Power Control based Fair Coexistence of LBT-Free 5G New Radio Small Cells with WiGig Networks

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Abstract**—In this paper, we present a power control technique to coexist in-building small cells of the Fifth-Generation (5G) New Radio (NR) in the 60 GHz band with the incumbent Access Points (APs) of the IEEE 802.11ad/ay standard, also termed as Wireless Gigabit (WiGig). Small cells are not Listen-Before-Talk (LBT) feature enabled. Moreover, each small cell is equipped with a dual-transceiver, one operating in the 28 GHz band exclusively while the other in the 60 GHz band opportunistically. The proposed technique allows each small cell to operate in the 60 GHz band only to serve its downlink traffic by switching its transmission power either to zero or to a minimum allowable level. The minimum power level results in the interference experienced by a WiGig AP (WiAP) that does not exceed its prior interference threshold level set by the WiGig operator to ensure its fairness while coexisting with a small cell. We derive average capacity, Spectral Efficiency (SE), and Energy Efficiency (EE) metrics for NR small cells. With system-level simulation results, it is shown that the proposed technique improves all these above metrics of small cells considerably while ensuring a fair coexistence of small cells with incumbent WiAPs by limiting the interference at a WiAP to the maximum allowable level (i.e., the interference threshold level).**

Keywords—5G; millimeter-wave; unlicensed band; new radio; small cell; IEEE 802.11 ad/ay; power control.

I. INTRODUCTION

The continuing growth in mobile devices and data traffic over the past decade causes mobile network operators (MNOs) to face tremendous challenges since the availability of the mobile spectrum for an MNO has not been increased correspondingly. Though several approaches, such as small cell deployments have been employed, no significant improvement toward addressing the growing demand to serve data traffic has been observed. This causes the focus of an MNO to shift from serving its data traffic by the allocated licensed spectrum only to the unlicensed spectrum bands as well. Globally, a large amount of spectrum is available in the unlicensed bands, including 2.4 GHz, 5 GHz, and 60 GHz. A major feature of the unlicensed bands is the ability of a user to get access freely to them. However, because of the presence of the incumbent WiFi networks in the unlicensed bands, proper co-channel interference (CCI) management is necessary to coexist a cellular network with a WiFi network in the same unlicensed band.

In this regard, by enabling cellular nodes (e.g., small cells) with Listen-Before-Talk (LBT) (Alhulayil and Lopez-Benitez, [1]), a fair coexistence of cellular and WiFi nodes can be made possible. The LBT is basically similar to the Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA). Instead of allowing a cellular node to always use a channel, it shares between a cellular node and a WiFi Access Point (AP) fairly (Zhang et al. [2]) by periodically stopping the cellular node to occupy the channel and detecting the activities of other shared nodes on the channel. Several studies also showed that the LBT is critical for a fair coexistence between a cellular network such as Long-Term Evolution (LTE) and a Wi-Fi network (Kwan et al. [3], Chaves et al. [4]). However, LBT is not used in all regions such as the United States of America (USA) and China where LBT is not required particularly for early commercialization (Lagen et al. [5]). Hence, cellular nodes are enabled with LBT, they do not have sensing capabilities such as the CSMA/CA protocol of WiFi networks to avoid a collision. In this regard, the coexistence of small cells can be provided by managing CCI with WiFi networks in time and power domains.

In this direction, numerous studies already addressed the coexistence issues between cellular and WiFi networks in the time-domain using the Almost Blank Subframe (ABS) based Enhanced Intercell Interference Coordination (eICIC) technique in LTE. For example, by employing ABSs, Almeida et al. [6] proposed a scheme to coexist LTE with WiFi in an unlicensed band. Likewise, Nihtilä et al. [7] proposed the LTE muting mechanism to allow access to the channel to WiFi users and Zhang et al. [8] presented an ABS-based coexistence scheme to avoid co-channel interference between small cells and WiFi systems.

With regard to providing the coexistence between cellular and WiFi networks in the power-domain, Huang et al. [9] discussed the coexistence of LTE/WiFi in the power domain such that by adjusting the output power of LTE nodes, the transmission opportunity of WiFi nodes can be changed. Sagari et al. [10] proposed Wi-Fi and LTE coordination algorithms based on optimization in the power and frequency domain. Further, Chaves et al. in [4] proposed to use the uplink power control to improve the performance of coexistence of LTE with WiFi by introducing an additional factor to the conventional uplink power control mechanism of LTE. Besides, Hang et al. [11] proposed a Power Control-based Spatial Reuse scheme to increase the probability of simultaneous transmissions of Licensed-Assisted Access (LAA) and WiFi. Moreover, in [12], Xia et al. studied the use of transmit power control, as well as clear channel assessment, mechanisms in unlicensed LTE systems by considering that all stations use the same fixed transmit power.

However, different from these above contributions in power-domain, in this paper, we present a simple, yet effective, transmit power control technique for in-building small cells of

Fifth-Generation (5G) New Radio (NR) to coexist with the incumbent WiFi Access Points (WiAPs) of the Wireless Gigabit (WiGig) in the 60 GHz band. In doing so, we first present the system architecture and the coexistence mechanism in Section II, followed by the mathematical analysis to derive average capacity, Spectral Efficiency (SE), and Energy Efficiency (EE) metrics for NR small cells in Section III. We evaluate the performance of the proposed technique in Section IV and conclude the paper in Section V.

II. SYSTEM ARCHITECTURE AND PROPOSED COEXISTENCE MECHANISM

Consider a set of small cells and WiAPs such that one from each set is deployed per apartment of any multistory building located within the coverage of a macrocell of a 5G NR operator. A set of picocells are also located within the macrocell coverage to offload some macrocell traffic. Each small cell or WiAP serves one User Equipment (UE) at a time. For clarity, we consider only one apartment to show the coexistence of a small cell and a WiAP as shown in Figure 1(a). From Figure 1(a), it can be found that each small cell is equipped with two transceivers, one operates in the 28 GHz band and the other in the 60 GHz band.

Since the 28 GHz band is a licensed band for an MNO, the transceiver operating at the 28 GHz band can serve both the uplink and downlink traffic at all time. However, since WiAPs operate in the 60 GHz band by default, and small cells are not Listen-Before-Talk (LBT) enabled, it can be possible that all WiAPs are blocked by the small cells due to having relatively a higher interference margin of a small cell than that of a WiAP. Hence, to overcome this problem, we propose the following power control technique to coexist small cells with WiAPs as shown in Figure 2(b).

Small cells of any 5G NR can get access to the 60 GHz band either when no UEs of any WiGig network are present within an apartment of a multistory building or when small cells of any 5G NR can operate in the 60 GHz band at a reduced transmission power causing less interference than that of the interference threshold set by the corresponding WiGig network, as shown in Figure 1(b).

The presence of a UE of a small cell can be sensed by the WiAP by detecting and measuring the 60 GHz channel energy, whereas the transmission of a WiAP can be identified either by the small cell using its transceiver operating at the 28 GHz or by the UE of the small cell in the uplink at the 28 GHz band. Note that the WiAP stops the transmission due to its inherent CSMA/CA protocol to avoid collision with the small cell. An example of opportunistic subframe allocation to small cells to coexist with WiAPs in the 60 GHz spectrum band by employing the proposed power control technique is shown in Figure 1(c) and is described in the following.

A subframe in the 60 GHz is allocated to either a small cell or a WiAP depend on the presence of their UEs at any time, as well as the level of interference experienced by the UE of the WiAP as compared to that of its threshold interference. More specifically, given that a UE of the small cell is present in an apartment, a subframe is allocated to a small cell only under the following conditions:

- when no UEs of the WiAP is present.
- when a UE of the WiAP is present, and the interference experienced by the WiAP UE is above the threshold interference.

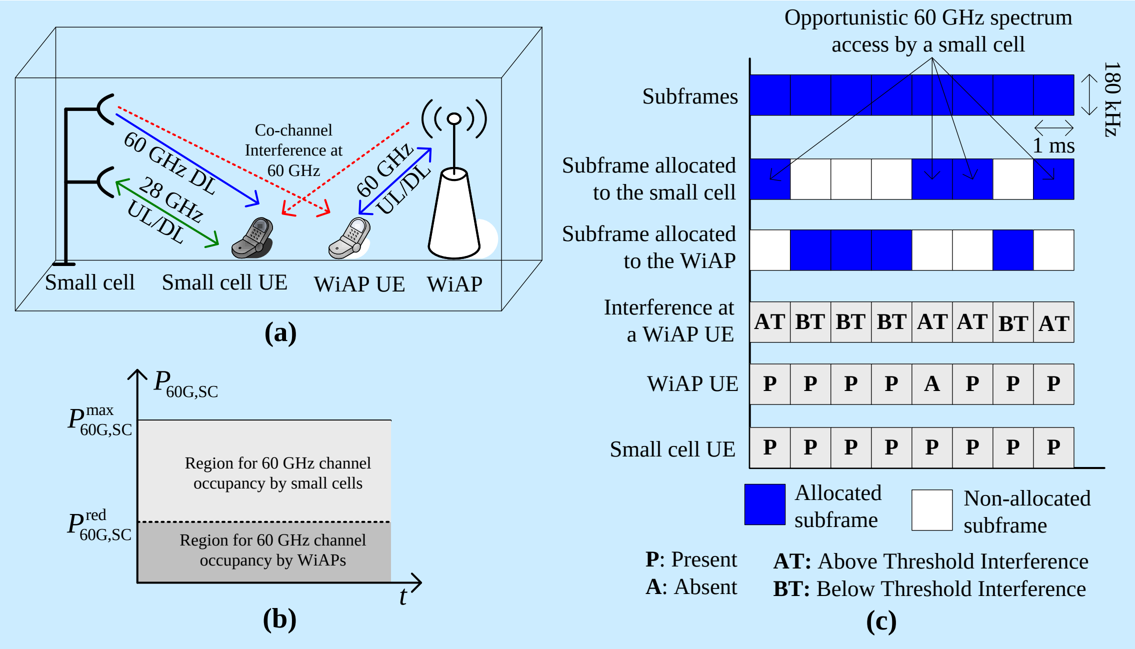


Figure 1. (a) Coexistence of a small cell and a WiAP in an apartment of a building. (b) Small cell transmission power control technique. (c) An example of opportunistic 60 GHz spectrum access by a small for a number of subframes.

However, if the interference experienced by the UE of the WiAP is below the threshold interference in a subframe, no collision can be detected by the CSMA/CA protocol of the WiAP, and hence, the corresponding subframe is allocated to the WiAP.

III. MATHEMATICAL ANALYSIS

Let S_{M}, S_{P}, and S_{F} denote, respectively, the number of macrocells of a 5G NR MNO, the number of picocells per macrocell, and the number of small cells in a building. Let $M_{2\mathrm{G}}$, $M_{28\mathrm{G}}$, and $M_{60\mathrm{G}}$ denote, respectively, the number of Resource Blocks (RBs) of 2 GHz, 28 GHz, and 60 GHz spectra where an RB is equal to 180 kHz. Also, let $\boldsymbol{T}$ denote the simulation run time with the maximum time of Q (in time step each lasting 1 ms) such that $\boldsymbol{T}=\{1, 2, 3,\ldots,Q\}$. Following [13], the arrival process of UEs of a 5G NR small cells and WiGig operators can be assumed to follow the Poisson processes with a mean λ_{NR} and λ_{WiG}, respectively, over a certain observation time T. Hence, the amount of time in terms of the number of Transmission Time Intervals (TTIs) that 5G NR small cells and WiAPs in a building serve their corresponding UEs in Q can be expressed, respectively, as follows.

$$T_{\mathrm{NR}} = \left\lceil \left(\frac{\lambda_{\mathrm{NR}}}{\left(\lambda_{\mathrm{NR}} + \lambda_{\mathrm{WiG}}\right)} \right) \times Q \right\rceil \tag{1}$$

Let P_{MC} and P_{PC} denote, respectively, the transmission power of a macrocell and a picocell. Let $I_{60\mathrm{G,WiG}}^{\mathrm{th}}$ denote the threshold interference value for a WiAP. Also, let $P_{60\mathrm{G,SC}}^{\max}$ and $P_{60\mathrm{G,SC}}^{\mathrm{red}}$ denote, respectively, the maximum transmission power and the reduced transmission power of a small cell when operating in the 60 GHz band. Let $I_{60\mathrm{G,SC}}$ denote the interference experienced by a WiAP due to $P_{60\mathrm{G,SC}}^{\mathrm{red}}$ such that $I_{60\mathrm{G,SC}} \le I_{60\mathrm{G,WiG}}^{\mathrm{th}}$. Hence, the transmission power of a small cell when operating at 60 GHz can be expressed as follows.

$$P_{60\mathrm{G,SC}} = \begin{cases} P_{60\mathrm{G,SC}}^{\max}, & \text{if } I_{60\mathrm{G,SC}} = 0 \\ P_{60\mathrm{G,SC}}^{\mathrm{red}}, & \text{if } I_{60\mathrm{G,SC}} \ne 0 \end{cases} \tag{2}$$

Now the received Signal-to-Interference-Plus-Noise Ratio (SINR) at RB=i in TTI=t at a UE of a small cell is given by

$$\rho_{t,i} = \left(\frac{P_{t,i}}{\left(N_{t,i}^{\mathrm{s}} + I_{t,i}\right)} \right) \times H_{t,i} \tag{3}$$

where $P_{t,i}$, $N_{t,i}^{\mathrm{s}}$, $I_{t,i}$, and $H_{t,i}$ denote, respectively, transmission power, noise power, interference power, and link loss at RB=i in TTI=t.

Using Shannon's capacity formula, a link throughput at RB=i in TTI=t for an MNO o in bps per Hz is given by [14]

$$\sigma_{t,i}\left(\rho_{t,i}\right) = \left\{ \begin{array}{ll} 0, & \rho_{t,i} < -10\,\mathrm{dB} \\ \beta \log_2\left(1+10^{\left(\rho_{t,i}(\mathrm{dB})/10\right)}\right), & -10\,\mathrm{dB} \le \rho_{t,i} \le 22\,\mathrm{dB} \\ 4.4, & \rho_{t,i} > 22\,\mathrm{dB} \end{array} \right\} \tag{4}$$

where β denotes the implementation loss factor.

The average capacity of all macrocell UEs of a 5G NR can be given by

$$\sigma_{2\mathrm{G}} = \sum\nolimits_{t=1}^{Q} \sum\nolimits_{i=1}^{M_{2\mathrm{G}}} \sigma_{t,i}\left(\rho_{t,i}\right) \tag{5}$$

where σ and ρ are responses over $M_{2\mathrm{G}}$ RBs of all macro UEs in $t \in \boldsymbol{T}$.

Now, the average capacity served by transceiver 1 of all small cells in the building is given by,

$$\sigma_{28\mathrm{G}}^{\mathrm{Tr\ 1}} = \sum\nolimits_{s=1}^{S_{\mathrm{F}}} \sum_{t \in \boldsymbol{T}} \sum\nolimits_{i=1}^{M_{28\mathrm{G}}} \sigma_{s,t,i}\left(\rho_{s,t,i}\right) \tag{6}$$

Similarly, the average capacity served by transceiver 2 of all small cells in the building is given by,

$$\sigma_{60\mathrm{G}}^{\mathrm{Tr\ 2}} = \sum\nolimits_{s=1}^{S_{\mathrm{F}}} \sum_{t\ \in \boldsymbol{T}_{\mathbf{NR}}} \sum\nolimits_{i=1}^{M_{60\mathrm{G}}} \sigma_{s,t,i}\left(\rho_{s,t,i}\right) \tag{7}$$

So, the total average capacity served by both transceivers of all small cells in the building is given by,

$$\sigma_{\mathrm{Dual\ Band}}^{\mathrm{Tr\ 1+Tr\ 2}} = \sigma_{28\mathrm{G}}^{\mathrm{Tr\ 1}} + \sigma_{60\mathrm{G}}^{\mathrm{Tr\ 2}} \tag{8}$$

Due to small coverage, low transmission power, and high distance-dependent path loss, we assume similar indoor signal propagation characteristics for both 28 GHz and 60 GHz. Hence, by linear approximation, the system-level average capacity, SE, and EE, respectively, for all small cells of a 5G NR is given by,

$$\sigma_{\mathrm{Sys}}^{\mathrm{5G\ NR}} = \sigma_{2\mathrm{G}} + \sigma_{\mathrm{Dual\ Band}}^{\mathrm{Tr\ 1+Tr\ 2}} \tag{9}$$

$$\gamma_{\mathrm{Sys}}^{\mathrm{5G\ NR}} = \frac{\sigma_{\mathrm{Sys}}^{\mathrm{5G\ NR}}}{\left(\left(M_{2\mathrm{G}} + M_{28\mathrm{G}}\right) \times Q\right)} \tag{10}$$

$$\varepsilon_{\mathrm{Sys}}^{\mathrm{5G\ NR}} = \frac{\left(\left(\begin{array}{l} \left(L \times S_{\mathrm{F}} \times \left(P_{28\mathrm{G,SC}} + P_{60\mathrm{G,SC}}\right)\right) + \\ \left(S_{\mathrm{P}} \times P_{\mathrm{PC}}\right) + \left(S_{\mathrm{M}} \times P_{\mathrm{MC}}\right) \end{array} \right) \times Q \right)}{\sigma_{\mathrm{Sys}}^{\mathrm{5G\ NR}}} \tag{11}$$

Note that for the SE estimation in (10), only the licensed spectra are considered since licensed spectra are not free of cost and each operator needs to pay for the spectrum licensing fee.

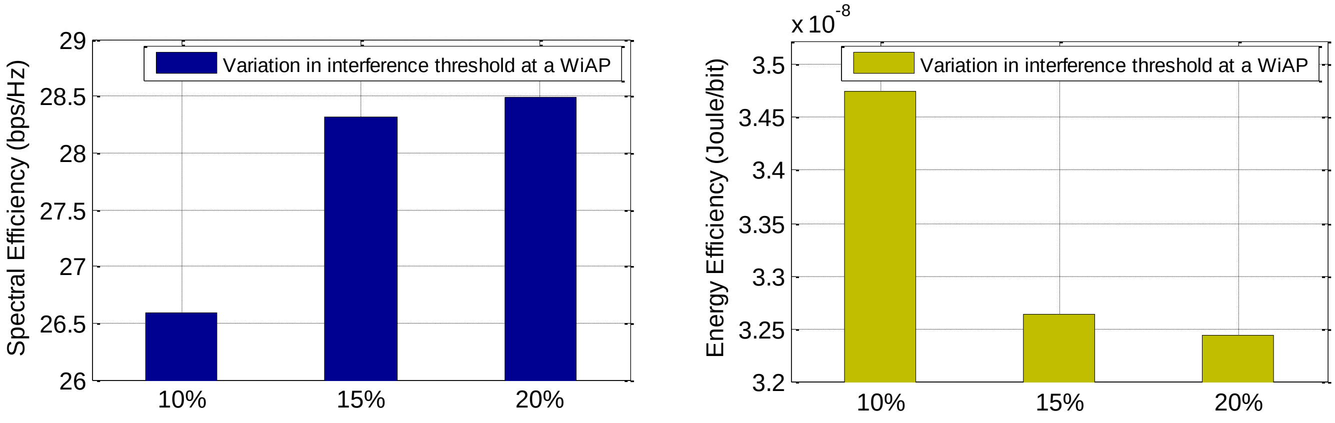
IV. PERFORMANCE EVALUATION AND COMPARISON

Table I shows the simulation parameters and assumptions used to evaluate the performances of the proposed technique. Figure 2 shows SE and EE responses of small cells in a building due to the variation in the interference threshold $I^{\mathrm{th}}_{\mathrm{60G,WiG}}$ at a WiAP. As the interference threshold requirement increases, i.e. the value of $I^{\mathrm{th}}_{\mathrm{60G,WiG}}$ decreases, both SE and EE performances of small cells of 5G NR improve nonlinearly. This is because, with an increase in $I^{\mathrm{th}}_{\mathrm{60G,WiG}}$, small cells can increase the transmission power in the 60 GHz band, resulting in improving the capacity logarithmically following (4). This, however, causes a corresponding reduction in the capacity, and hence the SE and EE performances of WiAPs. Moreover, using (7), an increase in the transmission time T_{NR} of small cells increases the overall capacity, and hence the SE and EE of small cells. In summary, T_{NR} and $I^{\mathrm{th}}_{\mathrm{60G,WiG}}$ play considerable role in trading-off the coexistence performances, in terms of the average capacity, SE, and EE, of both small cells of a 5G NR network and WiAPs of a WiGig network.

TABLE I
SIMULATION PARAMETERS AND ASSUMPTIONS

Parameters and Assumptions			**Value**
Number of 5G NR-U and WiGig operators, respectively			1, 1
Spectrum bandwidth of NR	2 GHz (Non-LOS), 28 GHz (LOS), and 60 GHz (LOS), respectively		10 MHz, 50 MHz, and 100 MHz
Number of cells	Macrocells, picocells, and small cells		1, 2, and 9
Interference threshold, $I^{\mathrm{th}}_{\mathrm{60G,WiG}}$			10%, 15%, and 20% of $P^{\mathrm{max}}_{\mathrm{60G,SC}}$
Cellular layout[2], inter-site distance (ISD)[1,2], transmission direction			Hexagonal grid, dense urban, 3 sectors per macrocell site, 1732 m, downlink
Total base station transmit power (dBm)	Macrocell[1] and picocell[1]		46 and 37
	Small cell operating in 28 GHz[1]		19
	Small cell operating in 60 GHz[1]		17.3
Co-channel small-scale fading model[1]	2 GHz		Frequency selective Rayleigh
	28 GHz		no small-scale fading effect
	60 GHz		no small-scale fading effect
Path loss	MBS and a UE[1]	Outdoor macrocell UE	$PL(\mathrm{dB})=15.3 + 37.6 \log_{10}R$, R is in m
		Indoor macrocell UE	$PL(\mathrm{dB})=15.3 + 37.6 \log_{10}R + L_{\mathrm{ow}}$, R is in m and $L_{\mathrm{ow}}=20$ dB
	PBS and a UE[1]		$PL(\mathrm{dB})=140.7+36.7 \log_{10}R$, R is in km
	SBS and a UE[1,2]	28 GHz	$PL(\mathrm{dB})=61.38+17.97 \log_{10}R$, R is in m
		60 GHz	$PL(\mathrm{dB})=68+21.7\log_{10}(R)$, R in m
Lognormal shadowing standard deviation (dB)	MBS[2] and PBS[1]		8 and 10
	SBS in 28 GHz and 60 GHz[2]		9.9 and 0.88
Antenna configuration			Single-input single-output for all BSs and UEs
Antenna pattern (horizontal)			Directional (120^0) for MBS[1], omnidirectional for PBS[1] and SBS[1]
Antenna gain plus connector loss (dBi)	MBS[2] , PBS[1], and SBS[1]		14, 5, and 5
UE antenna gain[2]	2 GHz, 28 GHz, and 60 GHz (Biconical horn)		0 dBi, 5 dBi, and 5 dBi
UE noise figure[2] , UE speed[1], and indoor macrocell UE[1]			9 dB (for 2 GHz) and 10 dB (for 28 GHz and 60 GHz), 3 km/hr, and 35%
Picocell coverage[1], the total number of macrocell UEs, and macrocell UEs offloaded to all picocells[1]			40 m (radius), 30, 2/15
3D multistory building and SBS models (square-grid apartments)	Number of buildings		1
	Number of floors per building		1
	Number of apartments per floor		9
	Number of SBSs per apartment		1
	Area of an apartment		10×10 m^2
Scheduler and traffic model[2]			Proportional Fair and full buffer
Type of SBSs			Closed Subscriber Group femtocell BSs
TTI[1], FPP, and PF scheduler time constant (t_c)			1 ms, 8 ms, and 100 ms
Total simulation run time			8 ms

taken [1]from [15], [2]from [16].



(a) **(b)**

Figure 2. SE and EE responses of 5G NR small cells due to the variation in the interference threshold in the percentage of $P_{\mathrm{60G,SC}}^{\max}$ at a WiAP.

With regards to the other existing techniques, the proposed technique benefits from the fact that it does not impact the air interface protocol of cellular systems, as well as can meet the global regulations. Moreover, this technique is typically used together with other coexistence techniques. However, it is less fair to resource allocations than other techniques and is typically interference measurement based [17].

V. CONCLUSION

In this paper, we have presented a transmission power control technique for LBT-free 5G NR small cells to coexist with WiAPs in the 60 GHz band within a building. With system-level simulation results, it has been shown that the proposed technique can improve the average capacity, SE, and EE of small cells of a 5G NR while ensuring fair coexistence with WiAPs by maintaining a maximum interference level at a WiAP limited to its interference threshold. More specifically, an increase in the interference threshold of WiAPs results in a nonlinear increase in the SE and EE of small cells while decreasing the SE and EE of WiAPs. However, an increase in the transmission time of either small cells or WiAPs causes a corresponding linear increase in the SE and EE. Hence, the transmission time and the interference threshold of WiAPs play noticeable roles in trading-off the coexistence performances of small cells of a 5G NR and WiAPs of a WiGig.

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