Impact of Packet Arrivals on Wi-Fi and Cellular System Sharing Unlicensed Spectrum

Yujae Song, Ki Won Sung, and Youngnam Han

***Abstract*—We investigate the coexistence performance of Wi-Fi and cellular systems under an unlicensed spectrum sharing environment. For this, we provide a mathematical framework based on queuing theory depicting the time-domain behaviors of a Wi-Fi access point and a cellular small-cell base station (SCBS) under unlicensed spectrum sharing. Based on the proposed framework, we make an analysis of the delay performance of both systems with respect to the changes in their packet arrival rates. Through the analysis, we identify the maximum allowable packet arrival rates of both systems, under which the required Wi-Fi delay performance is achieved without spectrum etiquette for coexistence at the cellular SCBS such as carrier-sensing adaptive transmission. This will serve as a guideline for the cellular SCBS on when it needs to employ the spectrum etiquette.**

***Index Terms*—Cellular, coexistence, queuing, small-cell, unlicensed, spectrum, Wi-Fi.**

I. INTRODUCTION

Recently, the potential of operating cellular small-cells in the unlicensed spectrum has been discussed by the 3rd Generation Partnership Project (3GPP) standardization group to address the scarcity of licensed spectrum for cellular networks [1]. In the unlicensed spectrum, the cellular small-cells are required to coexist well with other radio access technologies (RATs). To achieve this objective, efficient unlicensed spectrum sharing between them should be realized. Since the representative RAT in the unlicensed spectrum is Wi-Fi with IEEE 802.11 n/ac standards, the majority of researches focus on coexistence between cellular small-cells and Wi-Fi.

Challenges for the coexistence from the network architecture and radio resource management perspectives are presented in [2]–[6]. Among them, we direct our attention to an issue that Wi-Fi could be deprived of an opportunity to access the wireless medium in case of busy traffic at cellular small-cells. When both Wi-Fi and cellular small-cells have sporadic traffic, they can peacefully coexist with each other. However, as their packet arrivals increase, the cellular small-cells may monopolize the spectrum access, causing a large delay to Wi-Fi packets. To prevent such monopolization, medium access mechanisms determining the spectrum etiquette of cellular small-cells, which is also referred to as coexistence mechanisms, have been studied recently. The existing studies can be classified into two categories based on whether listen-before-talk (LBT) is required at cellular small-cells to access the unlicensed spectrum. Under the scenario that there is a regulatory requirement for LBT at cellular small-cells, the medium access mechanisms are studied in [7]–[9]. The mechanisms for the other case are investigated in [10]–[13]. However, to our best knowledge, there is no work offering a guideline on when cellular small-cells must employ these coexistence mechanisms.

The main contributions of this paper are listed as follows:

- We propose a mathematical framework based on queuing theory that models the time-domain behaviors of a Wi-Fi access point (AP) with the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism and a cellular small-cell base station (SCBS) without the regulatory requirement for LBT in the unlicensed spectrum.
- Based on the proposed framework, we investigate the mean packet delay of Wi-Fi AP and cellular SCBS as a coexistence performance metric, according to changes in their packet arrival rates.
- With help of our analysis, we identify the maximum allowable packet arrival rates of Wi-Fi AP and cellular SCBS, under which the required Wi-Fi performance is satisfied without the coexistence mechanisms at the cellular SCBS. This will serve as a guideline for the cellular SCBS on when it needs to employ the coexistence mechanisms.

II. SYSTEM MODEL

We consider a scenario where a Wi-Fi AP and a cellular SCBS share the unlicensed spectrum. They coexist on the same frequency channel and in the same collision domain. We assume that the cellular SCBS monitors and identifies the status of unlicensed spectrum on an on-going basis. If the channel is sensed to be idle when the cellular SCBS starts packet service, the cellular SCBS immediately occupies the channel for transmission. On the contrary, if the channel is sensed to be busy when the cellular SCBS starts packet service, the cellular SCBS waits until the channel is sensed to be idle, and then it occupies the channel for transmission as soon as the channel is sensed to be idle. To identify the status of unlicensed spectrum, the cellular SCBS uses the energy detection method. For the ease of analysis, it is assumed that the sensing duration for energy detection at the cellular SCBS is negligible. This could be acceptable because the sensing duration (e.g., within 4 μs) is much shorter than the expected

This paper is accepted for publication in IEEE Transactions on Vehicular Technology in February 2016.

Y. Song and Y. Han are with the Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Korea (e-mail: {ednb1008, ynhan}@kaist.ac.kr).

K. W. Sung is with the Communication Systems Department, KTH Royal Institute of Technology, 100 44 Stockholm, Sweden (e-mail: sungkw@kth.se).

channel occupancy time of cellular SCBS for transmission which is on the millisecond time scale [5].

We model the Wi-Fi AP and the cellular SCBS as two independent M/G/1 queues. Packet arrival for each node is assumed to be governed by a Poisson process with rate $\lambda_i, i \in \{w, c\}$, and they are treated in order of arrival in each queue. The packet service time for each node S_i is independent and identically distributed with the distribution function and the corresponding Laplace-Stieltjes transform (LST) $\tilde{S}_i(s)$. We define the channel occupancy time as the period of time during which a node actually occupies the channel for transmission. Based on this definition, the packet service time for each node can be divided into two parts: $S_i = S_{i,v} + S_{i,o}$, where $S_{i,o}$ is the channel occupancy time in service, and $S_{i,v}$ is the elapsed time before the channel occupancy time in service. To keep the analytical tractability, $S_{i,o}$ is assumed to be exponentially distributed with $E[S_{i,o}] = 1/\mu_i$.

III. Mean packet delay for Wi-Fi and cellular systems

A. Mean packet delay of cellular SCBS

Note that the packet service time of cellular SCBS can vary according to the status of Wi-Fi AP. Under the average fraction of time the Wi-Fi AP does not occupy the channel (i.e., $1-\lambda_w E[S_{w,o}]$), the cellular SCBS immediately occupies the channel when it starts packet service as follows:

$$S_{c,case1} = S_{c,o}. \tag{1}$$

On the other hand, under the opposite average fraction of time (i.e., $\lambda_w E[S_{w,o}]$), the cellular SCBS waits until the channel occupancy time of Wi-Fi AP is finished, and then it occupies the channel as soon as the channel is sensed to be idle as follows:

$$S_{c,case2} = R_{w,o} + S_{c,o}, \tag{2}$$

where $R_{w,o}$ is the residual time of $S_{w,o}$.

Accordingly, the packet service time of cellular SCBS is presented as

$$\begin{aligned} S_c &= (1-\lambda_w E[S_{w,o}]) S_{c,case1} + \lambda_w E[S_{w,o}] S_{c,case2} \\ &= \left(1 - \frac{\lambda_w}{\mu_w}\right) S_{c,o} + \frac{\lambda_w}{\mu_w}(R_{w,o} + S_{c,o}) \\ &\overset{(a)}{=} \frac{\lambda_w}{\mu_w} S_{w,o} + S_{c,o}, \end{aligned} \tag{3}$$

where (a) is obtained by using the memoryless property of exponential distribution. Based on (3), the LST of the packet service time of cellular SCBS can be expressed by following the fact that the LST of the sum of random variables equals the multiplication of the LST of each random variable as follows:

$$\tilde{S}_c(s) = \left(\frac{\mu_c}{s+\mu_c}\right)\left(\frac{a_w}{s+a_w}\right), \tag{4}$$

where $a_w = \mu_w^2/\lambda_w$.

By following the property of LST (i.e., $\widetilde{S}_c'(0) = -E[S_c]$ and $\widetilde{S}_c''(0) = (-1)^2 E[S_c^2]$), we can finally achieve the mean packet delay of cellular SCBS, which is determined as the sum of the mean packet service time and the mean waiting time in the queue as follows:

$$D_c = E[S_c] + \frac{\lambda_c E[S_c^2]}{2(1-\lambda_c E[S_c])}, \tag{5}$$

where $E[S_c]$ is the mean service time, and $\frac{\lambda_c E[S_c^2]}{2(1-\lambda_c E[S_c])}$ is the mean waiting time in the queue obtained from the Pollaczek-Khinchin (P-K) formula for the waiting time [14].

B. Mean packet delay of Wi-Fi AP

Similar to the packet service time of cellular SCBS, the packet service time of Wi-Fi AP can vary according to the status of cellular SCBS. The first case is regarding the average fraction of time the cellular SCBS does not occupy the channel (i.e., $1-\lambda_c E[S_{c,o}]$). In this case, the packet service time of Wi-Fi AP can be divided into three portions:

$$S_{w,case1} = S_{DIFS} + S_{back} + S_{w,o}. \tag{6}$$

The first term, denoted by S_{DIFS}, is the time spent until DCF interframe space (DIFS) is successfully completed without any interruption by packet arrivals at the cellular SCBS. The packet service of Wi-Fi AP initially starts with the monitoring of channel activity. If the channel is sensed to be idle for DIFS duration T_{DIFS}, the Wi-Fi AP generates a random backoff interval before the channel occupancy time. However, if the channel is busy (i.e., the cellular SCBS occupies the channel) within the DIFS duration, the Wi-Fi AP waits until the channel is sensed to be idle and restarts DIFS from the beginning, which is called the second DIFS attempt. In this case, the time period between a DIFS start and a DIFS restart due to the interruption of cellular SCBS can be given as a summation of the elapsed time until the channel is sensed to be busy within the DIFS duration $T_{elap,DIFS}$ and a busy period of cellular SCBS B_c (i.e., $T_{elap,DIFS} + B_c$). The busy period of cellular SCBS is between when a packet arrives at the empty cellular SCBS and when the queue of cellular SCBS goes back empty. Because there is no LBT requirement for the cellular SCBS, the Wi-Fi AP is unable to have idle channel during the busy period of cellular SCBS. Such time period can repeatedly occur with the probability that cellular SCBS packets arrive within the DIFS duration, which is presented as $P_{arr,DIFS} = 1 - \Pr[\text{No packet arrival at cellular during } T_{DIFS}] = 1 - e^{-\lambda_c T_{DIFS}}$. Based on the above description, S_{DIFS} can be expressed as

$$\begin{aligned} S_{DIFS} &= T_{DIFS} + (T_{elap,DIFS} + B_c)\left(\sum_{j=1}^{\infty} P_{arr,DIFS}^j\right) \\ &= T_{DIFS} + (T_{elap,DIFS} + B_c)(e^{\lambda_L T_{DIFS}} - 1), \end{aligned} \tag{7}$$

where $P_{arr,DIFS}^i$ means the probability that there are packet arrivals at the cellular SCBS within the DIFS duration at the i-th DIFS attempt, given that there are packet arrivals in the last i-1 DIFS attempts. Note that $T_{elap,DIFS}$ can vary with the number of packets expected to arrive at the cellular SCBS for the DIFS duration. Thus, the probability density function (PDF) of $T_{elap,DIFS}$ is presented as

$$f_{T_{elap,DIFS}}(t) = \sum_{n=1}^{\infty} f_{T_{elap,DIFS}}(t|N_{T_{DIFS}} = n) \frac{\Pr[N_{T_{DIFS}} = n]}{P_{arr,DIFS}}, \quad (8)$$

where $N_{T_{DIFS}}$ is the number of packets arriving at the cellular SCBS for the DIFS duration. In $f_{T_{elap,DIFS}}(t)$, $f_{T_{elap,DIFS}}(t|N_{T_{DIFS}} = n)$ is expressed as

$$\begin{aligned} f_{T_{elap,DIFS}}(t|N_{T_{DIFS}} = n) &= \frac{\Pr[T_{elap,DIFS} = t, N_{T_{DIFS}} = n]}{\Pr[N_{T_{DIFS}} = n]} \\ &= \frac{\Pr[T_{elap,DIFS} = t]\Pr[N_{T_{DIFS}-t} = n-1]}{\Pr[N_{T_{DIFS}} = n]} \\ &= \frac{n(T_{DIFS} - t)^{n-1}}{(T_{DIFS})^n}. \quad (9) \end{aligned}$$

Thus, $f_{T_{elap,DIFS}}(t)$ is rewritten as

$$\begin{aligned} f_{T_{elap,DIFS}}(t) &= \frac{\lambda_c e^{-\lambda_c T_{DIFS}}}{1 - e^{-\lambda_c T_{DIFS}}} \sum_{n=1}^{\infty} \frac{(\lambda_c (T_{DIFS} - t))^{n-1}}{(n-1)!} \\ &= \frac{\lambda_c e^{-\lambda_c t}}{1 - e^{-\lambda_c T_{DIFS}}}. \quad (10) \end{aligned}$$

With (10), the LST of $T_{elap,DIFS}$ can be obtained as

$$\tilde{T}_{elap,DIFS}(s) = \frac{\lambda_c}{s + \lambda_c} \frac{(1 - e^{-(s+\lambda_c)T_{DIFS}})}{1 - e^{-\lambda_c T_{DIFS}}}. \quad (11)$$

Also, the LST of the busy period of cellular SCBS is derived by using a Kendall functional equation [14] and (4), as given by

$$\begin{aligned} \tilde{B}_c(s) &= \tilde{S}_c\left(s + \lambda_c - \lambda_c \tilde{B}_c(s)\right) \\ &= \left(\frac{\mu_c}{s + \lambda_c - \lambda_c \tilde{B}_c(s) + \mu_c}\right)\left(\frac{a_w}{s + \lambda_c - \lambda_c \tilde{B}_c(s) + a_w}\right). \quad (12) \end{aligned}$$

Thus, $\tilde{B}_c(s)$ is a root of cubic equation. Note that the solutions of the cubic equation should be restricted to the case for which $0 \le \tilde{B}_c(s) \le 1$ for all $s \ge 0$. Using the derived (7), (11), and $\tilde{B}_c(s)$, we can obtain the LST of S_{DIFS} as follows:

$$\begin{aligned} \tilde{S}_{DIFS}(s) = &\tilde{T}_{DIFS}(s)\tilde{T}_{elap,DIFS}((e^{\lambda_c T_{DIFS}} - 1)s) \\ &\tilde{B}_c((e^{\lambda_c T_{DIFS}} - 1)s). \quad (13) \end{aligned}$$

The second term, denoted by S_{back}, is the time spent occurring in the Wi-Fi backoff process. The backoff interval is decremented as long as the channel is sensed to be idle. Otherwise, the backoff time is frozen during the busy period of cellular SCBS and reactivated when the channel is continuously sensed to be idle again for the DIFS duration. Both the backoff interval and the number of packets arriving at the cellular SCBS during the backoff interval are random variables, such that we can represent S_{back} as

$$\begin{aligned} S_{back}(T_{back}, N_{back}) = T_{back} + (\underbrace{B_c + S_{DIFS}}_{1} + ... + \underbrace{B_c + S_{DIFS}}_{N_{back}}), \quad (14) \end{aligned}$$

where T_{back} is the backoff interval, and N_{back} is the number of packets arriving at the cellular SCBS during T_{back}. Based on the above equation, the LST of S_{back} can be also represented as

$$\tilde{S}_{back}(s|T_{back}, N_{back}) = \tilde{T}_{back}(s)\left(\tilde{B}_c(s)\tilde{S}_{DIFS}(s)\right)^{N_{back}}. \quad (15)$$

The third term, denoted by $S_{w,o}$, is the channel occupancy time after the backoff interval reaches zero. Similar to $S_{c,o}$, the LST of $S_{w,o}$ is obtained as $\tilde{S}_{w,o}(s) = \left(\frac{\mu_w}{s+\mu_w}\right)$.

The second case deals with the average fraction of time the cellular SCBS occupies the channel (i.e., $\lambda_c E[S_{c,o}]$). In this case, the packet service time of Wi-Fi AP is expressed as

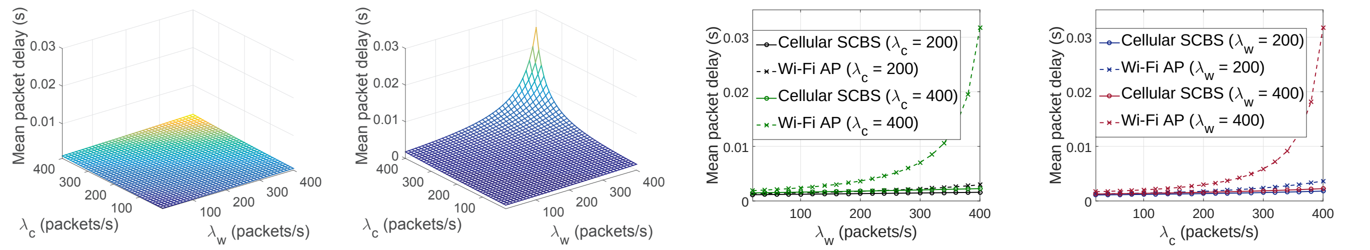
$$S_{w,case2}(T_{back}, N_{back}) = R_{c,busy} + S_{w,case1}(T_{back}, N_{back}), \quad (16)$$

where $R_{c,busy}$ is the residual busy period of cellular SCBS. To obtain the LST of $R_{c,busy}$, we adopt a similar procedure used to derive a relation for the duration of busy period [14]. First of all, we take all packets in the queue out of the queue and then focus on time spent due to the residual service time of cellular SCBS $R_{c,o}$. During $R_{c,o}$, new packets may arrive at the cellular SCBS. This number is denoted by $N_{R_{c,o}}$, and these packets are labeled by $P_1, ..., P_{N_{R_{c,o}}}$. As soon as $R_{c,o}$ is finished, we take packet P_1 into service. However, instead of letting other packets (i.e., $P_2, ..., P_{N_{R_{c,o}}}$) wait for their turn, we take them temporarily out of the queue. Packet P_2 will be put into the queue again and taken into service as soon as the queue is empty again, which means that packets arriving during the service of P_1 will be served first. Thus, it is as if P_1 initiates a new busy period for which P_2 has to wait. This busy period will be called a sub-busy period. In the same way, P_3 has to wait for the sub-busy period initiated by P_2, and so on. Finally, the sub-busy period due to $P_{N_{R_{c,o}}}$ terminates this iterative procedure. The sub-busy period due to P_i is denoted by $B_{c,i}$, and the corresponding busy period due to $R_{c,o}$ is denoted by $R_{c,busy,res}$. Then, we have the relation as

$$\begin{aligned} R_{c,busy,res} &= R_{c,o} + B_{c,1} + ... + B_{c,N_{R_{c,o}}} \\ &= S_{c,o} + B_{c,1} + ... + B_{c,N_{R_{c,o}}}. \quad (17) \end{aligned}$$

Notice that $N_{R_{c,o}}$ depends on $S_{c,o}$, and $B_{c,1}, ..., B_{c,N_{R_{c,o}}}$ are independent and all have the same distribution. When deriving the above relation, the packets arriving at the cellular SCBS $P_2, ..., P_{N_{R_{c,o}}}$ are not treated on a first-come first-served basis anymore, but this does not affect $R_{c,busy,res}$. This is because $R_{c,busy,res}$ is independent of the order in which the packets are served. We use the above relation to derive the LST of $R_{c,busy,res}$. By conditioning on the length of $S_{c,o}$, we have $\tilde{R}_{c,busy,res}(s) = \int_{t=0}^{\infty} E\left[e^{-sR_{c,busy,res}}|S_{c,o} = t\right] f_{S_{c,o}}(t)\,dt$, where $E\left[e^{-sR_{c,busy,res}}|S_{c,o} = t\right]$ is obtained by conditioning on $N_{R_{c,o}}$ as follows:

$$\begin{aligned} &E\left[e^{-sR_{c,busy,res}}|S_{c,o} = t\right] \\ &= \sum_{n=0}^{\infty} E\left[e^{-s(t+B_{c,1}+...+B_{c,n})}\right] \frac{(\lambda_c t)^n e^{-\lambda_c t}}{n!} \\ &= e^{-\left(s+\lambda_c-\lambda_c \tilde{B}_c(s)\right)t}. \quad (18) \end{aligned}$$



(a) Mean packet delay of cellular SCBS

(b) Mean packet delay of Wi-Fi AP

(c) Mean packet delays under the change in the packet arrival rate of Wi-Fi AP

(d) Mean packet delays under the change in the packet arrival rate of cellular SCBS

Fig. 1. Mean packet delay of cellular SCBS and Wi-Fi AP

Thus, we can obtain the LST of $R_{c,busy,res}$ as follows:

$$\begin{aligned}\tilde{R}_{c,busy,res}(s) &= \int_{t=0}^{\infty} e^{-\left(s+\lambda_c-\lambda_c\tilde{B}_c(s)\right)t} f_{S_{c,o}}(t)dt \\ &= \tilde{S}_{c,o}\left(s+\lambda_c-\lambda_c\tilde{B}_c(s)\right) \\ &= \frac{\mu_c}{s+\lambda_c-\lambda_c\tilde{B}_c(s)+\mu_c}. \end{aligned} \tag{19}$$

Second of all, we focus on the packets taken out of the queue when first considering $R_{c,busy}$. In this context, the information on the number of the packets in the queue, denoted by N_c^{queue}, is needed because we can also apply a similar relation deriving $R_{c,busy,res}$ to achieve $R_{c,busy}$, as given by

$$R_{c,busy} = R_{c,busy,res} + B_{c,1} + ... + B_{c,N_c^{queue}}. \tag{20}$$

Note that, since the packets of cellular SCBS arrive according to a Poisson process, we can see N_c^{queue} as $E\left[N_c^{queue}\right]$ from the Poisson Arrivals See Time Average (PASTA) property, and it can be given from Little's law as follows:

$$E\left[N_c^{queue}\right] = \lambda_c E\left[S_c\right]. \tag{21}$$

With (20) and (21), the LST of $R_{c,busy}$ is obtained as

$$\tilde{R}_{c,busy}(s) = \tilde{R}_{c,busy,res}(s)\left(\tilde{B}_c(s)\right)^{E\left[N_c^{queue}\right]}. \tag{22}$$

Accordingly, the packet service time of Wi-Fi AP can be expressed as $S_w(T_{back},N_{back}) = (1-\lambda_c E[S_{c,o}])S_{w,case1}(T_{back},N_{back}) + \lambda_c E[S_{c,o}]S_{w,case2}(T_{back},N_{back}) = S_{DIFS} + S_{back}(T_{back},N_{back}) + \frac{\lambda_c}{\mu_c}R_{c,busy} + S_{w,o}$. Then, we can obtain the LST of the packet service time of Wi-Fi AP on the same method used in (4) as follows:

$$\begin{aligned}\tilde{S}_w(s|T_{back},N_{back}) =& \tilde{S}_{DIFS}(s)\tilde{S}_{back}(s|T_{back},N_{back}) \\ & \tilde{R}_{c,busy}\left(\frac{\lambda_c}{\mu_c}s\right)\tilde{S}_{w,o}(s). \end{aligned} \tag{23}$$

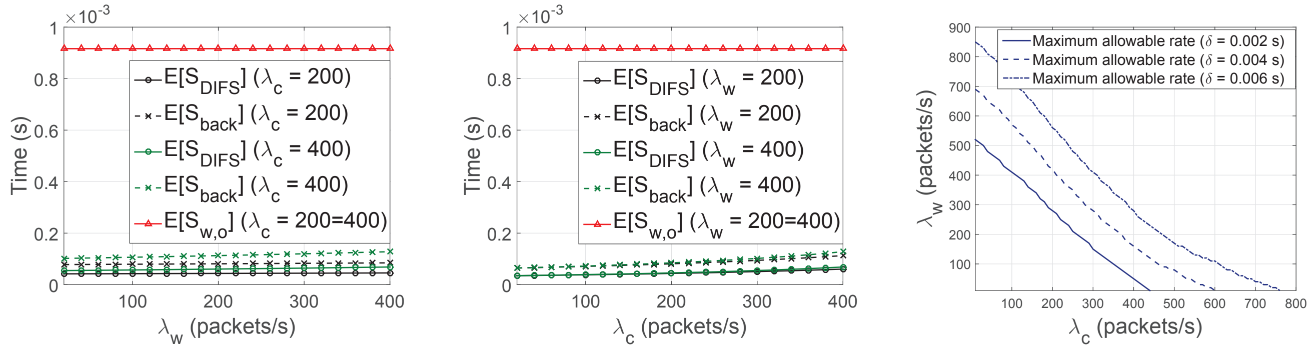
By following the property of LST, we can obtain the first and second moments of the packet service time of Wi-Fi AP under the given T_{back} and N_{back}, i.e., $E\left[S_w|T_{back},N_{back}\right] = -\tilde{S}_w'\left(0|T_{back},N_{back}\right)$ and $E\left[S_w^2|T_{back},N_{back}\right] = \tilde{S}_w''\left(0|T_{back},N_{back}\right)$. To obtain unconditional $E\left[S_w\right]$ and $E\left[S_w^2\right]$, the conditional moments are averaged by using their PDFs, as given by $E[S_w^k] = \int_{t=0}^{T_{back,\max}} \sum_{n=0}^{\infty} E[S_w^k|T_{back},N_{back}] \Pr(N_{back}=n,T_{back}=t) f_{T_{back}}(t)dt$, $k \in \{1,2\}$, where $T_{back,\max}$ is the maximum backoff window size, and $f_{T_{back}}(t)$ is the PDF of T_{back} which is uniformly distributed. Using the P-K formula, we can finally achieve the mean packet delay of Wi-Fi AP as follows:

$$D_w = E\left[S_w\right] + \frac{\lambda_w E\left[S_w^2\right]}{2\left(1-\lambda_w E\left[S_w\right]\right)}. \tag{24}$$

IV. Simulation Results

For numerical results, parameter values are set as follows: $T_{DIFS} = 36\times10^{-6}$ s, slot time = 9×10^{-6} s, contention window (CW) size = 8, $T_{back,\max}$ = slot time $\times$ CW size s, and backoff stage = 1. Also, the expected channel occupancy times of cellular SCBS and Wi-Fi AP are assumed to be equal, i.e., $E\left[S_{w,o}\right] = E\left[S_{c,o}\right] = 9.1632\times10^{-4}$ s. This is because the focus remains on the performance difference from different medium access mechanisms and packet arrival rates not different channel occupancy times between Wi-Fi and cellular nodes, but it can also be changed to reflect factors that affect the channel occupancy time, such as the physical layer configuration and the number of bits for a packet.

Figs. 1(a) and 1(b) show the mean packet delay of cellular SCBS and Wi-Fi AP according to changes in their packet arrival rates ($10 \le \lambda_c,\lambda_w \le 400$). It is observed that at all considered packet arrival rates, the mean packet delay of cellular SCBS is lower than that of Wi-Fi AP. More precisely, at low packet arrival rates (i.e., light-loaded Wi-Fi AP and cellular SCBS), the mean packet delay of cellular SCBS is lower than that of Wi-Fi AP, but the performance difference between them is not large. In this case, the performance difference is due to the different medium access mechanisms. Because the cellular SCBS does not have an LBT requirement to access the channel, it occupies the channel for transmission as soon as the channel is sensed to be idle. On the other hand, although the Wi-Fi AP senses that the channel is idle, it waits for a period of time (i.e., $S_{DIFS}+S_{back}$) before occupying the channel for transmission. This consequently leads to the relatively high mean packet delay of Wi-Fi AP compared to that of cellular SCBS, even though it has the same expected channel occupancy time as the cellular SCBS. At high packet arrival rates (i.e., heavy-loaded Wi-Fi AP and cellular SCBS), the mean packet delay of Wi-Fi AP increases very sharply compared to that of cellular SCBS, which is clearly seen in Figs. 1(c) and 1(d). This is because as packets at the cellular



(a) Time spent of each part in $S_{w,case1}$ under the change in the packet arrival rate of Wi-Fi AP

(b) Time spent of each part in $S_{w,case1}$ under the change in the packet arrival rate of cellular SCBS

(c) Allowable Wi-Fi packet arrival rate under different Wi-Fi packet delay thresholds

Fig. 2. Time spent of each part in $S_{w,case1}$ under different packet arrival rates & allowable Wi-Fi packet arrival rate under different Wi-Fi packet delay thresholds

SCBS are stacked in its queue due to the increase in the packet arrival rate of cellular SCBS, the Wi-Fi AP is unable to find the channel idle for quite a long time until the packet service of cellular SCBS is finished, leaving behind the empty cellular SCBS. Moreover, although the Wi-Fi AP senses the channel to be idle, there is a high probability that packets at the cellular SCBS arrive for the DIFS duration or backoff interval.

Figs. 2(a) and 2(b) show the time spent for each part in $S_{w,case1}$ (i.e., S_{DIFS}, S_{back}, and $S_{w,o}$) under the changes in their packet arrival rates. Given the parameter setting, $S_{w,o}$ is the dominant factor that influences on $S_{w,case1}$ among three parts, but the value of $S_{w,o}$ can be different according to the changes in their physical layer aspects such as the number of symbols in a packet, the number of antenna, etc. Also, it is also shown that S_{DIFS} and $S_{w,o}$ vary according to the changes in the packet arrival rates, whereas $S_{w,o}$ is constant regardless of the changes in the packet arrival rates.

Based on the above analysis, we can determine the maximum allowable packet arrival rate of Wi-Fi AP that satisfies the mean packet delay threshold for the Wi-Fi AP, denoted by δ, under the given packet arrival rate of cellular SCBS, as shown in Fig. 2(c). For example, under the conditions that the packet arrival rate of cellular SCBS is 100 packets/s and the Wi-Fi packet delay threshold is 0.002 s, the mean packet delay of Wi-Fi AP is investigated while increasing the packet arrival rate of Wi-Fi AP from 0. In this process, we can find the packet arrival rate of Wi-Fi AP under which the mean packet delay equals the Wi-Fi packet delay threshold (e.g., 400 packets/s), which refers to the maximum allowable packet arrival rate of Wi-Fi AP. With the help of it, we can offer a guideline with respect to operating a coexistence mechanism at the cellular SCBS that accounts for the packet arrival rates of Wi-Fi and cellular nodes as decision criterion. That is, if the packet arrival rate of Wi-Fi AP is lower than the maximum allowable packet arrival rate under the given packet arrival rate of cellular SCBS, the cellular SCBS does not need to employ coexistence mechanisms. Otherwise, the cellular SCBS should employ coexistence mechanisms to fulfill the Wi-Fi delay requirement.

V. Conclusion

We analyzed the impact of the packet arrival rates of Wi-Fi and cellular systems on the mean packet delays of both systems. The numerical results show that the packet arrival rates of both systems play an important role in determining the performance of the mean packet delays. In particular, the existence of heavy-loaded cellular SCBS without any coexistence mechanism in the unlicensed spectrum results in the severe performance degradation of Wi-Fi AP operating on the same channel. With the help of our analysis, we identified the maximum allowable packet arrival rates for the Wi-Fi AP under the given packet arrival rates of the cellular SCBS, where the required Wi-Fi performance is achieved without spectrum etiquette for coexistence at the cellular SCBS.

References

[1] 3GPP, "Study on Licensed-Assisted Access to unlicensed spectrum (Release 13)," 3GPP, Tech. Rep. 36.889, Jun. 2015.

[2] L. Liu, Y. Zhou, L. Tian, and J. Shi, "CPC-based backward-compatible network access for LTE cognitive radio cellular networks," *IEEE Commun. Mag.*, vol. 53, no. 7, pp. 93–99, Jul. 2015.

[3] F. Abinader, E. Almeida, F. Chaves, A. Cavalcante, R. Vieira, R. Paiva, A. Sobrinho, S. Choudhury, E. Tuomaala, K. Doppler, and V. Sousa, "Enabling the coexistence of LTE and Wi-Fi in unlicensed bands," *IEEE Commun. Mag.*, vol. 52, no. 11, pp. 54–61, Nov. 2014.

[4] A. Al-Dulaimi, S. Al-Rubaye, Q. Ni, and E. Sousa, "5G communications race: Pursuit of more capacity triggers LTE in unlicensed band," *IEEE Veh. Technol. Mag.*, vol. 10, no. 1, pp. 43–51, Mar. 2015.

[5] R. Zhang, M. Wang, L. Cai, Z. Zheng, and X. Shen, "LTE-unlicensed: the future of spectrum aggregation for cellular networks," *IEEE Wireless Commun. Mag.*, vol. 22, no. 3, pp. 150–159, Jun. 2015.

[6] F. Liu, E. Bala, E. Erkip, M. Beluri, and R. Yang, "Small-cell traffic balancing over licensed and unlicensed bands," *IEEE Trans. Veh. Technol.*, vol. 64, no. 12, pp. 5850–5865, Dec. 2015.

[7] Ericsson, "Discussion on LBT protocols," 3GPP, Tech. Rep. R1-151996, Apr. 2015.

[8] C. Chen, R. Ratasuk, and A. Ghosh, "Downlink performance analysis of LTE and WiFi coexistence in unlicensed bands with a simple Listen-Before-Talk scheme," in *Proc. VTC Spring*, May 2015, pp. 1–5.

[9] Y. Song, K. W. Sung, and Y. Han, "Coexistence of Wi-Fi and cellular with Listen-Before-Talk in unlicensed spectrum," *IEEE Commun. Lett.*, vol. 20, no. 1, pp. 161–164, Jan. 2016.

[10] S. Hajmohammad and H. Elbiaze, "Unlicensed spectrum splitting between femtocell and WiFi," in *Proc. ICC*, Jun. 2013, pp. 1883–1888.

[11] "LTE in unlicensed spectrum: Harmonious coexistence with Wi-Fi," White Paper, Qualcomm, Jun. 2014.

[12] H. Zhang, X. Chu, W. Guo, and S. Wang, "Coexistence of Wi-Fi and heterogeneous small cell networks sharing unlicensed spectrum," *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 158–164, Mar. 2015.

[13] C. Cano and D. J. Leith, "Coexistence of WiFi and LTE in unlicensed bands: A proportional fair allocation scheme," in *Proc. ICC Workshop*, Jun. 2015, pp. 10 354–10 359.

[14] I. Adan and J. Resing, *Queueing theory*. Department of Mathematics and Computing Science, Eindhoven University of Technology, 2001.