	I	I	I							

(x,y) : A downlink data which is expectedly transmitted at subframe y of frame x

Fig. 12. A normal and expected case of a downlink transmission starts at subframe 3 of frame N, where T_3^{COT} = 10 subframes, T_{PHY}= 2 subframes and T_{MAC}= 1 subframe.

Subframe N

Subframe Index	0	1	2	3	4	5	6	7	8	9
MAC processing	(N, 3)	(N, 4)	(N, 5)	**(N, 3)**	(N, 6)	(N, 7)	(N, 8)	(N, 9)	(N+1, 0)	(N+1, 1)
PHY basband signal processing		(N, 3)	(N, 3) (N,4)	(N, 4) (N, 5)	(N, 5) **(N, 3)**	**(N, 3)** (N, 6)	(N, 6) (N, 7)	(N, 7) (N, 8)	(N, 8) (N, 9)	(N, 9) (N+1, 0)
Data Transmission				**Fail**	(N,4)	(N, 5)	**(N, 3)**	(N, 6)	(N, 7)	(N, 8)
Channel Sate (I: Idle, B: Busy)				**B**	I	I	I	I	I	I

Subframe N+1

Subframe Index	0	1	2	3	4	5	6	7	8	9
MAC processing	(N+1, 2)									
PHY baseband signal processing	(N+1, 0) (N+1, 1)	(N+1, 1) (N+1, 2)	(N+1, 2)							
Data Transmission	(N, 9)	(N+1, 0)	(N+1, 1)	(N+1, 2)						
Channel Sate (I: Idle, B: Busy)	I	I	I	I						

(x,y) : A downlink data which is expectedly transmitted at subframe y of frame x

Fig. 13. A retransmission case of a downlink transmission starts at subframe 3 of frame N, where T_3^{COT} = 10 subframes, T_{PHY}= 2 subframes and T_{MAC}= 1 subframe.

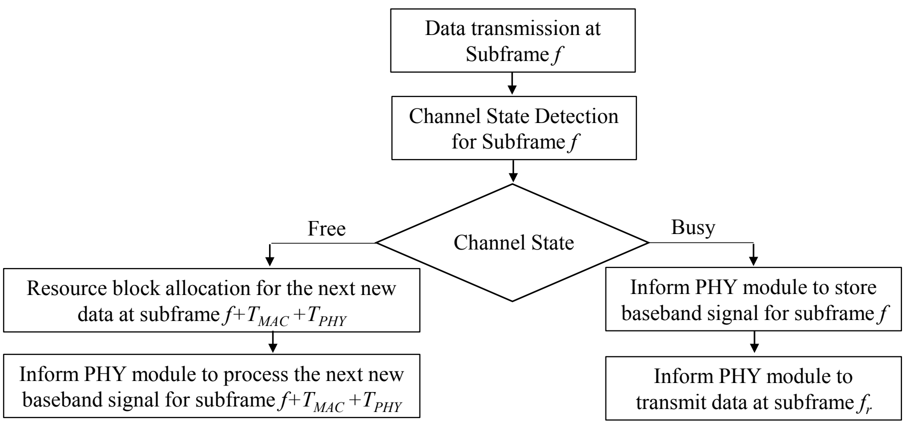

Fig. 14. A control flow chart of the decision when RSCH retransmits data for subframe f

VI. Future Work and Expected Results

Licensed Assisted Access (LAA) is one of the carrier aggregation technologies to offload data traffic from the licensed spectrum to unlicensed spectrum. For the fair coexistence with WiFi system, Listen Before Talk (LBT), also called Clear Channel Assessment (CCA), is performed by the eNodeB before the access of the unlicensed band. Due to the unpredictable channel state and the LTE downlink transmission constraints, downlink transmissions may not be on schedule. Therefore, this paper proposes a QoS-Oriented scheduler architecture, including Quality of Service (QoS) Scheduler (QSCH) and Resource Blocks Scheduler (RSCH) for providing QoS guarantee of each radio barrier with different QoS requirements and downlink bandwidth utilization enhancement in LTE over unlicensed band. The design architecture also takes hardware and software processing time into consideration from the implementation aspects, which is the first contribution until now. In the meanwhile, the scheduler also considers QoS of each barrier and the improvement of CPU utilization of the eNodeB. QSCH and RSCH are implemented in the eNodeB of a small cell currently and also can be implemented in the macro cell.

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