Uplink Channel Access Enhancement for Cellular Communication in Unlicensed Spectrum

JIHOON KIM, (Student Member, IEEE), JAEHONG YI, (Student Member, IEEE), AND SAEWOONG BAHK, (Senior Member, IEEE)
Department of Electrical and Computer Engineering, INMC, Seoul National University, Seoul 08826, South Korea
Corresponding author: Saewoong Bahk (sbahk@snu.ac.kr)
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ABSTRACT 3GPP cellular communications in unlicensed spectrum allow transmission only after completing listen-before-talk (LBT) operation. For downlink, the LBT operation helps cellular traffic to coexist well with Wi-Fi traffic. However, cellular uplink transmission is attempted only at the time specifically determined by the base station after having a successful LBT and the user equipment (UE) may suffer transmission failure and delayed transmission due to Wi-Fi interference. As a result, cellular uplink traffic does not coexist well with Wi-Fi traffic. This article mathematically analyzes the problem of unfairness between cellular and Wi-Fi for uplink channel access. To address the coexistence problem in unlicensed spectrum, we propose a standard-compliant approach, termed UpChance, which allows the UE to use a minimum length of uplink reservation signal and the base station to determine the optimal timing for the UE’s uplink transmission. Through ns-3 simulation, we verify that UpChance improves the performance of fairness and random access completion time by up to 88% and 99%, respectively.

INDEX TERMS eLAA, LTE-LAA, MulteFire, NR-U, uplink, unlicensed spectrum.

I. INTRODUCTION
Due to the high price and scarce bandwidth of licensed spectrum, cellular communication technologies have been developed to operate in unlicensed and licensed spectrum. The 3rd Generation Partnership Project (3GPP) has standardized long term evolution (LTE) based technologies such as LTE licensed-assisted access (LTE-LAA), enhanced LAA (eLAA), and further enhanced LAA (FeLAA) since 3GPP Release 13 [1]–[3]. LAA technologies use carrier aggregation (CA) to exploit licensed spectrum as an anchor carrier for control and data communication, while using unlicensed spectrum for data communication only. LTE-LAA makes cellular communication technologies in licensed spectrum such as device-to-device (D2D) offload their traffic to unlicensed spectrum [4].

MulteFire Alliance is in the process of standardizing a stand-alone technology that operates in unlicensed spectrum only [5]. Efforts to use cellular communications in unlicensed spectrum are not limited to LTE, but continued in 5G new radio (NR). The 3GPP has standardized NR in unlicensed spectrum (NR-U) since 3GPP Release 16 [6]. NR-U is considered for both LAA-based operation and stand-alone operation, and is being developed to operate in the sub 7 GHz and mmWave spectrum.

Cellular communications in unlicensed spectrum developed based on LTE-LAA technology use listen-before-talk (LBT) for channel access. LBT helps to determine whether the channel has been idle for a certain period before data transmission, which works similarly to carrier sense multiple access with collision avoidance (CSMA/CA) in Wi-Fi. In the case of downlink (DL) transmission, after the evolved Node B (eNB) successfully performs LBT, it transmits a DL reservation signal (DL-RS) to occupy the channel until the next slot/subframe boundary. The RS is a dummy signal to inform other communication devices that the channel is busy. It helps the eNB to start successful DL transmission when LBT is over.

Uplink (UL) transmission requires more procedures. The user equipment (UE) transmits a scheduling request (SR) to the eNB at a predetermined time. After the eNB receives the SR, it sends the UE a UL grant which carries uplink...
scheduling information. The UE is allowed to transmit the scheduled UL data only after a successful LBT. Due to its transmission at the predetermined time, the UE may not compete fairly against Wi-Fi devices. This means the channel may not be idle at the scheduled time the UE transmits.

The main contributions of this article are three-fold:

- We mathematically analyze the problem of unfairness between Wi-Fi and uplink cellular in unlicensed spectrum because legacy UL cellular access in the unlicensed spectrum does not compete fairly with Wi-Fi traffic.
- To address the unfairness problem, we propose a standard-compliant solution, UpChance, that aims to minimize the usage of UL reservation signal (UL-RS). It includes UE operation for sending a UL-RS and eNB operation for scheduling UL transmission optimally.
- Through ns-3 simulation, we evaluate the performance of UpChance in the presence of cellular and Wi-Fi traffic in terms of fairness and random access delay.

The rest of this article is organized as follows. We present the related work and preliminaries in Section II. We present the problem statement in Section III, and propose UpChance in Section IV. In Section V, we demonstrate the performance of UpChance through extensive simulations. Finally we conclude this article in Section VI.

II. RELATED WORK AND PRELIMINARIES

A. RELATED WORK

Much research is underway to improve the performance of cellular communications in the unlicensed spectrum. In particular, an important issue is the coexistence problem with other communication devices such as Wi-Fi. In [7], [8], the authors improve coexistence performance by modifying the LBT operation. However, these articles focus only on the DL performance of LTE. In [9], [10], the authors propose symmetric energy detection (ED) threshold or common preamble between Wi-Fi and unlicensed cellular for coexistence. Our work can achieve greater performance with these approaches in the asymmetric hidden scenario.

In [11]–[15], the authors improve coexistence performance by using Wi-Fi characteristics. These works apply part of Wi-Fi technology to LTE in the unlicensed spectrum for coexistence. Such modifications are undesirable for manufacturing real devices due to cost and scalability issues. We propose an approach to improve coexistence performance in a way that is not limited to any specific technology.

In [16]–[20], the authors focus on UL performance of LTE in the unlicensed spectrum. In [16], the authors propose efficient UL grant transmission. In [17], the authors avoid wasting resources due to hidden terminals through overscheduling. In [18], the authors propose a scheduling model that takes advantage of the flexible allocation in MulteFire. In [19], the authors mathematically analyze whether eLAA is suitable for coexistence with random access or scheduled access. In [20], the authors propose a dynamic channel selection method using a decentralized deep reinforcement learning approach. Through the channel selection method, eLAA avoids Wi-Fi interference. But they show limited improvement in terms of fairness and access delay. Our work highlights that cellular uplink transmission in unlicensed spectrum has a problem of not properly occupying the channel, especially when the channel is overloaded. To address this problem, we suggest that the UE uses additional Category 4 LBT (Cat. 4 LBT) and UL-RS, and the eNB uses appropriate scheduling considering network traffic.

B. PRELIMINARIES

LTE-LAA is first proposed in 3GPP Release 13 [1]. It exploits CA to use licensed and unlicensed spectrum at the same time, and uses unlicensed spectrum as an auxiliary carrier. LTE-LAA uses the unlicensed spectrum only for downlink. eLAA and FeLAA are the technologies proposed in 3GPP Release 14 and 15, respectively [2], [3]. eLAA includes uplink operation and FeLAA standardizes uplink partial subframe and autonomous uplink transmission.

In cellular communications in the unlicensed spectrum, there are two types of LBT operation for channel access: 25 µs LBT and Cat. 4 LBT. 25 µs LBT is a simple operation that senses the channel only for 25 µs without backoff operation. If the channel is idle for 25 µs, 25 µs LBT allows transmission. Cat. 4 LBT is a similar operation to CSMA/CA in Wi-Fi. A device waits for a defer period, and if the channel is idle for this period, it starts backoff operation with a backoff counter value randomly selected within its contention window size (CWS). When the backoff counter reaches zero, the device starts transmission.

For downlink access, the eNB uses 25 µs LBT for special frames such as discovery reference signal, and mostly uses Cat. 4 LBT because of its better coexistence with Wi-Fi compared to 25 µs LBT. After the eNB succeeds in Cat. 4 LBT, it transmits DL-RS until the next slot/subframe boundary and sends DL data.

For uplink access, the eNB chooses the LBT operation type for each UE and informs the UE of this through the UL grant. The eNB shares its channel occupancy time (COT) with the UE (shared COT) within the maximum COT [21]. For instance, if the eNB transmits DL for 4 ms and schedules UL for 4 ms, it may choose 25 µs LBT for the UE to transmit the scheduled UL data.

For the uplink data transmission, the UE should receive a scheduling message through a UL grant. The minimum interval between the UL grant and the scheduled subframe is 4 ms [24], and one UL grant allows transmission of up to four subframes, called multiple-subframe scheduling (MSS) [2]. If the shared COT does not exceed the maximum COT, the UE transmits UL data after a successful 25 µs LBT. If not, the UE should succeed in Cat. 4 LBT first. Fig. 1 illustrates an example of eLAA UL operation without Wi-Fi interference.

Random access of cellular communications in the unlicensed spectrum basically uses the same 4-step procedures as in the licensed spectrum. There are four message exchanges for random access [5], [6]. The UE first sends message
(msg) 1 called physical random access channel (PRACH) preamble at a PRACH slot if it succeeds in $25 \mu s$ LBT before the PRACH slot [5]. The PRACH slot is allotted periodically. The eNB replies to the UE with msg 2 within the random access response (RAR) window. The UE transmits msg 3 at the scheduled time using LBT operation whose type is chosen by the eNB. After receiving msg 3, the eNB transmits msg 4 using Cat. 4 LBT, and the random access operation ends.

### III. MATHEMATICAL ANALYSIS FOR UNFAIRNESS BETWEEN UPLINK CELLULAR AND WI-FI

In this section, we mathematically analyze the success probability of $25 \mu s$ LBT performed by the UE for uplink transmission. We consider PRACH scenario and UL data scenario.

#### A. PRACH SCENARIO

In the PRACH scenario, we consider a coexistence scenario of multiple Wi-Fi transmitters and one UE. All Wi-Fi transmitters have saturated traffic and the UE attempts to transmit a PRACH preamble at the PRACH slot. Fig. 2(a) illustrates the PRACH scenario. The UE fails in LBT due to Wi-Fi traffic when it attempts to transmit a PRACH preamble.

We analyze the probability that the UE successfully transmits a PRACH preamble at the PRACH slot based on the Bianchi model [22]. The Bianchi model classifies the channel of each slot into one of three states: successful transmission, collision, and idle. The ratio of each state is $P_s = \frac{T_s P_{tr} P_s}{T_s P_{tr} + T_c P_{tr} (1 - P_s) + \sigma (1 - P_{tr})}$.

The collision probability in a randomly chosen time is defined as

$$P_c = \frac{T_c P_{tr} (1 - P_s)}{T_s P_{tr} P_s + T_c P_{tr} (1 - P_s) + \sigma (1 - P_{tr})}.$$  

The idle probability at a randomly chosen time is defined as

$$P_{id} = \frac{\sigma (1 - P_{tr})}{T_s P_{tr} P_s + T_c P_{tr} (1 - P_s) + \sigma (1 - P_{tr})}.$$  

Using these probabilities, we can express the probability that the UE succeeds in $25 \mu s$ LBT at a randomly chosen time as

$$P_r = P_s \frac{\sigma}{T_s} + P_c \frac{\sigma}{T_c} + P_{id}.$$  

If the channel is in the successful transmission state ($P_s$) or collision state ($P_c$) at a randomly chosen time, $25 \mu s$ LBT succeeds only when the chosen time is in the last $\sigma$ duration of the state. This is because the last part of the successful transmission state and collision state consists of idle distributed coordination function (DCF) inter-frame space (DIFS) duration [22]. If the channel is idle at a randomly chosen time ($P_{id}$), $25 \mu s$ LBT always succeeds. The probability that the UE succeeds in $25 \mu s$ LBT at the PRACH slot is equal to $P_r$ due to Markov property of the Bianchi model.

To validate our analysis, we implement a coexistence simulator for Wi-Fi and eLAA using MATLAB. Fig. 3 shows the probability of the UE’s success in $25 \mu s$ LBT at the PRACH slot with varying number of contending nodes and Wi-Fi aggregated MAC protocol data unit (A-MPDU) lengths [29]. We observe that the analysis and simulation results become more similar as the number of contending nodes increases, which is consistent with the basic assumptions of the Bianchi model. In most situations, the probability of the UE’s success in $25 \mu s$ LBT is smaller than 4%. This means that the UE transmits a PRACH preamble with a very low probability under the saturated Wi-Fi traffic condition.

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1. The success probability of Cat. 4 LBT performed by the UE is lower than the success probability of $25 \mu s$ LBT performed by the UE. It is because $25 \mu s$ LBT does not have backoff operation and the defer period of Cat. 4 LBT is longer than $25 \mu s$.

2. The channel is idle for at least DIFS duration, regardless of the state of the previous slot.
B. UL DATA SCENARIO

For UL data transmission, we consider the case where multiple Wi-Fi transmitters and one eNB-UE pair coexist. All Wi-Fi transmitters have saturated traffic and the eNB-UE pair continues to transmit UL grant and UL data. Fig. 2(b) illustrates the UL data scenario. The UE attempts to transmit four scheduled UL subframes, but it fails in LBT due to Wi-Fi interference.

We analyze the expected number of successfully transmitted subframes per UL grant based on the Bianchi model [22] and frame-by-frame random walk model [23]. In the frame-by-frame random walk model, a transmission round consists of three periods: random backoff, transmission, and DIFS. In [23], \( X \) is a random variable denoting the total time of one transmission round, which is written as

\[
X = \sigma \ast bc_{\text{min}} + T_f + d,
\]

where \( bc_{\text{min}} \) is the minimum backoff counter value between two consecutive transmissions, \( T_f \) is the frame transmission duration, and \( d \) is the DIFS duration.

According to whether the previous transmission is UL grant or Wi-Fi, we define two kinds of \( bc_{\text{min}} \) distribution: \( bc_{\text{min}}^u \) and \( bc_{\text{min}}^w \). \( bc_{\text{min}}^u \) is the \( bc_{\text{min}} \) distribution between the UL grant transmission and the first Wi-Fi transmission after UL grant. When \( bc_{\text{min}}^u \) is \( v \), the minimum value of the backoff counter values of \( n \) Wi-Fi stations is \( v \) at the time the UL grant transmission ends. We define \( bc_{\text{min}}^u \) as

\[
\Pr (bc_{\text{min}}^u = v) = \left( \frac{CW_{\text{max}}}{\sum_{l=0}^{CW_{\text{max}}} g_l} \right)^n \left( \frac{CW_{\text{max}}}{\sum_{l=1}^{CW_{\text{max}}} g_l} \right)^n,
\]

where \( n \) is the number of contending Wi-Fi stations, \( CW_{\text{max}} \) is the Wi-Fi’s maximum contention window, and \( g_l \) is the probability that a Wi-Fi station has a backoff counter value \( l \) when the other nodes end transmissions. \( g_l \) equals the conditional probability that the backoff counter value is \( l + 1 \) under the non-zero backoff counter value.\(^3\) We define \( g_l \) as

\[
g_l = \frac{\sum_{i=0}^{m} b_{l+1}}{1 - \sum_{i=0}^{m} b_{l+1}},
\]

\( b_{l,k} \) is the stationary distribution that a Wi-Fi station has the backoff stage \( i \) and the backoff counter value \( k \), and \( m \) is the maximum backoff stage in the Bianchi model.

\[
b_{\text{min}}^w \] is the \( bc_{\text{min}} \) distribution between Wi-Fi transmissions. Considering the case of successful transmission and collision, we define \( bc_{\text{min}}^w \) as

\[
\Pr (bc_{\text{min}}^w = v) = P_s \left( S_v \times B_{v}^{n-1} - S_{v+1} \times B_{v}^{n-1} \right) + \sum_{i=2}^{n} \frac{P_i}{P_{tr}} \left( C_i^{v} \times B_{v}^{n-i} - C_{i+1}^{v} \times B_{v}^{n-i} \right),
\]

where \( P_i \) is the probability that \( i \) Wi-Fi stations simultaneously transmit at a slot, \( S_v, B_v, \) and \( C_v \) are the sum of backoff counter value distribution from \( v \) to \( CW_{\text{max}} \) of a Wi-Fi station that is in the state of successful transmission, idle, and collision, respectively. We express \( P_i \) as

\[
P_i = \left( \frac{n}{i} \right) \tau^i (1 - \tau)^{n-i},
\]

where \( \tau \) is the probability that a Wi-Fi station transmits in a randomly chosen slot [22]. We define \( S_v \) as

\[
S_v = \sum_{l=v}^{CW_{\text{max}}} h_l,
\]

where \( h_l \) is the probability that a Wi-Fi station has a backoff counter value \( l \) right after its successful transmission. We define \( h_l \) as

\[
h_l = \begin{cases} 1 & 0 \leq l \leq CW_{\text{min}}, \\ \\ 0 & l > CW_{\text{min}}. \end{cases}
\]

where \( CW_{\text{min}} \) is the Wi-Fi’s minimum contention window. \( h_l \) follows a discrete uniform distribution between 0 and \( CW_{\text{min}} \). We define \( B_v \) as

\[
B_v = \sum_{l=v}^{CW_{\text{max}}} g_l,
\]

and \( C_v \) as

\[
C_v = \sum_{l=v}^{CW_{\text{max}}} w_l.
\]

where \( w_l \) is the probability that a Wi-Fi station has a backoff counter value \( l \) after experiencing a collision. When a Wi-Fi station whose backoff stage is \( i \) encounters a collision, the next contention window size becomes \( 2^{i+1}(CW_{\text{min}} + 1) \). We define \( w_l \) as

\[
w_l = \frac{\sum_{i=0}^{m-1} \frac{b_{l+1}}{2^{i+1}(CW_{\text{min}} + 1)} + \frac{b_{l+1}}{CW_{\text{max}} + 1}}{\sum_{i=0}^{m} b_{l+1}},
\]

where \( i_s = \max (\lfloor \log_2 l \rfloor - \log_2 (CW_{\text{min}} + 1), 0) \).

To succeed in 25 \( \mu \)s LBT for the \( k \)-th scheduled UL subframe, the \( k \)-th scheduled UL subframe should be in one of two periods during one transmission round; one is the random backoff period and the other is the last \( \sigma \) period of the DIFS.
period. We define the probability that the UE succeeds in 25 µs LBT for the \( k \)th scheduled UL subframe as

\[
q_k = \sum_{r=1}^{r_{\text{max}}} \Pr \left( d + \sum_{j=1}^{r-1} x_j \leq D_k \leq \sum_{j=1}^{r} x_j - T_f \right) + \sum_{r=1}^{r_{\text{max}}} \Pr \left( d + \sum_{j=1}^{r} x_j - \sigma \leq D_k \leq d + \sum_{j=1}^{r} x_j \right),
\]

where \( D_k \) is the duration between the end of DL transmission of the eNB and the \( k \)th scheduled UL subframe, and \( r_{\text{max}} \) is the upper bound of the number of transmission rounds where \( r_{\text{max}} = \lceil D_k/(d + T_f) \rceil \). The first term on the right hand side indicates the probability that \( D_k \) is in the random backoff period of the \( r \)th transmission round. The second term represents the probability that \( D_k \) is in the last \( \sigma \) period of the DIFS period of the \( r \)th transmission round. \( x_j \) follows \( b_{c_{\text{min}}}^{U} \) distribution because the first transmission round follows immediately after UL grant transmission. \( x_j \) (\( j \geq 2 \)) follows \( b_{c_{\text{min}}}^{W} \) distribution because the \( j \)th transmission round comes after Wi-Fi transmission.

We define the probability that the UE succeeds in transmission at the first scheduled UL subframe as

\[
p_1 = q_1.
\]

The UE succeeds in transmission at the first scheduled UL subframe only when the UE succeeds in 25 µs LBT. We also define the probability that the UE succeeds in transmission at the \( k \)th scheduled UL subframe as

\[
p_k = p_{k-1} + (1 - p_{k-1}) \times q_k,
\]

where \( k \) ranges from 2 to MSS, \( p_k \) increases as \( k \) increases. This is because if the transmission succeeds in the \( (k-1) \)th scheduled subframe, the transmission also succeeds in the \( k \)th scheduled subframe. If the UE fails in transmission of the \( (k-1) \)th scheduled subframe, the UE succeeds in transmission of the \( k \)th scheduled UL subframe when it succeeds in 25 µs LBT at the \( k \)th scheduled UL subframe. The expected number of successfully transmitted subframes per UL grant is

\[
E[S] = \sum_{k=1}^{\text{MSS}} p_k.
\]

We validate the analysis for the UL data scenario using MATLAB simulator. Fig. 4 shows \( E[S] \) with various number of contending nodes and A-MPDU lengths. As in the PRACH scenario, we observe that the analysis and simulation results become closer as the number of contending nodes increases. \( E[S] \) is close to 0 except when the Wi-Fi A-MPDU length is 1 ms. That is, in the UL data scenario where the UE coexists with Wi-Fi under saturated traffic, UL data transmission is rarely successful.

IV. PROPOSED SCHEME

In this section, we propose a cellular uplink channel access scheme in the unlicensed spectrum, named UpChance, which is standard-compliant. The UE performs Cat. 4 LBT first and transmits a minimum length of UL-RS before transmitting data. The eNB schedules UL transmission with optimal delay scheduling, which helps the UE to occupy the channel.

A. UE OPERATION

Fig. 5(a) shows the overview of UE operation in UpChance. Each UE always measures the most recent \( N \) interference lengths to find the maximum interference length (\( I_{\text{max}} \)). An interference length is the duration of one interference packet.\(^4\) \( I_{\text{max}} \) is a maximum value among the \( N \) measured interference lengths. The UE compares \( I_{\text{max}} \) with the length of UL-RS (\( L_{\text{RS}} \)) because \( I_{\text{max}} \) is the most significant obstacle for the LBT success. \( I_{\text{max}} \) is an important parameter that shows how fairly the UE occupies the channel.

The UE starts additional Cat. 4 LBT operation after finishing an UL transmission.\(^5\) When the UE succeeds in the additional Cat. 4 LBT, it calculates \( L_{\text{RS}} \) and compares it with \( I_{\text{max}} \) to decide whether to transmit UL-RS. \( L_{\text{RS}} \) is the period from the current time (right after Cat. 4 LBT) to 25 µs before its scheduled UL transmission, varying from time to time. If \( L_{\text{RS}} \) is shorter than \( I_{\text{max}} \), the UE transmits UL-RS to occupy the channel. If not, the UE restarts additional Cat. 4 LBT with the backoff counter value zero until \( L_{\text{RS}} \) is shorter than \( I_{\text{max}} \). After enough time, \( L_{\text{RS}} \) becomes shorter than \( I_{\text{max}} \) and the UE transmits UL-RS during \( L_{\text{RS}} \).

If an interference packet longer than \( I_{\text{max}} \) occurs, the UE fails in occupying the channel due to the interference packet. Then, the UE updates \( I_{\text{max}} \) with the new interference length. This renewal increases the LBT success probability of the UE in the next attempt. The UE minimizes the use of UL-RS to ensure transmission of other devices whenever possible. The UE transmits UL-RS until 25 µs before the scheduled UL transmission. This helps 25 µs LBT to succeed with a very high probability. The failure of 25 µs LBT happens only when interference longer than UL-RS occurs simultaneously with UL-RS transmission. In this case, the UE increases the CWS

\(^4\)We consider consecutive interference packets with short inter-frame space (SIFS) idle period one interference packet. It is because SIFS is used for response frame such as acknowledgement frame of Wi-Fi.

\(^5\)This is the same as the post backoff operation of Wi-Fi.
value of Cat. 4 LBT according to the eLAA specification [2]. Thanks to the 25 μs idle time, UEs within the coverage of the UL-RS increase the success probability of 25 μs LBT for UL data transmission.

B. eNB OPERATION

Fig. 5(b) shows the overview of eNB operation in UpChance. Before scheduling, the channel saturation detection algorithm determines whether the channel is saturated. If the channel is unsaturated, the eNB schedules UL subframes with a minimum processing delay. If saturated, the eNB expects interfering traffic to come continuously. Considering the UE’s decoding time for the scheduling message and LBT failure, the eNB schedules UL transmission with a delay greater than the minimum processing delay, called ‘delayed scheduling’.

Each UE decodes the received scheduling message and then accesses the channel for UL transmission using Cat. 4 LBT. Scheduling UL transmission with a larger delay than the minimum processing delay allows the UE to avoid interference and prepare for channel access. If interference occupies the channel during the period that the UE attempts to occupy the channel, the UE cannot occupy the channel. To address this problem, we propose the eNB to use the channel saturation detection algorithm and delayed scheduling algorithm together.

1) CHANNEL SATURATION DETECTION

After measuring inter-packet intervals, the eNB determines whether the channel is saturated or not. Transmission of some consecutive packets is considered a ‘packet burst’ if inter-packet intervals are in the range of [DIFS, AIFS + 15 × σ], where AIFS stands for arbitration inter-frame space. This range includes most inter-packet transmission intervals when packets are continuously transmitted with LBT operation. When LTE-LAA eNBs coexist under saturated traffic, more than 98% of inter-packet transmission intervals fall into this range [26].

If an eNB transmits any packet as part of a packet burst, it considers the channel saturated and predicts that interfering packets will continuously arrive after its transmission. Otherwise, the eNB considers the channel unsaturated. As a delayed scheduling input, the eNB uses the result of packet burst detection including its own transmission.

2) DELAYED SCHEDULING

If the channel is detected as saturated, the eNB runs delayed scheduling to increase LBT success probability of the UE. The main idea of delayed scheduling is to use the latest interference length information to find the optimal delay for UL scheduling. The basic assumption is that the interference length in the near future (right after the eNB’s transmission) is likely to be equal to the recently measured interference length in the saturated channel. In delayed scheduling, the eNB considers all possible cases which occur after its transmission using the recent interference lengths. As a result of delayed scheduling, the eNB gets the optimal delay value \( D \). \( D \) indicates how much longer the interval between a scheduling message and the corresponding scheduled UL subframe is compared to the minimum processing delay. The pseudo-code of delayed scheduling is presented in Algorithm 1.

The input of delayed scheduling is a set of measured lengths of interference packets included in the current packet burst \( L \). The size of \( L \) is determined by how many interference packets exist in the current packet burst. The eNB performs an exhaustive search on all delay values \( d \) (line 4). For each \( d \), the eNB generates all possible interference patterns that can occur between the current DL transmission and the scheduled UL transmission. We define an interference pattern \( ip \) as a prediction of alternating idle period and busy period over a certain period of time. As a result, an \( ip \) consists of one or more (idle period, busy period) combinations, expressed as

\[
ip = \{ \bigcup_{k=1}^{n} (LT_i, L_j) \mid LT_i \in LT, L_j \in L, n = 1, 2, \ldots \}, \quad (19)
\]

\(6\) In LTE, the minimum processing delay between UL grant and scheduled UL transmission is 4 ms and the minimum delay between msg 2 and msg 3 in random access is 5 ms [24]. Each UE prepares UL transmission after decoding UL grant or msg 2. The time from the end of scheduling message decoding to UL transmission is about 1 ms [25]. Therefore, each UE has 1 ms to occupy the channel before its scheduled UL transmission.

\(7\) We do not consider SIFS as an inter-packet interval. If an inter-packet interval is point coordination function inter-frame space (PIFS), we exclude the following packet length from the calculation because it is an intermittent packet such as Wi-Fi beacon.

\(8\) The idle period occurs due to LBT time of devices and the busy period occurs due to interfere packets.
where $LT$ is a set of LBT times, $LT_i$ is an element of $LT$, $L_j$ is an element of $L$, and $n$ denotes the number of $(LT_i, L_j)$ combinations in an $ip$. Elements of $LT$ are in the range of $[\text{DIFS}, \text{AIFS}+15\times\sigma]$ as in the channel saturation detection algorithm.

To generate an $ip$, the eNB first selects one $(LT_i, L_j)$ combination in $LT$ and $L$ (lines 6–7). Then, the $(LT_i, L_j)$ combination is the only element of the current $ip$ and sum of $LT_i$ and $L_j$ is the length of the current $ip$ ($X$) (lines 8–9). If $X$ is larger than the time between the end of DL transmission and the time that the UE finishes decoding of the scheduling message ($T_d$), an $ip$ is completed (lines 12–13). If not, the eNB selects one more $(LT_i, L_j)$ combination in $LT$ and $L$ and repeats the above procedure using a recursive function (lines 10–11). The pseudo-code of the recursive function is presented in Algorithm 2. In the recursive function, the current $ip$ adds another $(LT_i, L_j)$ combination and updates its length, $X$ (lines 2–5). According to the updated $X$, the eNB completes an $ip$ or goes through another recursive function (lines 6–9).

After generating an $ip$, the eNB updates the performance metric $r_d$ for delayed scheduling for a given $d$ (line 13 in Algorithm 1 and line 9 in Algorithm 2). We define $r_d$ as

$$r_d = \sum_{ip} Pr_{d,ip} \frac{S_{d,ip}}{C_d}, \quad (20)$$

where $Pr_{d,ip}$ denotes the probability of the $ip$, $S_{d,ip}$ denotes the number of UL subframes expected to succeed with the given $ip$, and $C_d$ denotes the number of subframes required for a period from the scheduling message to the scheduled UL transmission. We can express $Pr_{d,ip}$ as

$$Pr_{d,ip} = \prod_{(LT_i, L_j)\in ip} Pr(LT = LT_i) \cdot Pr(L = L_j), \quad (21)$$

where $Pr(LT = LT_i)$ denotes the probability that LBT time equals $LT_i$, and $Pr(L = L_j)$ denotes the probability that the interference period is $L_j$. $Pr_{d,ip}$ decreases because $ip$ has more elements because it multiplies more probability terms. $S_{d,ip}$ varies according to the time the $ip$ ends, i.e., how long $X$ is. For example, if $X$ is a value between $T_d$ and the time between the end of DL and the first scheduled UL subframe ($T$), $S_{d,ip}$ is the number of scheduled UL data subframes because the UE will transmit all scheduled UL subframes with a high probability. As $X$ increases, $S_{d,ip}$ decreases because the number of remaining scheduled UL subframes decreases. $C_d$ is the delay between the start of eNB’s transmission which includes a scheduling message and the end of the scheduled UL subframes. As $d$ increases, $C_d$ also increases because the eNB schedules UL data transmission to rear subframes.

Fig. 6 is an example of $ip$ generation. In this example, the eNB selects the first LBT time and interference combination. Because the period of $(LT_1 + L_1)$ is smaller than $T_d$, the eNB selects the second LBT time and interference combination. Then, the $ip$ period $(LT_1 + L_1 + LT_2 + L_2)$ is larger than $T_d$. $LT_1$ has a $bc_{\min}$ distribution in Section III and $L_j$ has a discrete uniform distribution.
and an ip is generated. The ip ends at the second scheduled UL subframe. Thus, \( S_{d, ip} \) is two even though the eNB has scheduled four UL subframes. \( C_d \) is the period from the UL grant transmission to the end of the scheduled subframe transmission and \( Pr_{d, ip} \) is the product of the probabilities for each component of the ip.

As \( S_{d, ip} / C_d \) increases, the throughput of UL transmission increases because the UE transmits more UL subframes in the same period. \( r_d \) is the weighted average of \( S_{d, ip} / C_d \) for all ip’s. Therefore, the eNB can choose the optimal \( D \) to make \( r_d \) have the largest value.

V. PERFORMANCE EVALUATION

In this section, we evaluate the throughput and airtime fairness performance of UpChance in a coexistence environment of eLAA UL and Wi-Fi traffic. Then we show random access performance of UpChance when eLAA random access coexists with Wi-Fi traffic.\(^{12}\)

A. SIMULATION ENVIRONMENTS

For ns-3 simulation, we developed the eLAA module based on existing LTE and Wi-Fi modules [27]. eLAA and Wi-Fi interfere with each other, following the 3GPP urban micro (UMi) path loss model.\(^{13}\) We implemented file transfer protocol (FTP) traffic model, 2 \times 2 multiple-input multiple-output (MIMO), and LBT. Other detailed simulation parameters are summarized in Table 1. Wi-Fi traffic is always for downlink and eLAA continues to perform either UL transmission or random access according to the scenario.

An uplink grant schedules four UL subframes. In random access, msg 1 (PRACH preamble), msg 2 (RAR), msg 3, and msg 4 are transmitted. We consider two-cell and multi-cell topologies. Fig. 7(a) depicts the two-cell topology with one Wi-Fi cell and one eLAA cell. The Wi-Fi cell consists of one AP and one STA, and the eLAA cell consists of one eNB and one UE. Fig. 7(b) illustrates the multi-cell topology with four Wi-Fi cells and one eLAA cell.

For performance comparison, we consider three competitive schemes: 1) The baseline scheme is the legacy eLAA, which starts UL transmission only when 25 \( \mu \text{s} \) LBT succeeds without using RS, 2) UE only scheme applies only the UE operation of UpChance, and 3) DL-RS scheme allows the eNB to continuously transmit DL-RS after transmitting a UL grant or RAR, which helps the UE to occupy the channel until 25 \( \mu \text{s} \) before UL transmission.

B. UL DATA TRANSMISSION

We investigate the coexistence performance of UpChance according to the interference length when the channel is saturated. Fig. 8(a) shows throughput of Wi-Fi and eLAA with varying Wi-Fi A-MPDU length in the two-cell topology. Fig. 8(b) shows airtime performance of Wi-Fi and eLAA, and

\begin{equation}
J(x_1, x_2, \ldots, x_n) = \frac{\left( \sum_{i=1}^{n} x_i \right)^2}{n \sum_{i=1}^{n} x_i^2}. \tag{22}
\end{equation}

In the baseline scheme, Wi-Fi takes up most of the throughput and airtime regardless of the Wi-Fi A-MPDU length. This is because the baseline scheme cannot support the coexistence well under the saturated channel. UE only scheme shows better coexistence performance than the baseline scheme because the UE is able to use UL-RS. DL-RS scheme shows significantly lower throughput than the other three schemes.

UpChance shows a performance improvement of up to 88% in terms of fairness compared to the baseline scheme. When the Wi-Fi A-MPDU length is 1 ms or 3 ms, the results of UpChance and UE only scheme are the same because the result of delayed scheduling is the same as that of the legacy scheduling. In the other cases, UpChance occupies the channel more often compared to UE only scheme thanks to delayed scheduling. As a result, UpChance shows better performance than UE only scheme in various environments. The performance improvement increases with the interference length.

### TABLE 1. Simulation parameters.

| Simulation parameters          | Value       |
|-------------------------------|-------------|
| Simulation time               | 10 s        |
| File size                     | 0.25 MB     |
| Bandwidth                     | 20 MHz      |
| Wi-Fi PHY                     | 802.11ac, 2 \times 2 MIMO |
| maximum Wi-Fi A-MPDU bound    | 1–5 ms, 1,048,575 bytes |
| Wi-Fi rate adaptation         | Minstrel VHT|
| AP/eNB transmission power     | 23 dBm      |
| STA/UE transmission power     | 18 dBm      |
| Wi-Fi C/CCA threshold         | -82 dBm     |
| Wi-Fi CCA-C/ED threshold      | -92 dBm     |
| LTE CCA-C/ED threshold        | -72 dBm     |
| \( N \)                       | 20          |
| \( d_{\text{MAX}} \)         | 10          |
| \( L/T_{\text{min}} \)       | 34 \( \mu \text{s} \) |
| \( L/T_{\text{max}} \)       | 178 \( \mu \text{s} \) |

\(^{12}\)Random access follows the MulteFire specification because it is not defined in eLAA.

\(^{13}\)In realistic deployment in USA, most LAA deployments are in outdoor environments [28].

![FIGURE 7. Simulation topology.](image-url)

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We investigate the coexistence performance of UpChance in the multi-cell topology of four Wi-Fi cells and one eLAA cell. Fig. 9 shows throughput and airtime performance. Four Wi-Fi cells have four different Wi-Fi A-MPDU lengths of 5 ms, 4 ms, 3 ms, and 2 ms, respectively. The percentage of channel occupancy of each AP is proportional to the A-MPDU length. The baseline scheme rarely allows eLAA to occupy the channel similarly in the two-cell topology due to the limitations of the legacy LBT operation. UE only scheme shows more performance improvement of eLAA compared to the baseline scheme thanks to the use of UL-RS. DL-RS scheme increases eLAA performance and decreases network throughput compared to the baseline scheme. It wastes lots of time that can be exploited in the other schemes. UpChance shows improved eLAA performance due to the increased LBT success probability of the UE even under various interference lengths.

Fig. 10 shows the network throughput gain of UpChance compared to the baseline scheme according to the file size and the number of files per second of Wi-Fi in the two-cell topology under the unsaturated traffic condition. The product of x-axis and y-axis is the Wi-Fi source rate. For low Wi-Fi source rate, the throughput gain is also low due to low Wi-Fi traffic. With the Wi-Fi source rate, Wi-Fi transmission gradually hinders eLAA transmission, which acts as the baseline scheme. The more the hindrance, the greater the gain of UpChance. The throughput gain of UpChance increases by
random access performance of UpChance according to the Wi-Fi A-MPDU length.

FIGURE 12. Random access performance of UpChance in multi-cell topology.

C. RANDOM ACCESS

We investigate how well random access is performed in the coexistence environment. In the random access scenario, after completing random access, the UE attempts random access again in the next PRACH slot. Fig. 11 shows random access completion time according to the Wi-Fi A-MPDU length in the two-cell topology under saturated Wi-Fi traffic. The random access completion time is the time from when the transmission of msg 1 is desired until the transmission of msg 4 is finished. The results of the maximum y-axis expressed are those of not successfully completed random access.

The baseline scheme does not complete random access operation, regardless of the Wi-Fi A-MPDU length. This is because LBT for msg 3 is almost unsuccessful in an environment where Wi-Fi traffic is saturated. UE only scheme shows the random access completion time of 16.83 ms and 20.59 ms when the Wi-Fi A-MPDU length is 1 ms and 3 ms, respectively, which are much smaller than those shown by the baseline scheme. When the Wi-Fi A-MPDU length is 2 ms, 4 ms, and 5 ms, UE only scheme shows smaller performance improvement compared to the baseline scheme.

The probability of additional Cat. 4 LBT success of the UE varies greatly depending on the length of Wi-Fi frame transmitted immediately after msg 2 transmission, resulting in a large performance difference. When the Wi-Fi A-MPDU length is 1 ms and 3 ms, the transmission of Wi-Fi frame is highly likely to end during the period when the UE performs additional Cat. 4 LBT. Thus, the UE tends to occupy the channel during this period. On the other hand, when the Wi-Fi A-MPDU length is 2 ms, 4 ms, and 5 ms, the transmission of Wi-Fi frame is highly likely to continue for a period during which the UE performs additional Cat. 4 LBT. Thus, the UE is not likely to occupy the channel. As described above, the operation of UE only scheme is greatly affected by the interference.

DL-RS scheme shows more reliable performance than UE only scheme according to the Wi-Fi A-MPDU length. The random access completion time in DL-RS scheme gradually increases with the Wi-Fi A-MPDU length. This is because the probability of LBT success for msg 1 decreases with the Wi-Fi A-MPDU length. In addition, msg 3 transmission is guaranteed through DL-RS transmission, so the transmission probability of msg 3 is not affected by the Wi-Fi A-MPDU length.

UpChance shows the best performance in all the cases compared to the other schemes. It reduces random access completion time by up to 99% compared to the baseline. UpChance has a good ability to cope with various Wi-Fi A-MPDU lengths owing to its eNB operation. When the Wi-Fi A-MPDU length is 1 ms and 3 ms, UpChance shows the same performance as UE only scheme. This is because msg 3 is well transmitted even without the help of delayed scheduling at the eNB. When the Wi-Fi A-MPDU length is 2 ms, 4 ms, and 5 ms, UpChance shows significantly improved random access performance compared to UE only scheme. This is because msg 3 is scheduled by predicting when the Wi-Fi frame ends.

Fig. 12 shows random access completion time in the multi-cell topology. Four Wi-Fi APs have the Wi-Fi A-MPDU length of 5 ms, 4 ms, 3 ms, and 2 ms, respectively. The baseline scheme shows very high random access completion time because random access is rarely successful due to difficulties in transmission of msg 1 and msg 3 as in the two-cell topology. UE only scheme shows better performance than the baseline scheme due to the benefit of
UL-RS transmission. DL-RS scheme also has the random access completion time similar to that of UE only scheme. By guaranteeing the msg 3 transmission, it shows better performance than the baseline scheme, but worse performance than UpChance because of the poor msg 1 transmission probability. UpChance shows the best performance thanks to the use of UL-RS and delayed scheduling.\footnote{The performance gap between UE only scheme and UpChance in the random access scenario is larger than that in UL data scenario. This is because msg 2 schedules only one subframe for msg 3.}

Fig. 13 shows the random access completion time gain under unsaturated Wi-Fi traffic in the two-cell topology. The performance in UpChance increases with the Wi-Fi source rate. For low Wi-Fi source rate, random access works well even in the baseline scheme, so there is little random access completion time gain. With the Wi-Fi source rate, UpChance shows gradually improved performance compared to the baseline scheme owing to its successful transmission of msg 1 and msg 3. For the saturated channel, the baseline scheme rarely succeeds in random access. As a result, UpChance shows random access completion time gain of nearly 100% over the baseline scheme.

VI. CONCLUSION

In this article, we investigated the uplink channel access problem of cellular communication in the unlicensed spectrum through mathematical analysis, and proposed a standard-compliant solution named UpChance. The UE in UpChance uses a minimum length of uplink reservation signal for contention-based channel access, without harming the nature of UL multi-access. The eNB in UpChance detects channel saturation and schedules the UE’s uplink transmission with the best delay. Through ns-3 simulation, we evaluated the performance of UpChance in UL data transmission and random access scenarios. We confirmed that UpChance achieves fairness performance improvement of up to 88% in the UL data scenario, and the random access completion time gain of up to 99% in the random access scenario.
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JIHOON KIM (Student Member, IEEE) received the B.S. degree in electrical and computer engineering from Seoul National University in 2014, where he is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering. His current research interests include protocol design for cellular communication in unlicensed spectrum and coexistence issue between heterogeneous wireless networks in unlicensed spectrum.

JAEHONG YI (Student Member, IEEE) received the B.S. degree in electrical and electronic engineering from KAIST in 2012. He is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering. His research interests include protocol design for LTE in unlicensed spectrum and 5G new radio.

SAEWOONG BAHK (Senior Member, IEEE) received the B.S. and M.S. degrees in electrical engineering from Seoul National University in 1984 and 1986, respectively, and the Ph.D. degree from the University of Pennsylvania, in 1991. He was with AT&T Bell Laboratories as a Member of Technical Staff from 1991 to 1994, where he was involved in network management. From 2009 to 2011, he served as the Director of the Institute of New Media and Communications. He is currently a Professor with Seoul National University (SNU). He has been leading many industrial projects on 3G/4G/5G and the IoT connectivity supported by Korean industry. He has authored or coauthored more than 200 technical articles. He holds more than 100 patents. He is a member of the National Academy of Engineering of Korea and the Who’s Who Professional in Science and Engineering. He has been serving as the Chief Information Officer of SNU. He is the President of the Korean Institute of Communications and Information Sciences (KICS). He was a recipient of the KICS Haedong Scholar Award in 2012. He was on the Editorial Board of the Computer Networks Journal and the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS. He has been serving as the General Chair of the IEEE Wireless Communication and Networking Conference in 2020. He was the General Chair of the IEEE Dynamic Spectrum Access and Networks in 2018 and the Director of the Asia-Pacific Region of the IEEE ComSoc. He is an Editor of the IEEE Network Magazine. He was the TPC Chair of the IEEE VTC-Spring 2014 and the General Chair of JCCI 2015. He was the Co-Editor-in-Chief of the Journal of Communications and Networks.

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