Coexistence of Wi-Fi and Cellular with Listen-Before-Talk in Unlicensed Spectrum

Yujae Song, Ki Won Sung, *Member, IEEE*, and Youngnam Han, *Senior Member, IEEE*

***Abstract*—In this letter, we analyze the coexistence performance of Wi-Fi and cellular networks with different Listen-Before-Talk (LBT) procedures in the unlicensed spectrum. For this analysis, the behavior of a cellular base station is modeled as a Markov chain that is combined with Bianchi's Markov model depicting the behavior of a Wi-Fi access point. The proposed mathematical framework finds the optimal contention window size of cellular base stations, which maximizes the total throughput of both networks while satisfying the required throughput of each network. Numerical results show the validity of adjustment in the parameter of LBT.**

***Index Terms*—Cellular small cells, coexistence, Listen-Before-Talk (LBT), unlicensed spectrum, Wi-Fi.**

I. Introduction

In recent years, enabling cellular small cells in unlicensed frequency bands has garnered attention as a promising solution to the scarcity of licensed spectrum for cellular networks. In particular, the 3rd Generation Partnership Project (3GPP) standardization group has been considering supplementary uses of the downlink in Long Term Evolution (LTE) technology in the unlicensed spectrum, which is termed Licensed-Assisted Access (LAA).

The prevailing radio access technology (RAT) in the unlicensed spectrum is Wi-Fi with IEEE 802.11 n/ac standards. Thus, it is critical to ensure that the cellular small cells coexist well with Wi-Fi. However, the challenge is to design appropriate etiquette for cellular base stations (BSs) to access the unlicensed spectrum. Because Wi-Fi access points (APs) operate under the carrier sense multiple access with collision avoidance (CSMA/CA) algorithm, their performance could be severely degraded if cellular BSs occupy the spectrum aggressively. In contrast, enforcing excessive etiquette in cellular BSs might reduce the overall performance.

Several coexistence mechanisms for cellular BSs have been proposed in the literature [1]. The work of [2] presents an almost blank subframe mechanism without priority and an interference avoidance scheme based on cellular small cells estimating the density of nearby Wi-Fi APs to mitigate the interference between cellular and Wi-Fi networks. The impact of cellular interference on the Wi-Fi performance is discussed in [3] based on experimental evaluations in indoor environments. It is reported that an adaptive Listen-Before-Talk (LBT) mechanism for cellular BSs is one of the best practices for both cellular and Wi-Fi networks [4]. In [5], authors describe the challenges that occur in adopting the frame-based LBT procedure and then propose a load-based LBT procedure for a cellular network. To the best of our knowledge, the majority of existing studies are based on simulations or measurements with only a few exceptions. An analytic approach is presented in [6], but the LBT procedure discussed in the 3GPP and the impact of the LBT parameters on the coexistence performance have not yet been investigated.

In this work, a mathematical model is provided to evaluate the coexistence of Wi-Fi and LBT-enabled cellular networks sharing the unlicensed spectrum. The proposed model describes the LBT procedure of a cellular BS introduced in [7] as a Markov chain that is combined with Bianchi's Markov model [8] depicting the behavior of a Wi-Fi AP. Based on the proposed model, the throughput difference between the Wi-Fi APs and cellular BSs that results from the different medium access mechanisms of the two networks is investigated. In addition, because the two networks must coexist in a friendly manner, their *graceful coexistence* is defined as the condition in which the performance of an individual node under a network scenario with m Wi-Fi APs and n cellular BSs is not worse than that under a network scenario with only $m+n$ Wi-Fi APs. Using this definition, we first examine whether this graceful coexistence is feasible through adjusting the LBT parameter of the cellular BSs, particularly the contention window (CW) size. Then, the optimal CW size that maximizes the total throughput of the two networks under the graceful coexistence condition is obtained for cases with various physical data rates and numbers of nodes in each network. From this analysis, it is shown that the deployment of LBT-enabled cellular small cells with careful parameter settings instead of Wi-Fi APs can lead to improvement in overall performance while satisfying the performance requirements of each network.

II. Coexistence Performance Analysis

A scenario where m Wi-Fi APs and n cellular BSs share the unlicensed spectrum is considered. All Wi-Fi and cellular nodes are assumed to coexist on the same frequency channel and to locate within the range where energy detection is possible (i.e., within the range where the received power exceeds -62 dBm). To describe the behavior of a Wi-Fi AP in the unlicensed spectrum, Bianchi's Markov model is adopted where each Wi-Fi AP is modeled as a two-dimensional process under the assumptions of saturated traffic and ideal channel conditions. Also, the behavior of a cellular BS in

The manuscript is accepted for publication in IEEE Communication Letters in November 2015.

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).

the unlicensed spectrum is modeled as a one-dimensional Markov chain. In [8], the key approximation is that, at each transmission attempt, the collision probability of each Wi-Fi AP p_W is constant and independent regardless of the number of retransmissions experienced. As for the Wi-Fi APs, it is assumed that a collision at a cellular BS occurs with a constant and independent probability p_L.

A. Medium access mechanism of Wi-Fi AP

As stated above, the behavior of each Wi-Fi AP is modeled as a two-dimensional Markov chain (i,k) [8]. At the first attempt of a Wi-Fi AP to transmit a packet, the backoff stage i is set to 0 and it is increased by 1 up to the maximum value $I_{\max}$ if the transmission results in a collision. It is reset to 0 after a successful transmission. The backoff counter k is uniformly chosen in the range of $[0, C_i - 1]$, where $C_i = 2^i CW_{\min}$ is the CW size at the stage i and $CW_{\min}$ is the minimum CW size. When the channel is sensed to be idle, the backoff counter decreases by 1 and the transmission occurs at $k = 0$

Let $b_{i,k}^W$ denote the stationary probability of the Markov chain in state (i,k). The closed-form expression of stationary probability for this Markov chain is presented as

$$b_{i,k}^W = \frac{C_i - k}{C_i} b_{i,0}^W, \quad i = [0,m]\,, \ k \in [0, C_i - 1]\,. \tag{1}$$

After a few steps of manipulation, all states of the Markov chain can be expressed as functions of the value $b_{0,0}^W$ and the collision probability p_W. Then, $b_{0,0}^W$ is obtained by invoking the normalization condition of Markov chain, given by

$$b_{0,0}^W = \frac{2\left(1-2p_W\right)\left(1-p_W\right)}{\left(1-2p_W\right)\left(C+1\right) + p_W C\left(1-\left(2p_W\right)^m\right)}. \tag{2}$$

Therefore, the probability that a Wi-Fi AP transmits a packet in a randomly selected slot time is obtained as follows:

$$\begin{aligned} \tau_W &= \sum_{i=0}^{m} b_{i,0}^W = \frac{b_{0,0}^W}{1-p_W} \\ &= \frac{2\left(1-2p_W\right)}{\left(1-2p_W\right)\left(C+1\right) + p_W C\left(1-\left(2p_W\right)^m\right)}. \end{aligned} \tag{3}$$

B. Medium access mechanism of cellular BS

We adopt a LBT procedure with the random backoff with a contention window of fixed size for cellular BSs, namely LBT-RB, which is introduced as a medium access mechanism for LAA small cells [5], [7]. The procedure is similar to that of Wi-Fi APs described in Section II-A because it employs a backoff mechanism after a clear channel assessment (CCA).

The LBT procedure of a cellular BS consists of two stages. The first stage, which is called the CCA stage, begins with monitoring the channel activity for the duration of time called a CCA period. If the channel is sensed to be idle continuously for the CCA period, the cellular BS proceeds to the backoff stage. Otherwise, the cellular BS continues to monitor the channel until it is deemed idle for the uninterrupted duration of the CCA period. At the beginning of the backoff stage, the backoff counter z is uniformly chosen in the range of $[0, Z-1]$, where the value Z is the CW size of the cellular BSs. Then, the backoff counter is decremented by 1 as long as the channel remains idle, and then the transmission occurs at $z = 0$. If the channel becomes busy during the backoff, this stage stops and the LBT process reverts to the CCA stage. This is the difference with the CSMA/CA procedure of Wi-Fi APs. In addition, unlike the Wi-Fi APs following a binary exponential backoff in the presence of a collision, the CW size of the cellular BSs is fixed despite the occurrence of a collision.

Through setting that the lengths of the CCA and backoff counter are equal to the distributed inter-frame space (DIFS) and the slot time adopted in the Wi-Fi as recommended in [7], respectively, the behavior of a cellular BS applying the above-described LBT procedure is modeled as a Markov chain that is combined with the Markov chain modeling the behavior of a Wi-Fi AP, where each cellular BS is represented by a one-dimensional process z.

From the Markov chain for a cellular BS, the one-step transition probability is given as follows:

$$\Pr\left[z_\beta | z_\alpha\right] = \begin{cases} 1 - p_L + \frac{1}{Z} p_L, & \text{if } z_\alpha = z_\beta + 1,\ z_\alpha \neq 0, \\ \frac{1}{Z} p_L, & \text{if } z_\alpha \neq z_\beta + 1,\ z_\alpha \neq 0, \\ \frac{1}{Z}, & \text{if } z_\alpha = 0. \end{cases} \tag{4}$$

Let b_z^L denote the stationary probability of the chain in state z. Based on (4), the closed-form expression of stationary probability for this Markov chain is represented as follows:

$$b_z^L = \begin{cases} \frac{1}{Z} p_L + \frac{1}{Z}\left(1-p_L\right) b_0^L, \\ \text{if } \ z = Z-1, \\ \frac{1}{Z} p_L + \frac{1}{Z}\left(1-p_L\right) b_0^L + \left(1-p_L\right) b_{Z+1}^L, \\ \text{if } 0 \leq z < Z-1. \end{cases} \tag{5}$$

Therefore, the probability that a cellular BS transmits a packet in a randomly selected slot time is obtained as follows:

$$\tau_L = b_0^L = \frac{\frac{1}{Z} p_L \sum\limits_{j=1}^{Z} \left(1-p_L\right)^{j-1}}{1 - \frac{1}{Z}\left(1-p_L\right) \sum\limits_{j=1}^{Z} \left(1-p_L\right)^{j-1}}. \tag{6}$$

C. Collision probability and Throughput

Equations (3) and (6) indicate that τ_W and τ_L are functions of p_W and p_L, respectively. Because p_W (p_L) is the probability that at least two nodes out of m Wi-Fi APs and n cellular BSs simultaneously transmit in the same time slot, it can be expressed as

$$p_w = 1 - \left(1-\tau_W\right)^{m-1}\left(1-\tau_L\right)^n, \tag{7}$$

$$p_L = 1 - \left(1-\tau_W\right)^{m}\left(1-\tau_L\right)^{n-1}. \tag{8}$$

Equations (3), (6), (7), and (8) construct a nonlinear system of equations with four unknowns, i.e., τ_W, τ_L, p_W, and p_L, respectively, and it can be easily solved by standard numerical methods such as the "fsolve" function in Matlab.

Let $P_{th,W}$ ($P_{th,L}$) be the probability that at least one Wi-Fi AP (cellular BS) among the m Wi-Fi APs (n cellular

TABLE I
IEEE 802.11 AC PARAMETERS

Definition	Value
Number of bits for a packet	12000 bits
MAC and PHY header	272 and 128 bits
ACK	112 bits + PHY header
Propagation delay	0.1 μs
Slot time	9 μs
SIFS and DIFS	16 and 34 μs
CW size and backoff stage	16 and 3

BSs) transmits on the channel during a time slot. Then, it is represented as follows:

$$P_{th,W} = 1 - (1-\tau_W)^m,\ P_{th,L} = 1 - (1-\tau_L)^n. \tag{9}$$

Also, let $P_{s,W}$ ($P_{s,L}$) be the probability that exactly one Wi-Fi AP (cellular BS) makes a transmission attempt under the condition that at least one Wi-Fi AP (cellular BS) transmits, and this is presented as follows:

$$P_{s,W} = \frac{m\tau_W(1-\tau_W)^{m-1}}{P_{th,W}},\ P_{s,L} = \frac{n\tau_L(1-\tau_L)^{n-1}}{P_{th,L}}. \tag{10}$$

Note that the time duration of each state in the Markov chain is not the same. That is, it differs depending on its status: a successful transmission, a collision, or an idle state. Thus, the expected time spent per state is computed in order to convert the states into the amount of time, as described in (11). Here, σ_{idle} is the idle slot time, $T_{s,W}$ ($T_{s,L}$) is the expected time of a successful transmission for a Wi-Fi AP (cellular BS), $T_{c,W}$ ($T_{c,L}$) is the expected time of a collision between Wi-Fi APs (cellular BSs), and $T_{c,\mathrm{M}}$ is the expected time of a cross-network collision, i.e., a collision between Wi-Fi APs and cellular BSs, which is determined as the larger value between $T_{c,W}$ and $T_{c,L}$. Based on the expected time spent per state, the throughput of the Wi-Fi and cellular networks is expressed as follows:

$$S_W = \frac{p_{th,W}p_{s,W}(1-p_{th,L})D_W}{T_{state}}, \tag{12}$$

$$S_L = \frac{p_{th,L}p_{s,L}(1-p_{th,W})D_L}{T_{state}}, \tag{13}$$

where D_W and D_L are the total number of bits consisting of a packet in the Wi-Fi and cellular networks, respectively. Finally, the total throughput of both networks can be obtained as $S_{total} = S_W + S_L$.

III. Numerical Results

Numerical experiments examine how the different medium access mechanisms of two networks and the CW size of cellular BSs affect the coexistence performance. For this, we consider a scenario where m Wi-Fi APs and n cellular BSs coexist in the unlicensed spectrum, and it is compared with a scenario with $m+n$ Wi-Fi APs only. Note that the objective is to maximize the total throughput of two networks under the condition that graceful coexistence is achieved.

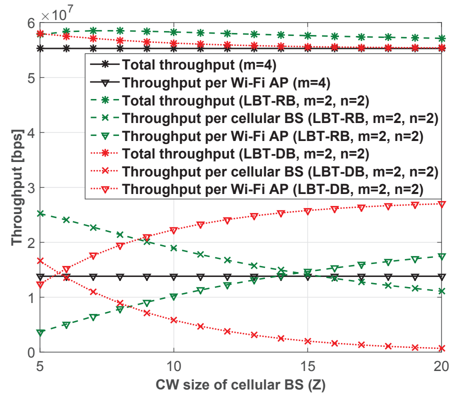


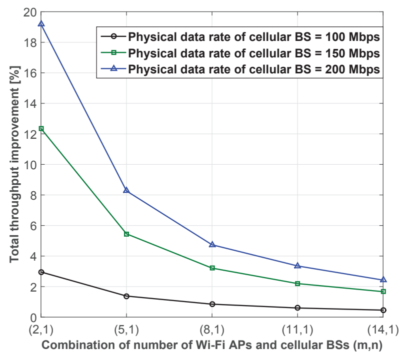
Fig. 1. Achieved throughputs according to the change in the CW size of cellular BS under different network scenarios and LBT schemes.

The parameters of Wi-Fi APs, which are summarized in Table 1, are adopted from the IEEE 802.11 ac standard [9]. It is assumed that the number of bits for a packet in cellular BSs is the same as that in Wi-Fi APs.

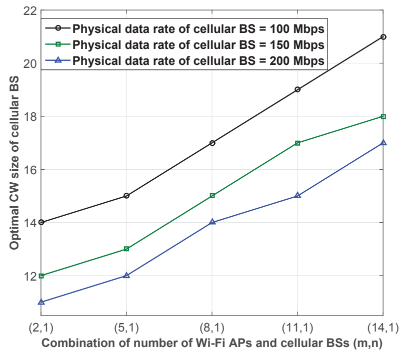
Fig. 1 presents the achieved throughputs of Wi-Fi APs and cellular BSs using the LBT-RB scheme according to the change in the CW size of the cellular BSs under the scenario with $m=2$, $n=2$. Furthermore, we consider another LBT scheme also introduced in [7], namely LBT with the deterministic backoff (LBT-DB), for comparison. LBT-DB has the deterministic duration for channel sensing which corresponds to the CCA time plus Z times as long as the slot time. Also, the same physical data rate (i.e., 100 Mbps) is assumed for the Wi-Fi APs and cellular BSs because the focus remains on the performance difference between the Wi-Fi and cellular nodes, which results from the different spectrum access mechanisms and the adjustment in the parameter of the LBT (i.e., CW size of the cellular network), not the different physical layer aspects. In Fig. 1, it is observed that, in both LBT schemes, the small CW size of the cellular BSs generally maximizes the total throughput of the two networks at the cost of significant performance degradation of the Wi-Fi APs. As the CW size increases, the cellular throughput decreases and the Wi-Fi throughput increases. For the LBT-RB scheme, there are CW sizes of the cellular BSs (Z=14, 15 in this example) that satisfy the graceful coexistence requirement (13.8 Mbps in this example). In contrast, for the LBT-DB scheme, there is no CW size that satisfies the graceful coexistence requirement, and the total throughput is lower than that of the LBT-RB scheme. For the reasons, the LBT-RB scheme has been considered by the majority of the companies participating in the coexistence evaluation [5].

Fig. 2 illustrates the impact of different network combinations and physical data rates of cellular BS on the optimal CW size and the corresponding total throughput improvement under graceful coexistence. As the physical data rate of cellular BS increases, the presence of cellular BS in the unlicensed spectrum achieves larger performance improvements in total throughput of networks, and it accompanies a smaller CW size. However, Fig. 2(a) also indicates that deploying a cellular BS in a dense Wi-Fi coverage area is not effective for improving

$$T_{state} = (1-p_{th,W})(1-p_{th,L})\sigma_{idle} + p_{th,W}p_{s,W}(1-p_{th,L})T_{s,W} + (1-p_{th,W})p_{th,L}p_{s,L}T_{s,L}$$
$$+ (1-p_{th,W})p_{th,L}(1-p_{s,L})T_{c,L} + p_{th,W}(1-p_{s,W})(1-p_{th,L})T_{c,W}$$
$$+ (p_{th,W}p_{s,W}p_{th,L}p_{s,L} + p_{th,W}p_{s,W}p_{th,L}(1-p_{s,L}) + p_{th,W}(1-p_{s,W})p_{th,L}p_{s,L} + p_{th,W}(1-p_{s,W})p_{th,L}(1-p_{s,L}))T_{c,\mathrm{M}}. \quad (11)$$



(a) Total throughput improvement with optimal CW size.



(b) Optimal CW size of cellular BS.

Fig. 2. Optimal CW size and corresponding total throughput improvement under graceful coexistence.

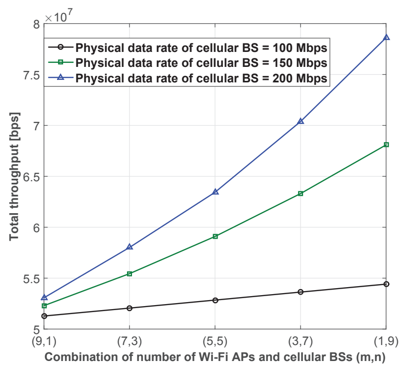


Fig. 3. Total throughput with various combinations of m and n under graceful coexistence.

the network performance even if the physical data rate of cellular BS is significantly higher than that of Wi-Fi AP.

Fig. 3 presents the performance of various combinations of m and n while maintaining $m+n$ fixed at 10. From Fig. 3, it is seen that under graceful coexistence, the increase in the number of cellular BSs results in improvements in the total throughput. However, unless the physical data rate of the cellular BSs is higher than that of the Wi-Fi APs, the gain in the total throughput is not significant with any combination of m and n.

IV. Conclusion and Future work

The coexistence performance of Wi-Fi and cellular networks was explored using different LBT procedures in the unlicensed spectrum. For this, an analytic model was provided to obtain the throughput of m Wi-Fi APs and n cellular BSs coexisting on the same frequency channel. The behavior of a LBT-enabled cellular BS was modeled as a Markov chain, and it was combined with Bianchi's model describing the behavior of a Wi-Fi AP. Also, *graceful coexistence* was defined to examine whether the deployment of cellular BSs instead of Wi-Fi APs leads to improvement in overall performance while satisfying the required performance of each network. From the performance analysis, the optimal CW size of the cellular BSs that maximizes the total throughput of the two networks under graceful coexistence was determined. Future work will investigate whether graceful coexistence is feasible under a more realistic environment when Wi-Fi and cellular nodes with different LBT procedures coexist in the unlicensed spectrum.

References

[1] J. Jeon, H. Niu, Q. Li, A. Papathanassiou, and G. Wu, "LTE in the unlicensed spectrum: Evaluating coexistence mechanisms," in *Proc. GLOBECOM Workshops*, Dec. 2014, pp. 740–745.

[2] 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.

[3] Y. Jian, C.-F. Shih, B. Krishnaswamy, and R. Sivakumar, "Coexistence of Wi-Fi and LAA-LTE: Experimental evaluation, analysis and insights," in *Proc. ICC Workshop*, Jun. 2015, pp. 10 391–10 397.

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

[6] 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.

[7] 3GPP, "Study on Licensed-Assisted Access to unlicensed spectrum (Release 13)," 3GPP, Tech. Rep. 36.889, Jun. 2015.

[8] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.

[9] E. H. Ong, J. Kneckt, O. Alanen, Z. Chang, T. Huovinen, and T. Nihtila, "IEEE 802.11ac: Enhancements for very high throughput WLANs," in *Proc. PIMRC*, Sep. 2011, pp. 849–853.