Dynamic Resource Adjustment for Coexistence of LAA and Wi-Fi in 5 GHz Unlicensed Bands

Jihoon Choi, Eunkyung Kim, and Sungcheol Chang

To enable the coexistence of Licensed Assisted Access (LAA) and Wi-Fi in 5 GHz unlicensed bands, a new channel access mechanism is proposed. Accounting for the fairness between LAA and Wi-Fi, the proposed mechanism finds the optimal transmission time ratio by adaptively adjusting the transmission durations for LAA and Wi-Fi. In addition, we propose a new analytical model for the distributed coordination function of IEEE 802.11 through some modifications of conventional analytical models for saturation and non-saturation loads. By computing the activity ratio of Wi-Fi, the proposed analytical model is able to control the time ratio between LAA and Wi-Fi, which is required for practical implementation of the proposed access mechanism. Through numerical simulations, the proposed channel access mechanism is compared with conventional methods in terms of throughput and utility.

Keywords: Long-Term Evolution, Wi-Fi, channel access, time adjustment, coexistence, unlicensed spectrum, LTE.

I. Introduction

The mobile communication systems based on 3rd Generation Partnership Project Long-Term Evolution (3GPP LTE) have been successfully commercialized in various countries. Current LTE systems are evolving to LTE-Advanced supporting up-to-date cellular technologies, such as enhanced multiple-input and multiple-output (MIMO) transmission; carrier aggregation; interference management and suppression; and enhanced channel coding, to improve spectral efficiency and provide higher data rates for broadband data services; high-resolution video and audio services; and real-time applications [1]–[3]. However, since the explosive increase in demand for mobile services is surpassing the improvement of spectral efficiency, mobile service providers are requiring more frequency bands. The frequency demand is also growing for ultra-high-definition television–based broadcasting and public protection and disaster relief services [4]–[5]; thus, it is very difficult to assign more licensed spectrum to cellular systems.

As an alternative, extending LTE to unlicensed spectrum has attracted great attention as a means to accommodate the rapid mobile data growth. Also, dual connection through licensed and unlicensed bands is one of the key technologies for 5th generation (5G) wireless networks.

LTE small cells can provide mobile communication services using a unified LTE network by aggregating unlicensed bands with licensed bands [6]–[7]. As presented in [7], the amount of unlicensed spectrum that is already allocated and planned to be allocated in the near future is comparable to that of licensed spectrum. In fact, some network operators have deployed Wi-Fi access points (APs) referred to as Carrier Wi-Fi to offload cellular traffic. However, LTE in unlicensed spectrum can offer better capacity and coverage than Carrier Wi-Fi because of

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higher multiple-access efficiency and less overhead [7]–[11], while providing smooth interworking between the licensed and unlicensed bands. For these reasons, standard activities related to LTE in unlicensed spectrum are in progress and mainly focus on licensed-assisted carrier aggregation operation, referred to as Licensed Assisted Access (LAA). In the LAA mode, the licensed bands are utilized as the primary downlink and primary uplink, and the unlicensed bands are only used as the secondary downlink (SDL) [12]. While LTE in licensed bands can guarantee a reliable quality of service (QoS), an LAA network finds it difficult to achieve a stable QoS because the unlicensed bands it utilizes are shared with other communication devices such as Wi-Fi, Bluetooth, and ZigBee. In particular, LAA in 5 GHz unlicensed bands needs to share the spectrum with Wi-Fi devices supporting IEEE 802.11n and IEEE 802.11ac.

In [13], a spectrum sharing rule among multiple unlicensed systems is theoretically formulated in terms of utility functions and solved by employing a game-theoretic approach. Coexistence mechanisms between license-exempt LTE and other systems have been investigated in [14]–[16] for secondary usage of TV white space spectrum. Channel access mechanisms for the LTE system have been studied in [17]–[20] considering coexistence with Wi-Fi devices supporting carrier sense multiple access with collision avoidance (CSMA/CA). The use of a clear-to-send message is suggested to reserve the channel resource for the uplink transmission of LTE in [17], and a utility function is defined to assign the unlicensed channel resource to LTE and Wi-Fi optimizing the transmission power of the licensed LTE in [18]. In the case of an LTE femtocell using a Wi-Fi-like channel access method, the impact of femtocell channel access parameters was investigated [19]. In [20], an adaptive channel access method is developed that adjusts the channel access probability of the unlicensed LTE based on the data rate and traffic requirement of Wi-Fi. For practical use, the channel access mechanisms in [18]–[20] need to be applied to an LAA system operating in a non-cooperative mode with Wi-Fi. However, it is impossible to implement the access methods in [18]–[20], because they require Wi-Fi system parameters, such as effective data rates and traffic requirements, which are not available to LAA.

In this paper, we propose a new channel access mechanism for the LAA system coexisting with Wi-Fi stations in unlicensed bands. The proposed mechanism predefines the frame duration and adjusts the transmission duration for LAA depending on the data rates and traffic loads of LAA and Wi-Fi. Considering the fairness between LAA and Wi-Fi, we define a utility function and find the optimal time ratio for channel sharing. To avoid direct estimation of the data rate and traffic load for Wi-Fi, we propose a new analytical model for Wi-Fi distributed coordination function (DCF) by modifying the analytical models in [21]–[22]. Using the proposed analytical model, it is determined if the Wi-Fi network necessitates more transmission time, and the time ratio between LAA and Wi-Fi is adaptively adjusted. Since the proposed model does not require the Wi-Fi data rate and traffic load, it can be implemented in a practical LAA system without changing existing Wi-Fi standards. Through numerical simulations, the proposed channel access mechanism is compared with the Wi-Fi-like access method, in which an LAA evolved Node B (eNB) competes with Wi-Fi stations using the 802.11 DCF model. In addition, we evaluate the proposed channel access mechanism depending on various time adjustment methods in terms of throughput and utility.

This paper is organized as follows. Section II introduces the channel access methods for LAA and Wi-Fi, and Section III proposes an adaptive algorithm that dynamically adjusts the time ratio between LAA and Wi-Fi. We present simulation results related to the proposed access mechanism in Section IV and provide conclusions in Section V.

II. Channel Access Methods for LAA and Wi-Fi

In this section, we introduce two kinds of channel access methods for coexistence of LAA and Wi-Fi in unlicensed spectrum, under the assumption that an LAA eNB can detect Wi-Fi signals through carrier sensing (CS). In the following channel access methods, Wi-Fi stations detect LAA signals in the same band through the physical CS mechanism without changing existing Wi-Fi devices, thereby it is assumed that the LAA data frame has no blank subframe or blank symbol in the middle of transmission.

1. Wi-Fi-Like Channel Access Method

Figure 1 presents the Wi-Fi-like channel access method in which the LAA eNB performs the channel access using the 802.11 DCF mode [23]. In this method, the LAA eNB competes with Wi-Fi stations to occupy the channel based on the CSMA/CA operation. A Wi-Fi station transmits a data

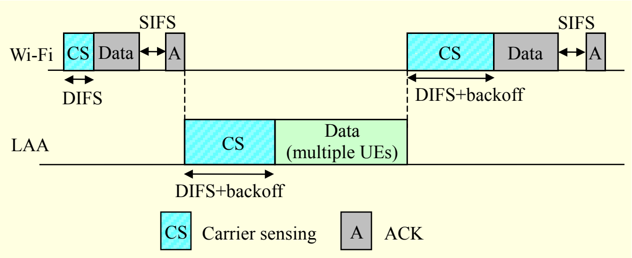

Fig. 1. Wi-Fi-like channel access for LAA data transmission.

packet followed by an acknowledgement (ACK) packet with the Short Interframe Space (SIFS). Then, the LAA eNB checks the channel through CS, and decreases the backoff counter when the channel is idle. If the backoff counter is zero and the channel is idle during the DCF Interframe Space (DIFS), then the LAA eNB transmits the data frame for multiple user equipments (UEs) using a frame format similar to that of the licensed band.

Suppose that there are N Wi-Fi stations. When we use the Wi-Fi-like access scheme for the LAA eNB, the whole network is equivalent to a Wi-Fi network with (N+1) stations except that the LAA eNB sends data frames to multiple UEs. Therefore, the coexistence problem can be easily solved by this access method. However, this method has the following drawbacks:

- The LAA eNB suffers from some channel capacity loss due to the random backoff operation. For example, the capacity loss can be avoided by employing the coexistence gap–based approach in [15].
- The LAA throughput is significantly influenced by transmission conditions of Wi-Fi stations. For example, the transmission time of the LAA eNB can be reduced by the relatively low spectral efficiency of Wi-Fi systems.

2. Proposed Channel Access Method

In this subsection, we propose a new channel access method in which the LAA eNB partitions the channel in time and dynamically adjusts the time ratio between LAA and Wi-Fi. Figure 2 describes the basic access policy of the proposed method. The LAA eNB predefines the frame duration, T_{frame}, which is divided into the transmission periods for LAA and Wi-Fi, denoted as T_1 and T_2, respectively. When a Wi-Fi transmission is completed before the beginning of T_1 as in Fig. 2(a), the LAA eNB performs CS during the LAA Interframe Space (LIFS) and transfers an LAA data frame for T_1. Wi-Fi nodes can detect the LAA data frame through the physical CS, so Wi-Fi stations do not start to send a new packet during the T_1 period. The Wi-Fi data transmission is resumed according to the random backoff process after the LAA data transmission is finished. Figure 2(b) denotes the channel access operation of the proposed method when a Wi-Fi data transmission is not finished in the T_2 period. In this case, the LAA data transfer is deferred until the Wi-Fi data transmission is completed to prevent a collision. Though the LAA data transmission is delayed by T_d in the first frame, the LAA transmission period is the same as that of Fig. 2(a). Instead, the Wi-Fi transmission period for the next frame is shortened by T_d to prevent the change of the average time ratio between LAA and Wi-Fi.

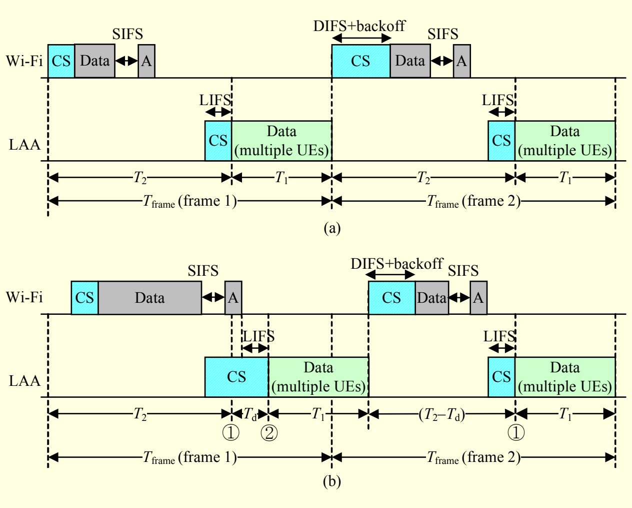

Fig. 2. Proposed channel access method: (a) when Wi-Fi transmission is completed in period T_2 and (b) when Wi-Fi transmission is not completed in period T_2 (LAA transmission is deferred).

The periodic time allocation for coexistence is initially proposed in [24] and refined for coexistence of LAA and Wi-Fi in [15]. In [15], however, the LAA eNB resumes the downlink transmission without attempting to assess the channel availability, thereby a collision can transpire amid the last Wi-Fi packet in the T_2 period and the following LAA frame. In contrast, the proposed access method avoids the collision between Wi-Fi and LAA by performing CS before resuming the LAA data transmission. As compared with the Wi-Fi-like access method, the proposed access scheme has no random backoff loss and guarantees the transmission time of LAA irrespective of the transmission conditions of coexisting Wi-Fi nodes. Therefore, the LAA throughput is limitedly influenced by Wi-Fi nodes. The Wi-Fi-like access scheme allocates the channel to the LAA eNB and Wi-Fi nodes in a proportionally fair sense. In contrast, the proposed access method needs to adjust the transmission periods T_1 and T_2 depending on the traffic loads of LAA and Wi-Fi. In a practical system, the parameters T_{frame}, T_1, and T_2 are unknown to Wi-Fi nodes and their adjustment is carried out in the LAA eNB without explicit knowledge of the Wi-Fi data rate and traffic load.

III. Proposed Algorithm for Adjustment of Time Ratio

This section derives an algorithm that adjusts the time ratio between LAA and Wi-Fi, used in the proposed access mechanism in Section II-2. In the derivation, the following is assumed:

- There are multiple Wi-Fi nodes, one LAA eNB, and multiple LAA UEs. While the Wi-Fi network supports both the uplink and downlink connections, the LAA only provides the downlink transmission.

- T_{frame} is a fixed parameter.
- T_1 and T_2 are adjusted in the range of $0 \le T_1, T_2 \le T_{\text{frame}}$ satisfying $T_1 + T_2 = T_{\text{frame}}$.
- LAA and Wi-Fi signals are perfectly detected by CS; that is, there is no detection error and no false alarm.
- There are no hidden terminals.

Firstly, by defining a utility function to share the channel, we find the theoretically optimal time ratio when the data rate and traffic load are available. Then, by modifying the optimal solution for practical use, an adaptive procedure is derived that adjusts T_1 and T_2. Finally, we derive a new Wi-Fi analytical model required to control T_2 in the adaptive procedure.

1. Theoretically Optimal Time Ratio

To formulate the spectrum sharing problem between LAA and Wi-Fi, we employ a utility function based on the proportional fairness [25]. Then, the problem of maximizing the utility function is given as

$$\begin{aligned} \max\ & U_{\text{PF}}(\tau_1,\tau_2) = \log(R_1\tau_1) + \log(R_2\tau_2) \\ \text{s.t. } & R_1\tau_1 \le L_1\ ,\ R_2\tau_2 \le L_2, \\ & \tau_1 + \tau_2 \le 1,\quad \tau_1,\tau_2 \ge 0, \end{aligned} \tag{1}$$

where R_1 and R_2 are the average data rates of LAA and Wi-Fi, and L_1 and L_2 are the traffic loads of LAA and Wi-Fi, respectively. The variables τ_1 and τ_2 are the activity ratios of LAA and Wi-Fi, respectively, which denote the time ratio occupying the channel for data transmission. Note that the logarithmic utility function in (1) is widely used for the resource allocation of coexisting systems [13], [18], [20]. Depending on the relative traffic load, the maximization problem can be solved in different ways. When the channel is capable of processing all traffic loads, the optimal solution is expressed as follows:

- Case 1: when $L_1/R_1 + L_2/R_2 < 1$,

$$\tau_1 = L_{R,1},\ \tau_2 = L_{R,2}, \tag{2}$$

where the relative traffic load $L_{R,i} = L_i/R_i$. Here, (2) is simply obtained by the constraints of (1). On the other hand, when the channel cannot deal with all traffic loads for LAA and Wi-Fi, the optimal solution can be found separately in the following three different cases:

- Case 2-1: when $L_1/R_1 + L_2/R_2 \ge 1$ and $L_1/R_1 \le 0.5$,

$$\tau_1 = L_{R,1},\ \tau_2 = 1 - L_{R,1}\ . \tag{3}$$

- Case 2-2: when $L_1/R_1 + L_2/R_2 \ge 1$ and $L_2/R_2 \le 0.5$,

$$\tau_1 = 1 - L_{R,2},\ \tau_2 = L_{R,2}\ . \tag{4}$$

- Case 2-3: when $L_1/R_1 > 0.5$ and $L_2/R_2 > 0.5$,

$$\tau_1 = \tau_2 = 0.5\ . \tag{5}$$

For Case 2-1, τ_1 is bounded by the traffic load constraint for LAA when τ_1 and τ_2 are equally increased to maximize the utility function. Thus, the transmission time is maximally assigned to τ_1 considering the traffic load constraint and the remaining time is allocated to τ_2. In a similar manner, for Case 2-2, the transmission time is firstly assigned to τ_2 and the remaining time is allocated to τ_1. In Case 2-3, τ_1 and τ_2 are bounded by the constraint of (1) when τ_1 and τ_2 are equally increased. So, the optimal solution is given by (5).

Now, let us define $t_1(n)$ and $t_2(n)$ as the assigned time ratios for LAA and Wi-Fi at iteration n, respectively. While the activity ratio is the time ratio used for data transmission, the assigned time ratio means the time ratio assigned to a communication system. So, it is satisfied that $\tau_1 \le t_1(n)$ and $\tau_2 \le t_2(n)$. Also, it is assumed that the channel is occupied by either LAA or Wi-Fi; that is, $t_1(n) + t_2(n) = 1$. Under these constraints, we develop an adaptive procedure to adjust $t_1(n)$ and $t_2(n)$. In Case 1, $t_1(n)$ and $t_2(n)$, to ensure the optimal τ_1 and τ_2 of (2), are denoted as

$$L_{R,1} \le t_1(n) \le 1 - L_{R,2}, \tag{6}$$

$$L_{R,2} \le t_2(n) \le 1 - L_{R,1}. \tag{7}$$

Also, in Cases 2-1, 2-2, and 2-3, the optimal activity ratios are obtained only when $t_1(n) = \tau_1$ and $t_2(n) = \tau_2$. Suppose that R_1, R_2, L_1, and L_2 are known. Then, $t_1(n)$ and $t_2(n)$ for achieving the optimal activity ratios can be found in the following procedure:

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1) Initialization: $n = 0$, $t_1(0) = t_2(0) = 0.5$.
2) If $R_1 t_1(n) \ge L_1$, $R_2 t_2(n) \ge L_2$,
       $t_1(n+1) = t_1(n)$, $t_2(n+1) = t_2(n)$.                          (8)
3) Else if $R_1 t_1(n) \ge L_1$, $R_2 t_2(n) < L_2$,
       $t_1(n+1) = t_1(n) - \Delta t$, $t_2(n+1) = t_2(n) + \Delta t$,    (9)
   where $\Delta t$ is the step-size parameter for time ratio adjustment.
4) Else if $R_1 t_1(n) < L_1$, $R_2 t_2(n) \ge L_2$,
       $t_1(n+1) = t_1(n) + \Delta t$, $t_2(n+1) = t_2(n) - \Delta t$.    (10)
5) Else if $R_1 t_1(n) < L_1$, $R_2 t_2(n) < L_2$,
   If $t_1(n) == t_2(n)$, use equation (8).
   Else if $t_1(n) > t_2(n)$, use equation (9).
   Else if $t_1(n) < t_2(n)$, use equation (10).
6) $n = n + 1$ and repeat steps 2)–5).
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In the above procedure, step 2) means that the effective data rate is equal to or greater than the traffic load for both LAA and Wi-Fi. In other words, both LAA and Wi-Fi are unsaturated; so, $t_1(n)$ and $t_2(n)$ are not changed. Step 3) denotes that LAA is unsaturated and Wi-Fi is saturated, thereby $t_1(n)$ is decreased while $t_2(n)$ is increased. In a similar manner, $t_1(n)$ is increased and $t_2(n)$ is decreased in step 4). Since both LAA and Wi-Fi systems are saturated in step 5), $t_1(n)$ and $t_2(n)$ are updated to the direction that the two values become identical.

The above adaptation procedure is performed by the LAA eNB. However, since R_2 and L_2 are not available in the LAA eNB, the above procedure cannot be implemented in practical systems.

2. Proposed Adaptive Algorithm for Time Adjustment

In this subsection, we develop a practical algorithm for time ratio adjustment that uses the saturation status for LAA and Wi-Fi. Considering the time variation of R_1 and L_1, we define $R_1(n)$ and $L_1(n)$ as the LAA data rate and traffic load at iteration n, respectively. Since $R_1(n)$ and $L_1(n)$ are available to the LAA eNB, the saturation status for LAA can be determined by

$$d_{\text{LAA}}(n) = R_1(n)\frac{T_1(n)}{T_{\text{frame}}} - L_1(n), \tag{11}$$

where $T_1(n)$ is the LAA transmission period at iteration n. If $d_{\text{LAA}}(n) > 0$, then the effective data rate of LAA is greater than the traffic load; thus, the LAA is unsaturated. Otherwise, the LAA is judged to be saturated. On the other hand, since the data rate and traffic load of Wi-Fi are not available, the saturation status for Wi-Fi is determined by comparing the theoretically computed Wi-Fi activity ratio with the measured value. Specifically, we define a metric for Wi-Fi as follows:

$$d_{\text{Wi-Fi}}(n) = \frac{\frac{T_2(n)-\Delta T}{T_2(n)}U_{\text{t}}\left(T_2(n)-\Delta T\right) - U_{\text{m}}(n)}{U_{\text{m}}(n)}, \tag{12}$$

where $T_2(n)$ is the Wi-Fi transmission period at iteration n, $U_{\text{m}}(n)$ is the measured Wi-Fi activity ratio at iteration n, and $U_{\text{t}}(x)$ denotes the theoretically computed activity ratio when the Wi-Fi transmission period is x. Computing $U_{\text{t}}(x)$ in a practical Wi-Fi system is explained in Section III-3. When the Wi-Fi is not saturated, $U_{\text{t}}(x)$ is inversely proportional to x and satisfies the following relationship:

$$U_{\text{t}}\left(T_2(n)-\Delta T\right) = \frac{T_2(n)}{T_2(n)-\Delta T}U_{\text{t}}\left(T_2(n)\right), \tag{13}$$

where ΔT is the step-size parameter for time adjustment. Therefore, when the Wi-Fi is unsaturated and the theoretical activity ratio is identical with the measured value, $d_{\text{Wi-Fi}}(n)$ becomes zero. In contrast, $U_{\text{t}}(T_2(n) - \Delta T)$ is similar to $U_{\text{t}}(T_2(n))$ in the case when the Wi-Fi system is saturated. Thus, $d_{\text{Wi-Fi}}(n)$ has a negative value. Using this property, the Wi-Fi system is determined to be unsaturated if $d_{\text{Wi-Fi}}(n) > \alpha$, where α is a decision threshold; otherwise, it is judged to be saturated.

Based on the saturation information for LAA and Wi-Fi, we obtain a practical method for time ratio adjustment by modifying the adaptive procedure in Section III-1. Since T_{frame} is fixed in the proposed channel access mechanism, adjusting the time ratio is equivalent to altering $T_1(n)$ and $T_2(n)$. So, the time adjustment scheme is described with respect to $T_1(n)$ and $T_2(n)$ as follows:

1) Initialization: $n = 0$, $T_1(0) = T_2(0) = 0.5T_{\text{frame}}$.
2) Decision of the LAA saturation status: use equation (11).
3) Decision of the Wi-Fi saturation status: use equation (12).
4) Update of $T_1(n)$ and $T_2(n)$:
   (i) If both LAA and Wi-Fi are unsaturated,
   $$T_1(n+1) = T_1(n),\ T_2(n+1) = T_2(n). \tag{14}$$
   (ii) Else if LAA is unsaturated and Wi-Fi is saturated,
   $$T_1(n+1) = T_1(n) - \Delta T,\ T_2(n+1) = T_2(n) + \Delta T. \tag{15}$$
   Else if LAA is saturated and Wi-Fi is unsaturated,
   $$T_1(n+1) = T_1(n) + \Delta T,\ T_2(n+1) = T_2(n) - \Delta T. \tag{16}$$
   Else if both LAA and Wi-Fi are saturated,
   If $T_1(n) == T_2(n)$, use equation (14).
   Else if $T_1(n) > T_2(n)$, use equations (15).
   Else if $T_1(n) < T_2(n)$, use equations (16).
5) $n = n + 1$ and repeat steps 2)–4).

Since the above time adjustment procedure uses the Wi-Fi activity ratio instead of the Wi-Fi data rate and traffic load, it can be implemented in a practical LAA eNB coexisting with Wi-Fi networks. For practical use, it is crucial to accurately compute the theoretical Wi-Fi activity ratio. This issue is discussed in the following subsection.

3. Estimation of Wi-Fi Activity Ratio

In [21], an analytical model is provided to compute the 802.11 DCF saturation throughput. In [22], the analytical model is enhanced by accounting for the channel state during the backoff countdown process and further extended to unsaturated traffic cases. In this subsection, a new analytical model is derived to estimate the Wi-Fi activity ratio under a mixed-load condition in which some Wi-Fi nodes are under saturated load and the rest are under unsaturated load. The aim of the Wi-Fi analytical model is to compute the activity ratio instead of the throughput, thereby the complicated enhanced model of [22] is not necessary. So, the proposed analytical model adopts the saturation model in [21] and extends it for the analysis of a mixed load by modifying the non-saturation model in [22]. Note that the accuracy of the analytical model in the case of a mixed load is critical to the performance of the proposed channel access mechanism.

Suppose that all Wi-Fi stations have a saturation load; that is, full buffer traffic. From the Markov Chain model for the backoff window size in [21], the probability that a station transmits in a randomly chosen slot time, γ, is given by

$$\gamma = \frac{2(1-2p)}{(1-2p)(\mathrm{CW}_{\min}+1)+p\mathrm{CW}_{\min}\left(1-(2p)^m\right)}, \tag{17}$$

where $\mathrm{CW}_{\min}$ and $\mathrm{CW}_{\max}$ are the minimum and maximum backoff window sizes, respectively, $m = \log_2(\mathrm{CW}_{\max}/\mathrm{CW}_{\min})$, and p is the probability that a transmitted packet encounters a collision. Also, when a station transmits a packet, a collision occurs if at least one of the remaining stations transmits in a given slot. This yields the following equation:

$$p = 1-(1-\gamma)^{N-1}, \tag{18}$$

where N is the number of active Wi-Fi stations. Equations (17) and (18) with two unknowns γ and p can be solved by numerical iterations. By modifying the saturation throughput of [21], the activity ratio for saturation load is expressed as

$$V_N = \frac{P_{\mathrm{s}}T_{\mathrm{s}}}{P_{\mathrm{s}}T_{\mathrm{s}}+(P_{\mathrm{b}}-P_{\mathrm{s}})T_{\mathrm{c}}+(1-P_{\mathrm{b}})T_{\mathrm{i}}}, \tag{19}$$

where P_{s} is the probability that a slot time contains the beginning of a successful packet transmission, P_{b} is the probability that a slot time is busy, T_{s} is the duration of a successful transmission, T_{c} is the duration of a collided transmission, and T_{i} is a slot time. Using γ and p, P_{s} and P_{b} are denoted as

$$P_{\mathrm{s}} = N\gamma(1-\gamma)^{N-1}, \tag{20}$$

$$P_{\mathrm{b}} = 1-(1-\gamma)^{N}. \tag{21}$$

With the basic access scheme of the DCF, T_{s} is calculated as

$$T_{\mathrm{s}} = \mathrm{DIFS}+\mathrm{E}[T_{\mathrm{p}}]+\mathrm{SIFS}+T_{\mathrm{ACK}}, \tag{22}$$

where $\mathrm{E}[T_{\mathrm{p}}]$ is the average transmission duration of a physical packet and T_{ACK} is the transmission duration of the ACK packet. Also, T_{c} is written as

$$T_{\mathrm{c}} = \mathrm{DIFS}+\mathrm{E}[T_{\mathrm{p}}^{*}]+\mathrm{SIFS}+T_{\mathrm{ACK}}, \tag{23}$$

where $\mathrm{E}[T_{\mathrm{p}}^{*}]$ is the average of the largest transmission duration for the packets involved in a collision. When we neglect the probability that three or more packets collide, $\mathrm{E}[T_{\mathrm{p}}^{*}]$ is given by

$$\mathrm{E}[T_{\mathrm{p}}^{*}] = \int_0^{T_{\mathrm{p,max}}}\left(1-F^2(x)\right)\mathrm{d}x, \tag{24}$$

where $T_{\mathrm{p,max}}$ is the maximum packet transmission duration and $F(x)$ is the cumulative distribution function (CDF) of T_{p}. In a practical system, the LAA eNB estimates N, $T_{\mathrm{p,max}}$, and $F(x)$ by receiving the Wi-Fi signals during a predetermined period.

In general, the number of saturated stations for a mixed load is unknown, even when N is known. So, the proposed analytical model starts to compute the activity ratio, assuming that m stations are saturated and $(N-m)$ stations are unsaturated, where $0 \le m \le N$. Given m, the proposed model calculates the service rate and verifies the number of saturated stations by comparing the service rate and the stations' arrival rates. The proposed analytical model iteratively computes the activity ratio for varying m, until m is equal to the estimated number of saturated stations. Suppose that packet arrivals for the kth station follow a Poisson distribution with rate λ_k. To model the unsaturated stations, we need to compute the probability P_0 that a station's queue is empty. Since the service rate is proportional to the arrival rate in non-saturation load, it is assumed that P_0 is identical for all unsaturated stations. For convenience, suppose that $\lambda_1 \le \lambda_2 \le \cdots \le \lambda_N$. Then, given m, $\{\lambda_1, \lambda_2, \ldots, \lambda_{N-m}\}$ represent the arrival rates for unsaturated stations. Using the queuing model for the DCF in [26], P_0 is denoted as

$$P_0 = 1-\frac{\frac{1}{N-m}\sum_{k=1}^{N-m}\lambda_k}{\mu} = 1-\frac{\mathrm{E}[D]}{N-m}\sum_{k=1}^{N-m}\lambda_k, \tag{25}$$

where μ is the average service rate and $\mathrm{E}[D]$ is the average channel access delay of each station. Suppose that B_k is the probability that the number of active stations is k. The number of active stations for a non-saturation load varies depending on P_0; thus, B_k follows a binomial distribution, given by

$$B_k = \binom{N-m}{k-m}(1-P_0)^{k-m}P_0^{N-k}, \tag{26}$$

where $B_0 = B_1 = \ldots = B_{m-1} = 0$ and $m \le k \le N$. Note that k includes m saturated stations. D_k is defined as the average channel access delay when k stations are contending for the channel. Then, D_k can be computed by the saturation model in (17)–(24) as follows:

$$D_k = kT_{\mathrm{s}}/V_k\ . \tag{27}$$

Using (27), the expectation of channel access delay in the case of a mixed load can be obtained as

$$\mathrm{E}[D] = \frac{1}{1-B_0}\sum_{k=m}^{N}D_kB_k = \frac{1}{1-B_0}\sum_{k=m}^{N}\frac{kT_{\mathrm{s}}}{V_k}B_k\ . \tag{28}$$

Equation (28) is used to calculate a new value for P_0 in (25). In other words, (25)–(28) are repeatedly computed until P_0, B_k, and $\mathrm{E}[D]$ converge to steady-state values. Since the service rate μ is given by the reciprocal of $\mathrm{E}[D]$, the number of saturated stations can be estimated by

$$M = \mathrm{sum}\left(\lambda_k > \frac{1}{\mathrm{E}[D]}; 1 \le k \le N\right), \tag{29}$$

where $\mathrm{sum}(x_k)$ means the number of stations satisfying the condition x_k. When M is not equal to m, it implies that the initial guess of m is not correct. Therefore, (25)–(29) are iteratively computed for various m, until M is equal to m. Then, the theoretical activity ratio in the case of a mixed load is computed as

$$U_{\mathrm{t}}(x) = \sum_{k=M}^{N} V_k B_k , \tag{30}$$

where x means the Wi-Fi transmission duration when measuring the arrival rates of Wi-Fi stations.

The proposed analytical model for a mixed load is summarized as follows:

1) Initialization: $m = 0$, $P_0 = P_{0,\mathrm{old}} = 0.5$.
2) Computation of B_k: use equation (26).
3) Computation of E[D]: use equation (28).
4) Computation of P_0: use equation (25).
5) Filtering of P_0 and update of $P_{0,\mathrm{old}}$:

$$P_0 = 0.5P_0 + 0.5P_{0,\mathrm{old}},\ P_{0,\mathrm{old}} = P_0. \tag{31}$$

6) If P_0 is converged, go to step 7). Else, repeat steps 2)–5).
7) Calculation of M: use equation (29).
8) If $M = m$, then compute the activity ratio using (30); otherwise, $m = m + 1$, $P_0 = P_{0,\mathrm{old}} = 0.5$, and go to step 2).

When $M = 0$, the above proposed model is identical with the non-saturation analysis model in [22] except for the simplified computation of V_k. Also, it is the same as the saturation model in [21] when $M = N$.

For practical use, the arrival rates $\{\lambda_k\}$ are measured by receiving the Wi-Fi packets during a predetermined period. For an unsaturated station, the arrival rate is equal to the number of successfully transmitted data packets per observation period. For a saturated station, the measured arrival rate becomes the average service rate, μ, because the packet transmission rate is bounded by μ. Thus, it is impossible to estimate the exact arrival rate. Fortunately, when $m \geq M$, the arrival rates for saturated stations are not used to calculate P_0 in (25) and (31). Also, the proposed time adjustment method in Section III-2 requires the computation of $U_{\mathrm{t}}(T_2(n) - \Delta T)$, which utilizes the revised arrival rate given by

$$\lambda_{k,\mathrm{rev}} = \frac{T_2(n)}{T_2(n) - \Delta T} \lambda_{k,\mathrm{est}} , \tag{32}$$

where $\lambda_{k,\mathrm{est}}$ denotes the measured arrival rate for the kth station. Due to the increase of the arrival rate by (32), the station whose arrival rate is bounded by μ is classified into the saturated station even when the measured arrival rate is slightly less than μ by some estimation error. Therefore, the measurement error in the saturated stations' arrival rates has very little impact on the performance of the proposed analytical model.

IV. Simulation Results

In this section, the proposed channel access method is compared with the Wi-Fi-like channel access method, and the performance of the proposed channel access method is evaluated with respect to various time ratio adjustment schemes. We performed system-level simulations considering the coexistence of LAA and Wi-Fi. We assumed a single cell scenario for both the LAA eNB and the Wi-Fi AP, which are colocated with the same coverage. Also, it was assumed that the number of LAA UEs is the same as the number of Wi-Fi stations. According to the standards, Wi-Fi provides the downlink and uplink transmissions while LAA supports only the downlink. In the simulation, we used the parameters defined in Table 1 for LAA eNB, Wi-Fi stations, and the proposed time adjustment method. We employed the New Model C line-of-sight in [27] for path-loss computation and fading generation. To determine the modulation and coding schemes for LAA and Wi-Fi, it was assumed that the spectral efficiency is equal to 0.6 C_{MIMO}, where C_{MIMO} is the Shannon spectral efficiency for the MIMO channel. The simulation time was at least 50 s for each drop and the simulation results were obtained by averaging the values for 100 independent drops.

Table 1. Simulation parameters for LAA eNB, Wi-Fi stations, and proposed time adjustment method.

Parameter	Value and description
Transmit power	20 dBm for both LAA eNB and Wi-Fi
Max. communication distance	50 m
Carrier frequency	5.8 GHz (unlicensed band)
Bandwidth	20 MHz
Number of antennas	2 transmit and 2 receive antennas
Frame format	LTE FDD frame format for LAA 802.11ac frame format for Wi-Fi
Scheduling	Round robin for LAA 802.11 DCF for Wi-Fi
Packet size	Randomly selected from {512, 1,024, 2,048, 4,096, 8,192} bytes
Antenna gain	Transmit antenna gain = 6 dBi Receive antenna gain = 0 dBi
Cable loss	6 dB
Noise figure	8 dB
Inter-frame space	SIFS = 16 μs, DIFS = LIFS = 34 μs
Wi-Fi slot time	9 μs
Contention window	$\mathrm{CW}_{\min} = 31$; and $\mathrm{CW}_{\max} = 1{,}023$
Parameters for the proposed method	$T_{\mathrm{frame}} = 10$ ms, $\Delta T = 1$ ms, $\alpha = -0.03$ Update interval of $T_1(n)$ and $T_2(n) = 1$ s

1. Comparison of Channel Access Methods

In Fig. 3, the proposed channel access method is compared

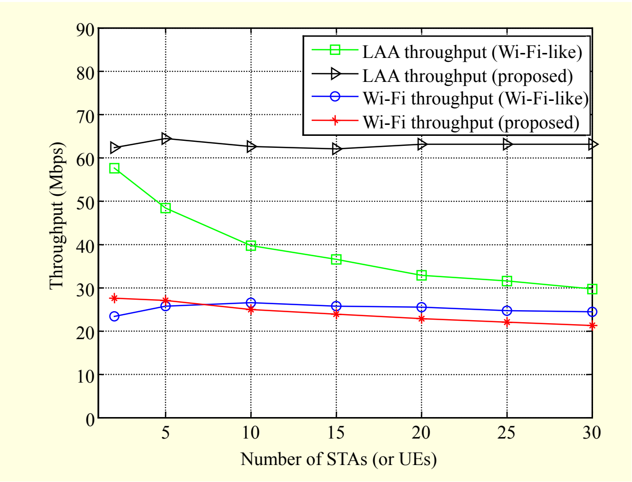

Fig. 3. Throughput comparison between Wi-Fi-like channel access method and proposed access scheme, when time ratio is fixed to 0.5 for proposed method.

with the Wi-Fi-like access method, when the time ratio is fixed to 0.5 for the proposed method and all LAA UEs and Wi-Fi stations have full buffer traffic. In the Wi-Fi-like access scheme, the LAA throughput is rapidly decreasing and the Wi-Fi throughput is very slowly decreasing, as the number of stations (or UEs), N, increases. In the proposed access scheme, the LAA throughput is almost constant, irrespective of N; the Wi-Fi throughput is slowly decreasing as N increases. In the Wi-Fi-like access method, the LAA eNB contends with Wi-Fi stations to occupy the channel, thereby its throughput decreases with increasing numbers of Wi-Fi stations. In contrast, since the proposed access method assigns a dedicated transmission duration for the LAA eNB, the LAA throughput is not changed without respect to N. The Wi-Fi stations in the Wi-Fi-like access scheme occupy more channel resource than those in the proposed access method; however, the throughput gain is less than 3.0 Mbps. As presented in [7]–[11], Wi-Fi has more overhead and less multiple access efficiency than LAA, so the time ratio reduction of the LAA eNB causes large LAA throughput loss and small Wi-Fi throughput gain. For this reason, the proposed access method is more beneficial than the Wi-Fi-like access scheme when considering the entire throughput of LAA and Wi-Fi.

2. Time Ratio Adjustment for Proposed Channel Access Method

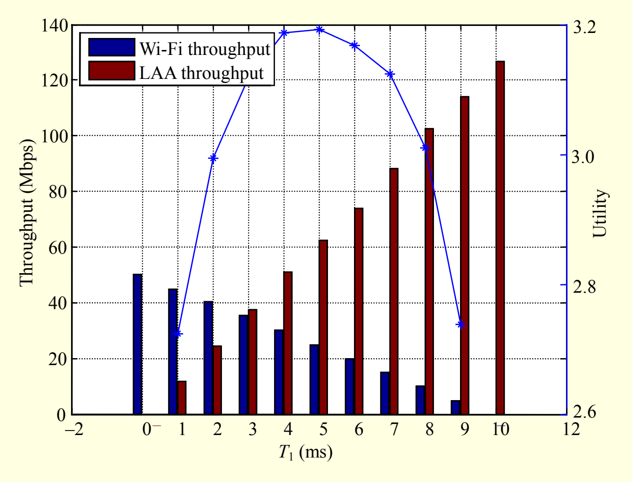

Fig. 4. Throughput and utility of proposed channel access method, when N is 10 and T_1 is fixed to varying values.

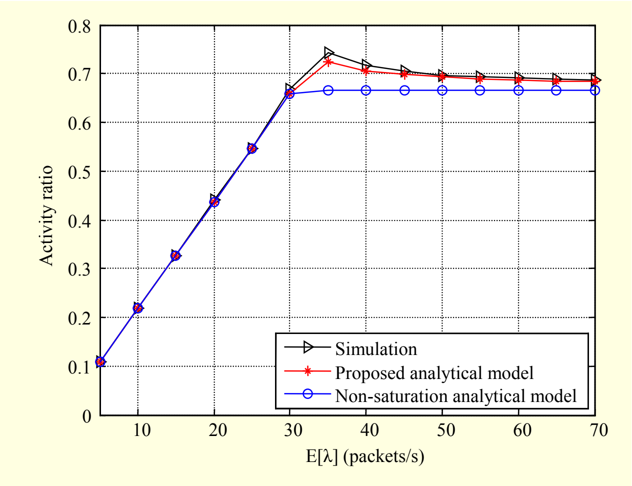

Fig. 5. Activity ratio comparison between theory and experiment, when number of stations is 20.

Figure 4 shows the throughput and utility of the proposed access method when $N = 10$ and the transmission duration of LAA, T_1, is within the following range: 0 ms ≤ T_1 ≤ 10 ms. As with Fig. 3, full buffer traffic was assumed for LAA and Wi-Fi. When the channel was fully occupied by Wi-Fi, the throughput was 50.2 Mbps. The LAA throughput reached 126.8 Mbps, when T_1 = 10 ms. As mentioned in Fig. 3, the throughput difference between LAA and Wi-Fi arises from the discrepancy of the overhead and the multiple access efficiency. In the case where the channel is shared by LAA and Wi-Fi, the throughput of each system is proportional to the assigned time ratio. As presented in (5), the utility function is maximized when $T_1 = T_2$, due to the full buffer traffic. The utility function in Fig. 4 confirms the theoretical result.

Now, we evaluate the accuracy of the proposed analytical model in Section III-3. To realize a mixed load condition, we assume that the packet arrivals to the Wi-Fi stations follow a Poisson distribution whose arrival rates are given by

$$\lambda_k = \frac{2k}{N+1}\mathrm{E}[\lambda] \qquad (k = 1, 2, \ldots, N), \tag{33}$$

http://dx.doi.org/10.4218/etrij.15.2415.0033

where $N = 20$ and $\mathrm{E}[\lambda]$ is the mean arrival rate for all Wi-Fi stations. Figure 5 presents the activity ratios obtained by the analytical models and the simulation. When $\mathrm{E}[\lambda] < 30$, all Wi-Fi stations are unsaturated; thus, both the non-saturation model in [22] and the proposed model show good agreement with the numerical results. When $\mathrm{E}[\lambda] > 30$, the non-saturation model computes the activity ratio under the condition that all stations are saturated. In contrast, the proposed analytical model evaluates the activity ratio by separately accounting for the saturated and non-saturated stations. Therefore, the proposed model computes the activity ratio more accurately than the non-saturation model in the mixed load condition. Since the proposed channel access mechanism necessitates the saturation status of Wi-Fi, it is very important to precisely estimate the activity ratio in the transient region where the Wi-Fi system starts to be saturated. Therefore, the proposed analytical model is more advantageous than the non-saturation model.

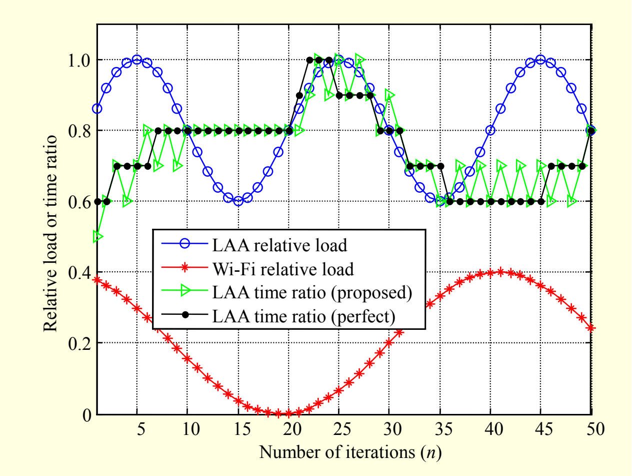

Fig. 6. LAA time ratio obtained by proposed time ratio adjustment method and optimal LAA time ratio when $N = 10$, $0.6 \leq L_1/R_1 \leq 1.0$, and $0 \leq L_2/R_2 \leq 0.4$.

Table 2. Throughput and utility of proposed access method depending on time ratio adjustment schemes, when $N = 10$.

Relative loads	Perfect adjustment (Mbps)	Proposed adjustment (Mbps)	Fixed to $T_1 = T_2 = 5$ ms (Mbps)
Scenario 1: $0.10 \leq L_{R,1} \leq 0.70$ $0.10 \leq L_{R,2} \leq 0.70$	LAA = 46.4 Wi-Fi = 22.1 $U_{\mathrm{PF}} = 3.01$	LAA = 45.6 Wi-Fi = 21.9 $U_{\mathrm{PF}} = 3.00$	LAA = 42.9 Wi-Fi = 20.4 $U_{\mathrm{PF}} = 2.94$
Scenario 2: $0.05 \leq L_{R,1} \leq 0.55$ $0.20 \leq L_{R,2} \leq 1.00$	LAA = 35.8 Wi-Fi = 30.5 $U_{\mathrm{PF}} = 3.04$	LAA = 34.5 Wi-Fi = 30.4 $U_{\mathrm{PF}} = 3.02$	LAA = 35.8 Wi-Fi = 24.7 $U_{\mathrm{PF}} = 2.95$
Scenario 3: $0.20 \leq L_{R,1} \leq 1.00$ $0.05 \leq L_{R,2} \leq 0.55$	LAA = 63.6 Wi-Fi = 16.9 $U_{\mathrm{PF}} = 3.03$	LAA = 62.8 Wi-Fi = 16.5 $U_{\mathrm{PF}} = 3.02$	LAA = 51.5 Wi-Fi = 16.9 $U_{\mathrm{PF}} = 2.94$
Scenario 4: $0.00 \leq L_{R,1} \leq 0.40$ $0.60 \leq L_{R,2} \leq 1.00$	LAA = 24.0 Wi-Fi = 42.8 $U_{\mathrm{PF}} = 3.01$	LAA = 21.9 Wi-Fi = 43.2 $U_{\mathrm{PF}} = 2.97$	LAA=24.4 Wi-Fi = 29.4 $U_{\mathrm{PF}} = 2.86$
Scenario 5: $0.60 \leq L_{R,1} \leq 1.00$ $0.00 \leq L_{R,2} \leq 0.40$	LAA = 90.4 Wi-Fi = 11.3 $U_{\mathrm{PF}} = 3.00$	LAA = 90.6 Wi-Fi = 10.6 $U_{\mathrm{PF}} = 2.98$	LAA = 61.8 Wi-Fi = 11.5 $U_{\mathrm{PF}} = 2.85$

Finally, we evaluate the performance of the proposed channel access method with various time ratio adjustment schemes. The arrival rates for Wi-Fi were obtained by (33), and the arrival rates for LAA were defined as

$$\lambda_{\mathrm{LAA},k} = \frac{2k}{N+1}\mathrm{E}[\lambda_{\mathrm{LAA}}] \qquad (k = 1, 2, \ldots, N), \tag{34}$$

where $\mathrm{E}[\lambda_{\mathrm{LAA}}]$ is the mean arrival rate for all LAA UEs. The traffic load variations for LAA and Wi-Fi were reflected in the simulation by changing $\mathrm{E}[\lambda_{\mathrm{LAA}}]$ and $\mathrm{E}[\lambda]$ as follows:

$$\mathrm{E}[\lambda_{\mathrm{LAA}}(n)] = a_1 + b_1 \sin(2\pi n / 20), \tag{35}$$

$$\mathrm{E}[\lambda(n)] = a_2 + b_2 \sin\left((2\pi n / 43) + \theta\right), \tag{36}$$

where a_1, a_2, b_1, and b_2 are constants determined by the variation range of the relative loads L_1/R_1 and L_2/R_2, and θ is a random phase uniformly distributed over $[0, 2\pi)$. Figure 6 compares the LAA time ratio, $t_1(n)$, obtained by the proposed time adjustment scheme in Section III-2 and the theoretically optimal time ratio achieved by (2)–(5), when $N = 10$, $0.6 \leq L_1/R_1 \leq 1.0$ and $0 \leq L_2/R_2 \leq 0.4$. The time ratio obtained by the proposed scheme is very close to the optimal value, except that the proposed method exhibits some oscillations by the ping-pong effect. Also, the proposed adjustment method shows slight loss due to the 1-tap latency for adaptation. Table 2 compares the throughput and utility of the proposed access method depending on the time ratio adjustment schemes, when $N = 10$ and the relative traffic loads of LAA and Wi-Fi are varied according to scenarios 1–5. As expected in the results of Fig. 6, the performance of the proposed adjustment method is very close to that of the perfect adjustment in all scenarios. When the LAA relative load is similar to the Wi-Fi relative load, as in scenario 1, the access method with a fixed time ratio exhibits a good performance close to the perfect adjustment. However, the access method with a fixed ratio presents huge throughput loss (up to 28.8 Mbps) when the two relative loads are different. As a result, the proposed channel access method can achieve a significant throughput gain by employing the time adjustment method in Section III-2, as compared to the case with a fixed time ratio.

V. Conclusion

In this paper, we proposed a channel access mechanism for coexistence of LAA and Wi-Fi, and developed a practical algorithm to adjust the time ratio between LAA and Wi-Fi using a Wi-Fi analytical model. It was shown through numerical simulations that the proposed method is more advantageous than existing channel access schemes in terms of throughput and utility. Since the proposed access scheme does not require the Wi-Fi data rate and traffic load, it can be implemented in a practical LAA eNB coexisting with Wi-Fi. Also, the proposed access mechanism is expected to contribute to developing access technologies for 5G mobile networks using unlicensed frequency spectrum.

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