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Research Article

An Overview and Mechanism for the Coexistence of 5G NR-U (New Radio Unlicensed) in the Millimeter-Wave Spectrum for Indoor Small Cells

Rony Kumer Saha

Radio and Spectrum Laboratory, KDDI Research, Inc., 2-1-15 Ohara, Fujimino-shi, Saitama, Japan

Correspondence should be addressed to Rony Kumer Saha; rony107976@gmail.com

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In this paper, we first give an overview of the coexistence of cellular with IEEE 802.11 technologies in the unlicensed bands. We then present a coexistence mechanism for Fifth-Generation (5G) New Radio on Unlicensed (NR-U) small cells located within buildings to coexist with the IEEE 802.11ad/ay, also termed as Wireless Gigabit (WiGig). Small cells are dual-band enabled operating in the 60 GHz unlicensed and 28 GHz licensed millimeter-wave (mmW) bands. We develop an interference avoidance scheme in the time domain to avoid cochannel interference (CCI) between in-building NR-U small cells and WiGig access points (APs). We then derive average capacity, spectral efficiency (SE), and energy efficiency (EE) performance metrics of in-building small cells. Extensive system-level numerical and simulation results and analyses are carried out for a number of variants of NR-U, including NR standalone, NR-U standalone, and NR-U anchored. We also analyze the impact of the spatial reuse of both mmW spectra of multiple NR-U anchored operators with a WiGig operator. It is shown that NR-U anchored provides the best average capacity and EE performances, whereas NR-U standalone provides the best SE performance. Moreover, both vertical spatial reuse intrabuilding level and horizontal spatial reuse interbuilding level of mmW spectra in small cells of an NR-U anchored can improve its SE and EE performances. Finally, we show that by choosing appropriate values of vertical and horizontal spatial reuse factors, the proposed coexistence mechanism can achieve the expected SE and EE requirements for the future Sixth-Generation (6G) mobile networks.

1. Introduction

1.1. Background. The continuing demand for high capacity and data rate in cellular networks due to the growth of mobile devices to serve rich and diverse multimedia contents enforces mobile network operators (MNOs) to redesign the existing networks. Global mobile traffic is more than doubling each year [1], and in line with so, the introduction of the Fifth-Generation (5G) New Radio (NR) to serve a large volume of data traffic has increased the burden on the licensed spectrum bands of an MNO [2]. Serving such a large volume of data traffic in the unlicensed spectrum in addition to the licensed one of an MNO is an effective solution, and accordingly, the 3rd Generation Partnership Project (3GPP) has recently started expanding the operation of cellular networks to unlicensed bands in 2015 with the Long-Term Evolution (LTE) in 3GPP Release-13 [3]. However, the IEEE 802.11-based Wireless Fidelity (WiFi) technologies have been developed and are in operation globally over a wide range of unlicensed bands, including 2.4 GHz, 5 GHz, and 60 GHz bands, since 1997 [4]. Hence, to operate in these unlicensed bands without interfering with each other, an appropriate mechanism is necessary for cellular networks to coexist with the incumbent WiFi networks.

1.2. Related Work. Numerous research studies addressed the coexistence of WiFi with cellular networks such as LTE and 5G NR. Notably, with regard to the LTE and WiFi (LTE/-WiFi) coexistence, the authors in [3] elaborated LTE/WiFi coexistence mechanism in time, frequency, and power aspects. Further, the authors in [5] presented an analytical model for the characterization of achievable throughputs of

WiFi and LTE on Unlicensed band (LTE-U) networks in spatially distributed scenarios in the downlink. Furthermore, the authors in [6] carried out a performance analysis of 3GPP LTE and IEEE 802.11 Wireless Local Area Networks (WLAN) using a fractional bandwidth sharing mechanism. Besides, the authors in [7] reviewed the state-of-the-art LTE/WiFi coexistence mechanisms and showed their incorporation into the industry standards.

Likewise, regarding the 5G New Radio Unlicensed (NR-U) and WiFi (5G NR-U/WiFi) coexistence, the authors in [8] addressed the coexistence of 5G NR-U/WiFi in the 6 GHz band, and in [9], the authors addressed the coexistence of WiFi with the beam-based 5G NR-U in the millimeter-wave (mmW) bands. Moreover, in [2], the authors investigated the performance of the 5G NR-U/WiFi coexisted network by implementing a mode selection procedure in 5G NR to use either the licensed spectrum band or the unlicensed spectrum band. Furthermore, the authors in [4] presented a system-level evaluation of 5G NR-U/WiFi coexistence in the 60 GHz unlicensed mmW band. Likewise, in [10], the authors presented a system-level simulation-based study on the coexistence of NR-based access to unlicensed spectrum and an IEEE technology, i.e., Wireless Gigabit (WiGig), at 60 GHz bands. Besides, in [11], the authors reported on extensions to a popular and open-source network simulator, ns-3, to build an NR-U system-level simulator and to model the coexistence of NR-U and IEEE 802.11 technologies in the available unlicensed spectrum bands. Further, [12] examined the downlink performance of NR-U and WiGig technologies under intertechnology interference from each other in the 60 GHz band. The author also presented stochastic models for signal-to-interference-plus-noise ratio (SINR) and data rate under a dense small cell setting.

Besides, several research studies proposed to use the almost blank subframe- (ABS-) based Enhanced Intercell Interference Coordination (eICIC) technique in LTE to address the coexistence issue between WiFi and cellular systems in the unlicensed band in the time-domain. For example, by reusing the concept of ABS, the authors in [13] proposed a simple scheme to exist the LTE system with the WiFi system in an unlicensed band and showed an improved throughput per WiFi user performance. Likewise, the authors in [14] proposed an adaptive coexistence scheme between LTE and WiFi by utilizing the ABS. Further, the authors in [13] proposed a modified version of ABSs called null subframes during which no reference signal is transmitted for reusing these blank subframes by the WiFi and showed that the throughput of WiFi increases with an increase in null subframes. Furthermore, the authors in [15] provided a performance evaluation of coexistence between LTE and WiFi systems and showed some of the challenges faced by each technology. Specifically, in an office scenario, the authors showed with simulation results that the LTE system performance is slightly affected by coexistence, whereas WiFi is impacted considerably. Likewise, the authors in [16] proposed to manage the coexistence between LTE-U and WiFi using an X2 interface where the ABSs are configured and communicated by LTE-U macrocells using X2 interface to allow WiFi data transmission during ABSs without any interruption from macrocells.

1.3. Problem Statement. Since existing MNOs are facing difficulty from the cost and scarcity of the available licensed spectrum, compared to the unlicensed spectrum available in the low-frequency bands, the unlicensed spectrum in the high-frequency mmW bands is a potential solution to address both the cost and scarcity issues for the 5G mobile networks. Particularly, due to the license-free access to the unlicensed band and wide spectrum bandwidth availability in the unlicensed, as well as licensed, mmW spectrum, both the spectrum licensing cost and scarcity can be minimized. However, to operate in unlicensed bands, certain regulatory requirements, including the use of Listen Before Talk (LBT) as a spectrum-sharing mechanism, a maximum channel occupancy time, a minimum occupied channel bandwidth requirement, and power limits [4], must be met. These regulatory requirements vary among regions and bands.

From Table 1, it can be found that most existing works investigated NR-U mainly under the LBT protocol as a native feature of NR-U. This, however, is not the case for the LTE since LBT has been introduced later to LTE, which has a different medium access control (MAC) mechanism from that of NR-U. Even though LBT is able to provide better fairness than other coexistence mechanisms, it suffers also from several bottlenecks. Firstly, LBT introduces extra delay due to the contention time overhead that leads to inefficient channel usage. Secondly, the use of LBT in LTE requires considerable changes in the original LTE MAC mechanism. Thirdly, the impact of IEEE 802.11 standards varies on how LBT is implemented since not all LBT schemes provide fair existence. Fourthly, if the duration of transmission bursts was too long, WiFi access points (APs) may get experienced large packet delays and jitter.

Moreover, LBT is not required by all regions in the world such as the USA, South Korea, and China. In such regions, more simple mechanisms such as blank subframes are preferable. In this regard, the allocation of air time between cellular and IEEE 802.11 nodes plays an important role in the fairness of unlicensed spectrum allocation and, hence, the overall coexistence performance. The major advantage of using blank subframes is that it requires fewer changes in the air interface of cellular standards such as LTE and hence can be deployed in a short term. For nonadjacent subframes, by reporting the duration and occurrence of blank subframes to WiFi APs during the negotiation phase, the transmission of WiFi APs can be suitably confined with the subframes to avoid interference with cellular nodes such as LTE.

Another noticeable factor is the operation of the high-frequency mmW spectrum. In this regard, a wider contiguous bandwidth is available in the 60 GHz band, which is not currently very crowded. Due to these reasons, the 60 GHz band is considered an attractive unlicensed band for 5G NR-U [9, 17]. Moreover, the small coverage and high internal/external walls and floor penetration losses in the 60 GHz unlicensed band make it suitable to operate with the small cells in indoor environments, particularly, in dense urban multistory buildings.

Table 1: A comparison of this paper with existing works on the coexistence of cellular and IEEE 802.11 technologies.

Reference	Contribution summary	Operating frequency	Coexistence technologies	Major investigation	Impact analysis	Environment	Cellular deployment	Cellular channel access mechanism	Spectrum reuse
[5]	An analytical model for the characterization of achievable throughputs of Wi-Fi and LTE-U networks in spatially distributed scenarios in the downlink	5.3 GHz	LTE-U for cellular and WiFi for IEEE 802.11	Throughput	Energy detection and carrier sense threshold	Indoor/outdoor (generalized scenario)	LTE-U	CSAT	No
[10]	A system-level simulation-based study on the coexistence of NR-based access to unlicensed spectrum and an IEEE technology, i.e., Wireless Gigabit (WiGig), at 60 GHz bands	60 GHz	NR-U for cellular and WiGig for IEEE 802.11	Relative performance of channel access mechanism	Latency, throughput, occupancy	Indoor (single-floor building)	NR-U standalone	LBT and duty-cycle	No
[11]	A report on extensions to a popular and open-source network simulator, ns-3, to build an NR-U system-level simulator and to model the coexistence of NR-U and IEEE 802.11 technologies in the available unlicensed spectrum bands	60 GHz	NR-U for cellular and WiGig for IEEE 802.11	Coexistence of NR-U and WiGig	Bandwidth, channel access scheme, energy detection threshold, and beamforming	Indoor (single-floor building)	NR-U standalone	LBT and duty-cycle	No
[12]	The paper examines the downlink performance of NR-U and WiGig technologies under inter-technology interference from each other in the 60 GHz band. Stochastic models for signal-to-interference-plus-noise ratio (SINR) and data rate under a dense small cell setting are presented	60 GHz	NR-U for cellular and WiGig for IEEE 802.11	Stochastic analysis for downlink performance of NR-U and WiGig in the 60 GHz band	Downlink SINR and data rate	Outdoor (urban microcells)	NR-U standalone	LBT	No
[13]	A coexistence scheme between LTE and WiFi that reuses the concept of almost blank subframes in LTE	900.0 MHz	LTE-U for cellular and WiFi for IEEE 802.11	Mean user throughputs	Configurations of blank subframes, floor configuration	Indoor single floor and indoor multifloor	LTE only and LTE coexistence	Blank subframes	No
[28]	Coexistence of Wi-Fi and Fourth-Generation (4G) cellular networks (LTE/LTE-A) sharing the unlicensed spectrum by presenting an almost blank subframe (ABS) scheme without priority to mitigate the cochannel interference from small cells to Wi-Fi systems to facilitate their coexistence while sharing the same unlicensed spectrum	2.4 GHz	LTE-U for cellular and WiFi for IEEE 802.11	Cellular capacity and quality of service of WiFi	Cell traffic loads, static and dynamic interference mitigation schemes	Outdoor (3-tier cellular and Wi-Fi heterogeneous network)	LTE only and LTE coexistence	Random almost blank subframe allocation	No

Table 1: Continued.

Reference	Contribution summary	Operating frequency	Coexistence technologies	Major investigation	Impact analysis	Environment	Cellular deployment	Cellular channel access mechanism	Spectrum reuse
[16]	Derive a new adaptive LBT mechanism and virtualized core network for the best practices in both Wi-Fi and LTE-U technologies	5 GHz	LTE-U for cellular and WiFi for IEEE 802.11	Throughputs and end-to-end delay of LTE-U and LTE only	Number of users	Outdoor	LTE only and LTE coexistence	Almost blank subframe, LBT	No
[2]	Investigate the WiFi and 5G NR coexisted network with NR base stations implementing the mode selection procedure to use either the licensed spectrum band or the unlicensed spectrum band. Leveraging the stochastic geometry, a tractable mathematical framework to characterize the medium access probability, the conditional coverage probability for different types of access points, and the overall coverage probability is presented	2.4 GHz, 5 GHz	LTE-U for cellular and WiFi for IEEE 802.11	Overall coverage probability for this coexisted network	SIR threshold, mode selection probability, and sensing threshold	Outdoor	NR standalone, NR-U standalone	Almost blank subframe, LBT	No
This paper	Propose a coexistence mechanism for NR-U in-building small cells to coexist with WiGig where each small cell operates in both the 60 GHz unlicensed and 28 GHz licensed mmW bands. An interference avoidance scheme by modifying the concept of ABS to avoid CCI in the 60 GHz unlicensed spectrum is presented to develop an analytical model for the evaluation of NR-U under different cellular deployment scenarios in the 60 GHz. Moreover, an overview of the coexistence of NR-U with WiGig networks is discussed at the very beginning of the paper	60 GHz	NR-U and WiGig	Average capacity, spectral efficiency, and energy efficiency	Transmission time, horizontal and vertical reuse factors	Indoor	NR standalone, NR-U standalone, and NR-U anchored	Blank subframes	Both intrabuilding and interbuilding levels

Besides, because of the regulatory restrictions on the transmission power in the unlicensed bands, like LTE Unlicensed [7], 5G NR-U is expected to be operated in the small cells deployed in the indoor coverage. Hence, as an extension of the LTE on Unlicensed bands or Licensed Assisted Access (LAA), 5G NR-U will aggregate the candidate 28 GHz or 38 GHz 5G licensed mmW spectrum and the 60 GHz unlicensed mmW spectrum [17]. Therefore, NR is considered deploying in several scenarios such as NR standalone, NR-U standalone, and NR-U anchored. Furthermore, due to high floor and wall penetration losses in the 60 GHz band, the same unlicensed spectrum can be reused more than once in small cells within a building, as well as adjacent buildings to serve the high data rate and capacity demands of indoor users.

However, research and investigation studies on the 5G NR-U operating in both the licensed and unlicensed mmW spectra for in-building small cells using non-LBT based coexistence mechanisms are in the early stage. Moreover, like [18], detailed mathematical modeling and analysis of major performance metrics, including average capacity, spectral efficiency (SE), and energy efficiency (EE), for 5G NR-U, are yet to be addressed, which we aim to contribute in this paper.

1.4. Contribution. Unlike existing studies, in this paper, following a brief overview of operating cellular technologies in the unlicensed bands, we propose a fully blank subframe- (FBS-) based coexistence mechanism and derive optimal air time allocations to cellular/IEEE 802.11 nodes in terms of blank subframes for 5G NR-U operating in both the licensed and unlicensed mmW spectra for in-building small cells. We model and analyze major performance metrics, including average capacity, SE, EE, and spatial spectrum reuse of the same spectra more than once within each building, as well as between adjacent buildings, of small cells. Moreover, modeling and analyses are carried out for 5G NR-U under different deployment scenarios, including NR standalone, NR-U standalone, and NR-U anchored. The performance of the proposed mechanism is then justified against fulfilling the expected SE and EE requirements for the Sixth-Generation (6G) mobile networks. More specifically, we contribute the following in this paper:

(i) We first give a brief overview, highlighting issues, challenges, and possible solution alternatives, for the coexistence of cellular and incumbent IEEE 802.11 technologies in the unlicensed bands

(ii) We then present an FBS-based coexistence mechanism and develop an interference avoidance scheme in time domain by modifying the concept of ABS for the LTE system to avoid cochannel interference (CCI) between in-building small cells of the 5G NR-U operator and the incumbent WiGig operator in the 60 GHz unlicensed mmW spectrum

(iii) We model traffic activity of in-building small cells and derive optimal number of FBSs, average capacity, SE, and EE responses of in-building 5G NR-U small cells coexisting with the IEEE 802.11ad/ay (i.e., WiGig) and operating in the 28 GHz licensed and 60 GHz unlicensed mmW bands

(iv) We carry out a system-level performance analysis for a number of variants of 5G NR-U, including 5G NR standalone that operates only in the 28 GHz licensed mmW spectrum, 5G NR-U standalone that operates only in the 60 GHz unlicensed mmW spectrum, and 5G NR-U anchored that operates in both the 28 GHz licensed mmW spectrum and the 60 GHz unlicensed mmW spectra

(v) We then analyze the impact of reusing unlicensed spectrum spatially within each building, as well as varying the number of 5G NR-U operators

(vi) Finally, we compare the SE and EE performances of the proposed coexistence scheme against the expected SE and EE requirements for the future 6G mobile networks

To demonstrate the position of this paper in comparison with the existing works, Table 1 shows a comparison in the scope of a number of the existing works discussed in Section 1.2 with respect to this paper.

1.5. Organization. We organize the paper as follows. A brief overview, including key issues, challenges, and possible solutions, for the coexistence of a cellular network with an incumbent WiFi network in the unlicensed bands is given in Section 2. In Section 3, system architecture, coexistence mechanism, and CCI interference management are discussed. In Section 4, we model traffic activity of in-building small cells and derive average capacity, SE, and EE metrics for the 5G NR-U anchored, as well as 5G NR-U standalone. In Section 5, we carry out extensive system-level numerical and simulation results and analyses for a single NR-U operator, as well as multiple NR-U operators, by varying both the vertical and horizontal spatial spectrum reuse factors and compare the SE and EE performances of the proposed coexistence scheme against the expected SE and EE requirements for the future 6G mobile networks. We conclude the paper in Section 6. A list of abbreviations and a list of selected notations are given, respectively, in Tables 2 and 3.

2. Coexistence of Cellular Networks in the Unlicensed Bands: An Overview

Cellular technology is an allocation-based mechanism that uses continuous transmission of data in consecutive frames using a centralized scheduler located mainly in the macrocell BSs. However, WiFi technology is a contention-based mechanism that uses opportunistic transmission using distributed coordination function (DCF). DCF is a contention-based mechanism [19] that uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol to detect the energy level to get access to a channel. In CSMA/CA [20], a WiFi AP senses the channel first to detect if any other WiFi AP is occupying the channel before sending its data to

Table 2: A list of acronyms/abbreviations.

Acronym/abbreviation	Definition
3GPP	3rd Generation Partnership Project
5G	Fifth-Generation
5G NR-U/WiFi	5G New Radio Unlicensed and WiFi
6G	Sixth-Generation
ABS	Almost blank subframe
AP	Access point
BS	Base station
CCA	Clear channel assessment
CCI	Cochannel interference
COT	Channel occupancy time
CSAT	Carrier Sense Adaptive Transmission
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DCF	Distributed coordination function
EE	Energy efficiency
eICIC	Enhanced Intercell Interference Coordination
FBS	Fully blank subframe
FPP	FBS pattern period
hRF	Horizontal reuse factor
LAA	Licensed assisted access
LBT	Listen Before Talk
LTE	Long-Term Evolution
LTE/WiFi	LTE and WiFi
LTE-U	LTE Unlicensed
MAC	Medium access control
MBS	Macrocell base station
mmW	Millimeter-wave
MNO	Mobile network operator
NR Std	NR standalone
NRA	National Regulatory Agency
NR-U	New Radio on Unlicensed Band
NR-U Anch	NR-U anchored
NR-U Std	NR-U standalone
PBS	Picocell base station
RB	Resource block
SBS	Small cell base station
SE	Spectral efficiency
TTI	Transmission time interval
UE	User equipment
vRF	Vertical reuse factor
WiAP	Wireless Gigabit Access Point
WiGig	Wireless Gigabit

avoid the collision with the existing occupant. If the WiFi AP finds that the channel is idle, it can start transmitting its data over the channel. Otherwise, it selects a random back-off timer so that it starts its transmission only when the timer decreases to zero [21]. Besides, the interference level of a cellular network is likely to be above the threshold used by a WiFi network to detect the vacancy of a channel.

Because of these disparities mentioned above in interference levels, as well as MAC layer procedures, of two systems (i.e., the absence of a contention-based mechanism like CSMA/CA to sense the channel status and the continuous transmission of data in a cellular network), if cellular and WiFi networks operate at the same frequency and location, WiFi APs may get blocked by a cellular network, leading the coexistence between them difficult to achieve. Since, due to employing CSMA/CA, a WiFi AP is used to back off its transmission when a channel is found busy, a cellular node as well should give up its transmission over the same channel to avoid any contention or collision with the WiFi AP. In other words, a cellular network needs to have a feature like CSMA/CA to avoid collision with a WiFi network to exist fairly with one another.

The 3GPP defines the fair coexistence between cellular networks such as LTE and WiFi (in the 5 GHz) as follows: *the capability of an LAA network not to impact WiFi networks active on a carrier more than an additional WiFi network operating on the same carrier, in terms of throughput and latency* [22, 23]. Likewise, for 5G NR-U, the coexistence requirement with WiGig remains the same as that in LAA such that the existence of an NR-U network cannot impact the performance of WiGig more than an additional WiGig network would do [24]. Hence, to ensure a fair coexistence of a 5G NR-U node with a WiGig AP in the unlicensed bands, an NR-U node needs to use a fair and efficient coexistence mechanism, called LBT [21]. Numerous research studies also showed that the LBT is critical for a fair coexistence between a cellular network and a WiFi network [25].

The LBT mechanism is fundamentally similar to the CSMA/CA mechanism; i.e., it does not allow a cellular node to always use a channel. Instead, it shares a channel between a cellular node and a WiFi AP on a fair basis [19]. In doing so, LBT enables a cellular node to periodically stop the occupancy of a channel and detect the activities of other shared nodes at a millisecond level. More specifically, to check the availability of a channel, a cellular node listens to the channel for a period called clear channel assessment (CCA) to detect the energy level. In this regard, an energy detection threshold is defined by the regional regulatory requirements to transmit over an unlicensed channel [26]. If the cellular node receives an energy level higher than the threshold level, the node considers that the channel is busy. However, if the energy level detected is below the threshold level, the cellular node can use the channel for a fixed time period, called channel occupancy time (COT). The idle period should be at least 5 percent of the COT [19], and the energy threshold level can be made adaptive, particularly in the downlink [21].

However, LBT is not required to be employed in all regions and all cellular standards. For example, in countries such as Europe and Japan, LBT features are mandatory for the 5 GHz and 60 GHz bands, whereas in other regions such as the United States and China, LBT is not required for early commercialization [9, 27]. Similarly, unlike LTE-U, which is deployed in regions requiring no LBT feature, LBT is

Table 3: A list of selected notations.

Notation	Description
O_{M} and O_{W}	Number of 5G NR-U operators and WiFi operators in a country
O and L	Total number of operators and total number of buildings per macrocell, respectively
T_o and T_{FPP}	An optimum value of the number of FBSs over T_{FPP} of any operator o and FBS pattern period, respectively
$p(s)$	Probability of s number of active in-building stations of an operator o on a floor fl in a building
$\lambda_{o,s}$	The expected value of the number of in-building user equipments (UEs) of any operator o on a floor fl within a building
$W_{\mathrm{AP},o}$	Number of WiAPs of WiGig operator o on each floor of any building
$S_{\mathrm{F},o}$ and $S_{\mathrm{F,total}}$	Number of small cell base stations of 5G NR-U operator o per floor and per building, respectively
Q and $\varepsilon_{\mathrm{RF}}$	Maximum simulation run time and vertical spectrum reuse factor per building, respectively
$M_{2,o}$, $M_{28,o}$, and $M_{60,o}$	Number of RBs of 2 GHz, 28 GHz, and 60 GHz spectra, respectively, of an operator o
$P_{2,\mathrm{M}}$, $P_{2,\mathrm{P}}$, P_{28}, and P_{60}	The transmission power of a macrocell, a picocell, transceiver 1 of each small cell, and transceiver 2 of each small cell, respectively
$\rho_{t,i,o}$ and $\sigma_{t,i,o}(\cdot)$	SINR and the corresponding link throughput at RB = i in TTI = t for an operator o in bps per Hz
$\sigma_o^{\text{NR-U Anch}}(\cdot)$, $\gamma_o^{\text{NR-U Anch}}(\cdot)$, and $\kappa_o^{\text{NR-U Anch}}(\cdot)$	System-level average capacity, SE, and EE, respectively, of operator o

employed to LTE-LAA standard formalized by 3GPP Release 13 to meet any regional regulatory requirement.

Since in regions where LBT is not mandatory, cellular networks such as LTE-U do not need to have sensing schemes like CSMA/CA in WiFi [21], WiFi may suffer from accessing the shared channel. Hence, to avoid this issue, a separate mechanism is required. In this regard, to address this issue of a cellular network enabled with no LBT feature, the existence of a cellular node with a WiFi AP can be made in the time domain by periodically turning on and off the transmission of the cellular node to allow the WiFi AP to transmit during the off periods. Note that because the exchange of messages for the crosscoordination between different systems is difficult due to the disparity in their protocol development processes described above and vendor differences [28], a noncollaborative coexistence mechanism is suitable for a cellular node and a WiFi AP.

Carrier Sense Adaptive Transmission (CSAT) [29] and FBS allocation are two representative techniques to provide time-domain coexistence [30, 31]. In CSAT, time is divided into cycles also called CSAT cycles where each cycle consists of on and off periods. Cellular nodes operate during the on period, whereas WiFi APs operate during the off period. Depending on the channel utilization of WiFi APs, the ratio of on to off periods is adjusted to secure fair coexistence. Frequent small gaps (also called punctured subframes) are provided with the on period so that WiFi AP can access these punctured subframes to transmit its delay-sensitive or critical control packets.

Likewise, the ABS-based eICIC technique is an effective procedure to allow the fair coexistence of a cellular node with a WiFi AP [32]. ABSs are low-power subframes that allow only the transmission of the control and reference signals of a cellular node. During ABSs, WiFi APs can detect the vacancy of a channel to transmit data by WiFi APs using the contention-based CSMA/CA protocol. Note that instead of ABSs, FBSs can be used in the unlicensed bands since there is no backward compatibility constraint with previous releases. This is because unlicensed bands are new and do not have to have backward compatibility issues to be maintained with previous generations so that at least control and reference signals are needed to be transmitted at low power during ABSs.

Hence, an FBS is an ABS without transmitting control and reference signals such that it is also termed as absolutely a silent subframe. Note that allocating more subframes to WiFi AP will eventually increase the throughput of the cellular node and vice versa. Moreover, the allocation of FBSs in a time frame can be periodic and aperiodic (or random) [28], and the fairness in resource allocation can be ensured by adopting the number of subframes allocated for WiFi APs in each radio frame [7]. Like CSAT, an FBS also provides divisions in air time to share by a cellular node and WiFi AP resulting in no transmission of cellular nodes is permitted so that WiFi APs can be allowed to transmit. Based on the local traffic of WiFi APs' traffic load, the number of FBSs can be set. Moreover, FBSs can offer more flexibility than CSAT as the number of subframes can be made adaptive dynamically at the frame level and the position of FBSs in a frame could be noncontiguous.

Hence, in short, the NR-U needs either LBT or FBS-based eICIC technique to protect WiGig from blocking by it. In this paper, we consider investigating the later scenario, i.e., NR-U operating in a region where LBT is not mandatory to employ a cellular node to coexist with a WiGig AP. More specifically, we consider noncollaborative coexistence to apply between NR-U and WiGig by using the FBS-based eICIC such that WiGig can detect and access the vacant channel during FBSs and transmits using its CSMA/CA protocol, which we present in what follows.

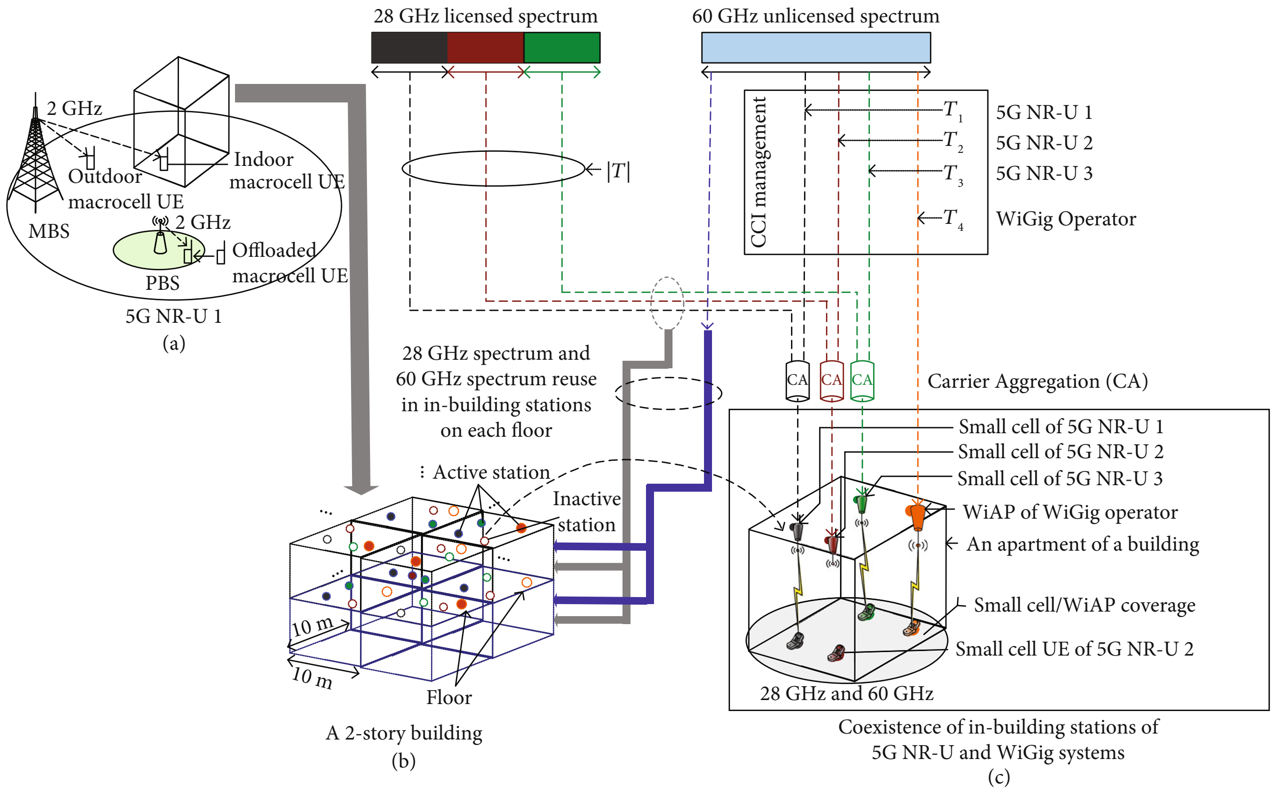


FIGURE 1: (a) The system architecture of 5G NR-U 1. (b) A 2-story building of small cells of all operators. (c) Coexistence three small cells of three 5G NR-U operators and a WiAP of one WiGig operator.

3. System Architecture, Coexistence Scheme, and Interference Management

3.1. System Architecture. Assume that an arbitrary number of O_M 5G NR-U operators and O_W WiGig operators are in service in a country. Each NR-U operator has three types of base stations (BSs), namely, macrocell BSs (MBSs), picocell BSs (PBSs), and small cell BSs (SBSs). We consider a similar architecture for each NR-U operator such that only one NR-U operator (e.g., NR-U operator 1) is detailed as shown in Figure 1(a). Macrocell user equipments (UEs) can be located indoors and offloaded by outdoor PBSs. Other than the offloaded macrocell UEs, macrocell UEs in the indoor, as well as outdoor, areas are served by an MBS. SBSs and WiGig stations are deployed indoors (i.e., only within multistory buildings), one per apartment per operator in a building (Figure 1(b)). Due to the small coverage and low transmission power of an SBS, as well as a WiGig station, we assume that an SBS or a WiGig station of any operator serves only one UE at a time.

As an extension of the LTE-U or LAA introduced in 3PPP Release-13 [17], we assume that each SBS of an NR-U is both licensed and unlicensed bands enabled using the carrier aggregation technologies, and each band uses a separate transceiver for operation (Figure 1(c)). Due to the favorable propagation characteristics and the availability of large spectrum bandwidths, we consider that each SBS operates in high-frequency bands, including the 28 GHz licensed mmW band using its transceiver 1 and the 60 GHz unlicensed band using its transceiver 2, to cover a small area at high capacity and high data rates indoors as shown in Figure 1(c). However, both MBSs and PBSs of any NR-U operator operate in the 2 GHz band to cover a large area outdoors.

Each 5G NR-U operator is allocated to an equal amount of the 28 GHz licensed spectrum such that no CCI can be generated from the licensed spectrum. However, due to an unlicensed band, all operators, including all 5G NR-U operators and WiFi operators, can access the 60 GHz spectrum simultaneously (Figure 1(c)), resulting in generating CCI among them. We present a time-domain-based interference avoidance scheme to avoid CCI generated from the 60 GHz unlicensed spectrum among all 5G NR-U operators and WiGig operators in the following section.

3.2. Proposed Coexistence Mechanism. We present a coexistence mechanism to operate 5G NR operators in the 60 GHz unlicensed spectrum with incumbent WiGig operators as follows: "A small cell of a 5G NR operator can share the unlicensed 60 GHz spectrum with a WiGig access point (WiAP) of an incumbent WiGig operator in a multistory building subject to avoiding CCI between them. Moreover, due to a high floor penetration loss in mmW bands, both the 60 GHz unlicensed spectrum and the dedicated 28 GHz licensed spectrum of each 5G NR-U operator can be reused to its small cells on each floor of a building."

In this regard, small cells of each 5G NR-U operator are allocated to a dedicated portion of the 28 GHz licensed

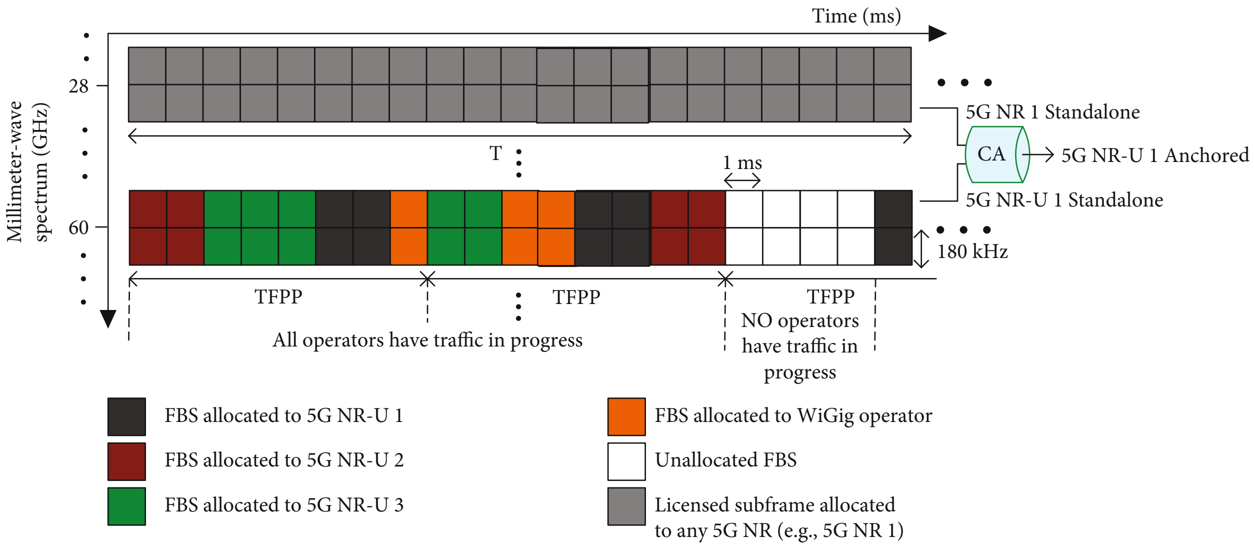


Figure 2: CCI interference avoidance mechanism to coexist 5G NR-U and WiGig operators. CA: carrier aggregation.

spectrum by the National Regulatory Agency (NRA) or any third party at the cost of licensing fee. However, due to an unlicensed band, small cells of a 5G NR-U operator can access the whole countrywide 60 GHz spectrum without paying any licensing fees. Further, to avoid CCI of small cells of any 5G NR-U operator in the unlicensed 60 GHz band with WiAPs of any incumbent WiGig operator, a time-domain CCI avoidance scheme following the concept of the ABS-based eICIC technique for the LTE system can be developed, which we describe in the following section. Furthermore, since the floor penetration loss of mmW signals is high enough [33] to cause insignificant or no CCI among small cells located on adjacent floors, both the 28 GHz licensed and the 60 GHz unlicensed spectra can be reused to small cells of any 5G NR-U operator on each floor of a building, resulting in improving the mmW spectrum utilization.

3.3. Interference Management. Since each 5G NR-U operator is allocated to a dedicated portion of the 28 GHz licensed spectrum, no CCI is originated among 5G NR-U operators. However, when operating in the 60 GHz unlicensed spectrum, CCI is originated among all operators, including 5G NR-U operators, as well as WiGig operators, due to accessing the same unlicensed spectrum by all operators. Such CCI in the unlicensed band can be avoided by allocating UEs of each operator orthogonally to the same 60 GHz unlicensed band in the time domain. In time-domain CCI avoidance, UEs of different operators are allocated at a different time such that no two operators can get access to the 60 GHz unlicensed spectrum simultaneously.

One approach to defining an optimal amount of time to transmit data by each operator, in terms of transmission time intervals (TTIs), is to consider the average number of UEs of each operator over a certain duration of time T. In this regard, typically, the average number of UEs of one operator differs from the other over T on any floor of a building. This causes the UEs of an operator to get deprived of scheduling sufficient radio resources to them as compared to UEs of other operators. Hence, to overcome the effect of such uneven distribution of UEs within in-building environments, we propose to employ the concept of the ABS-based eICIC technique by modifying ABSs to FBSs, which is defined as subframes with no control signaling, such that an operator o is allowed to access the unlicensed 60 GHz spectrum only during the number of FBSs allocated to it per FBS pattern period (FPP) T_{FPP} with respect to that of other operators as shown in Figure 2.

Let O_{M} and O_{W} denote, respectively, the number of 5G NR-U operators and WiFi operators in a country. Let $O = (O_{\mathrm{M}} + O_{\mathrm{W}})$ denote the total number of operators such that $o \in \mathbf{O} : \mathbf{O} = \{1, 2, \cdots, O\}$. We assume that the arrival process of UEs of each operator (both 5G NR-U and WiFi) follows the Poisson process with a mean $\{\lambda_1, \lambda_2, \cdots, \lambda_O\}$ over T. To allow the maximum fairness in the radio resource allocation among operators, we assume that an optimum value of the number of FBSs (i.e., TTIs) T_o over T_{FPP} of any operator o can be obtained in the percentage of T_{FPP} by taking the ratio of the average number of its UEs to the sum of the average number of UEs of all operators λ_{S} per floor of a building over T as follows:

$$T_o = \left\lceil \left(\frac{\lambda_o}{\lambda_{\mathrm{S}}} \right) T_{\mathrm{FPP}} \right\rceil, \tag{1}$$

$$T_o = \left\lceil \left(\frac{\lambda_o}{\sum_{o=1}^{O} \lambda_o} \right) T_{\mathrm{FPP}} \right\rceil. \tag{2}$$

Since the number of FBSs for any operator o over any T_{FPP} is strictly an integer, T_o is leveled to the nearest integer value in the above expression. Note that the value of T_o in (1) can be updated depending on the control signaling overhead and the backhaul delay constraints. More specifically, the expression of T_o in (1) is suitable for nonideal backhauls with high delay and low control signaling overhead requirements, i.e., when the value of T is large enough such that there exists a nonzero value of λ_o for each operator o. However, if T can be small enough (e.g., T is comparable to T_{FPP}) such as for ideal backhauls low delay and high control signaling overheads such that λ_o can be zero for any operator o, T_o can be expressed as follows, which is proved in Proof 1:

$$T_o = \left\lceil \left(\left(\frac{\lambda_o}{\sum_{o=1}^{O} \left(1_{v_o}(\lambda_o) \times \lambda_o \right)} \right) T_{\mathrm{FPP}} \right) \right\rceil. \tag{3}$$

Proof 1. Let the observation time $T = T_{\mathrm{FPP}}$ since the minimum value of T could be as low as T_{FPP}. Because a UE of small cells of any operator o over any T_{FPP} may not exist on a floor of a building l, λ_{S} can be expressed as follows:

$$\lambda_{\mathrm{S}} = \sum_{o=1}^{O} \left(1_{v_o}(\lambda_o) \times \lambda_o \right), \tag{4}$$

where $v_o \in \{\lambda_1, \lambda_2, \lambda_3, \cdots, \lambda_O\}$. $1(\cdot)$ defines that $1(\cdot) = 1$ if λ_o exists in the set v_o; otherwise, $1(\cdot) = 0$. Now, using (1), we can write the following:

$$T_o = \left\lceil \left(\left(\frac{\lambda_o}{\sum_{o=1}^{O} \left(1_{v_o}(\lambda_o) \times \lambda_o \right)} \right) T_{\mathrm{FPP}} \right) \right\rceil. \tag{5}$$

□ □

4. Problem Formulation

4.1. Modeling Traffic Activity of Small Cells. According to [18], sessions or call arrivals can be modeled as a Poisson process. Since given the present state, the future state is independent of the past state, the traffic activity of an in-building station (either an SBS or a WiAP) can be modeled as a two-state Markov chain such that the off-state to on-state transition rate of an in-building station is denoted by λ, whereas the on-state to off-state transition rate is denoted by μ. Let $p(0), p(1), p(2), \cdots, p(S_{\mathrm{F}})$ denote on-state probabilities of in-building stations of an operator o on any floor fl, corresponding to its number of active in-building stations $s \in \{0, 1, 2, \cdots, S_{\mathrm{F}}\}$. The values of these probabilities can be found following the birth-death process. Let $\lambda/\mu = \varepsilon$ such that the probability of s number of active in-building stations of an operator o on a floor fl in a building is given by [18]

$$p(s) = \frac{S_{\mathrm{F}}!}{s!(S_{\mathrm{F}} - s)!} \times \varepsilon^{s} \times \frac{1}{(1+\varepsilon)^{S_{\mathrm{F}}}}. \tag{6}$$

Since an in-building station can serve a maximum of one UE at a time, the number of stations is equal to the number of in-building UEs that can be served at once for any operator o. Hence, the expected value of the number of in-building UEs of any operator o on a floor fl within a building is given by

$$\lambda_{o,s} = E[s] = \sum_{s=0}^{s=S_{\mathrm{F}}} (s \times p(s)). \tag{7}$$

4.2. Mathematical Analysis. Assume that the maximum number of WiAPs $W_{\mathrm{AP},o}$ of each WiGig operator o and the number of SBSs $S_{\mathrm{F},o}$ of any 5G NR-U operator o are the same on each floor of any building, i.e., $\forall o S_{\mathrm{F},o} = W_{\mathrm{AP},o} = S_{\mathrm{F}}$. Let $S_{\mathrm{F,total}}$ denote the maximum number of small cells of any 5G NR-U operator o per building such that $S_{\mathrm{F,total}} = \varepsilon_{\mathrm{RF}} \times S_{\mathrm{F}}$, where $\varepsilon_{\mathrm{RF}}$ is the number of floors per building, defining the vertical spectrum reuse factor per building.

Assume that L denotes the number of buildings per macrocell coverage such that $l \in \{1, 2, \cdots, L\}$ of each 5G NR-U operator. Assume that there are S_{M} macrocells per 5G NR-U operator and S_{P} picocells per macrocell. Let $M_{2,o}$, $M_{28,o}$, and $M_{60,o}$ denote, respectively, the number of resource blocks (RBs) of 2 GHz microwave spectrum, 28 GHz licensed mmW spectrum, and 60 GHz unlicensed mmW spectrum of an operator o where an RB is equal to 180 kHz. Note that for all operators, $M_{60,o}$ is the same, i.e., $\forall o M_{60,o} = M_{60}$. Assume also that for all operators, transceiver 1 and transceiver 2 of each small cell operate at the transmission power of P_{28} and P_{60}, respectively, whereas the transmission powers of a macrocell and a picocell are denoted as $P_{2,\mathrm{M}}$ and $P_{2,\mathrm{P}}$, respectively.

Let $\mathbf{T}$ denote simulation run time with the maximum time of Q (in time step each lasting 1 ms) such that $\mathbf{T} = \{1,2,3, \cdots, Q\}$, and hence, $|\mathbf{T}| = Q$. Let $\mathbf{T}_o$ denote the number of FBSs of operator o over $\boldsymbol{T}$. Let t_o denote an FBS of operator o such that $t_o \in \mathbf{T}_o$. Using Shannon's capacity formula, a link throughput at RB = i in TTI = t for an operator o in bps per Hz is given by [34–37]

$$\sigma_{t,i,o}\left(\rho_{t,i,o}\right) = \left\{ \begin{array}{cc} 0, & \rho_{t,i,o} < -10\,\mathrm{dB} \\ \beta \log_2\left(1 + 10^{\left(\rho_{t,i,o}(\mathrm{dB})/10\right)}\right), & -10\mathrm{dB} \leq \rho_{t,i,o} \leq 22\,\mathrm{dB} \\ 4.4, & \rho_{t,i,o} > 22\,\mathrm{dB} \end{array} \right\}, \tag{8}$$

where β denotes the implementation loss factor. Like 4G LTE, β takes into account the modulation and coding schemes and the Hybrid Automatic Repeat Request mechanisms available in 5G NR [9, 36–39].

The total capacity of all macro UEs serving at the 2 GHz microwave spectrum of any operator o can be expressed as

$$\sigma_{2,o} = \sum_{t=1}^{Q} \sum_{i=1}^{M_{2,o}} \sigma_{t,i,o}\left(\rho_{t,i,o}\right), \tag{9}$$

where σ and ρ are responses over $M_{2,o}$ RBs of all macro UEs in $t \in \mathbf{T}$ for an operator o.

Recall that transceiver 1 of an SBS of each operator o operates at the 28 GHz licensed spectrum such that the capacity served by transceiver 1 of an SBS of an operator o is given by

$$\sigma_{28,o,s}^{\mathrm{Tr1}} = \sum_{t \in \mathbf{T}} \sum_{i=1}^{M_{28,o}} \sigma_{t,i,o}\left(\rho_{t,i,o}\right). \tag{10}$$

Note that the same 28 GHz spectrum is reused to small cells per floor. If all SBSs in each multistory building serve simultaneously in $t \in \mathbf{T}$, then, the aggregate capacity served by transceiver 1 of all SBSs per floor, as well as per building, of operator o is given, respectively, by

$$\begin{aligned} \sigma_{28,o,fl}^{\mathrm{Tr1}} &= \sum_{s=1}^{S_{\mathrm{F}}} \sigma_{28,o,s}^{\mathrm{Tr1}}, \\ \sigma_{28,o,l}^{\mathrm{Tr1}} &= \varepsilon_{\mathrm{RF}} \times \sigma_{28,o,fl}^{\mathrm{Tr1}}. \end{aligned} \tag{11}$$

Now, transceiver 2 of all SBSs of operator o per building operates at the 60 GHz spectrum in $t_o \in \mathbf{T}_o$ such that the capacity served by transceiver 2 of an SBS of an operator o is given by

$$\sigma_{60,o,s}^{\mathrm{Tr2}} = \sum_{t_o \in \mathbf{T}_o} \sum_{i=1}^{M_{60}} \sigma_{t,i,o}\left(\rho_{t,i,o}\right). \tag{12}$$

If all SBSs of operator o in each multistory building serve simultaneously in $t_o \in \mathbf{T}_o$, the aggregate capacity served by transceiver 2 of all SBSs per floor, as well as per building, is given, respectively, by

$$\begin{aligned} \sigma_{60,o,fl}^{\mathrm{Tr2}} &= \sum_{s=1}^{S_{\mathrm{F}}} \sigma_{60,o,s}^{\mathrm{Tr2}}, \\ \sigma_{60,o,l}^{\mathrm{Tr2}} &= \varepsilon_{\mathrm{RF}} \times \sigma_{60,o,fl}^{\mathrm{Tr2}}. \end{aligned} \tag{13}$$

Then, the total aggregate capacity served by transceiver 1 and transceiver 2 of all dual-band SBSs per building of operator o is given by

$$\sigma_{\mathrm{MB},o,l} = \sigma_{28,o,l}^{\mathrm{Tr1}} + \sigma_{60,o,l}^{\mathrm{Tr2}}, \tag{14}$$

$$\sigma_{\mathrm{MB},o,l} = \varepsilon_{\mathrm{RF}} \times \left(\sigma_{28,o,fl}^{\mathrm{Tr1}} + \sigma_{60,o,fl}^{\mathrm{Tr2}}\right). \tag{15}$$

4.2.1. 5G NR-U Anchored.

Due to a short distance between a small cell UE and its SBS and a low transmission power of an SBS, we assume similar indoor signal propagation characteristics for both mmWs for all L buildings per macrocell of an operator o. Then, by linear approximation, the system-level average aggregate capacity of operator o for $l > 1$ is given by

$$\sigma_o^{\text{NR-U Anch}}(L) = \sigma_{2,o} + \left(L \times \sigma_{\mathrm{MB},o,l}\right), \tag{16}$$

$$\sigma_o^{\text{NR-U Anch}}(L) = \sigma_{2,o} + \left(L \times \varepsilon_{\mathrm{RF}} \times \left(\sigma_{28,o,fl}^{\mathrm{Tr1}} + \sigma_{60,o,fl}^{\mathrm{Tr2}}\right)\right). \tag{17}$$

The SE for L buildings is then given by

$$\gamma_o^{\text{NR-U Anch}}(L) = \frac{\sigma_o^{\text{NR-U Anch}}(L)}{\left(\left(M_{2,o} + M_{28,o}\right) \times Q\right)}. \tag{18}$$

Similarly, the EE for L buildings is given by

$$\kappa_o^{\text{NR-U Anch}}(L) = \frac{\left(\left(L \times S_{\mathrm{F}} \times \left(P_{28} + P_{60}\right)\right) + \left(S_{\mathrm{P}} \times P_{2,\mathrm{P}}\right) + \left(S_{\mathrm{M}} \times P_{2,\mathrm{M}}\right)\right)}{\left(\sigma_o^{\text{NR-U Anch}}(L)/Q\right)}. \tag{19}$$

It is to be noted that for the SE estimation, only the licensed spectra, i.e., 2 GHz and 28 GHz spectra, of each operator o are considered due to paying the licensing fee by the respective operator to use these bands. That is why 60 GHz unlicensed spectrum is not accounted for in the SE estimation because of free of charge to use this band. In other words, only the licensed spectra are considered as the effective spectra of any operator.

4.2.2. 5G NR Standalone and 5G NR-U Standalone.

5G NR standalone and 5G NR-U standalone operate only in the licensed and unlicensed bands, respectively. The system-level average capacity for NR standalone and NR-U standalone can be expressed, respectively, as follows:

$$\sigma_o^{\text{NR Std}}(L) = \sigma_{2,o} + \left(L \times \varepsilon_{\mathrm{RF}} \times \sigma_{28,o,fl}^{\mathrm{Tr1}}\right), \tag{20}$$

$$\sigma_o^{\text{NR-U Std}}(L) = \sigma_{2,o} + \left(L \times \varepsilon_{\mathrm{RF}} \times \sigma_{60,o,fl}^{\mathrm{Tr2}}\right). \tag{21}$$

Likewise, following (18) and (19), SE and EE can be expressed using (20) for NR standalone and (21) for NR-U standalone.

5. Performance Evaluation

5.1. Simulation Model

5.1.1. Default Simulation Parameter and Assumption.

Table 4 shows the simulation parameters and assumptions used to evaluate the performance of the proposed scheme. Performance results are generated by a simulator, which is built based on the mathematical analysis given in Section 4, as well as the assumptions, parameters, and models given in Table 4, using the computational tool MATLAB R2012b version running on a personal computer. Default simulation assumptions and parameters used for the performance evaluation are in line with the recommendations from the standardization bodies such as the 3GPP and International Telecommunication Union-Radiocommunication Sector (ITU-R). More specifically, the simulator is developed taking into account the following assumptions and parameters.

Following [40], omnidirectional biconical horn antennas for all small cells and their UEs with a gain of 5 dB are assumed. Moreover, the proportional fair scheduler to improve the fairness performance in the resource allocation and the full buffer model for the traffic demand in all time over a duration Q are considered for each NR-U operator.

Table 4: Simulation parameters and assumptions.

Parameters and assumptions			Value
Maximum number of operators		5G NR-U and WiGig	3 and 1
Carrier spectrum bandwidth per 5G NR-U operator		2 GHz non-LOS	10 MHz (for macrocells and picocells)
		28 GHz LOS	50 MHz (for small cells)
		60 GHz LOS	100 MHz (for small cells and WiGig access points)
For each 5G NR-U operator			
Cellular layout[2], intersite distance (ISD)[1,2], transmission direction			Hexagonal grid, dense urban, 3 sectors per macrocell site, 1732 m, downlink
Number of cells		Macrocells, picocells, and small cells per building	1, 2, and 48
Total BS transmit power (dBm)		Macrocell[1] and picocell[1,4]	46 and 37
		Small cell operating in 28 GHz[1,3,4,6]	19
		Small cell operating in 60 GHz[1,3,4,6]	17.3
Cochannel small-scale fading model[1,5,6]		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	$PL(\text{dB}) = 15.3 + 37.6\log_{10}R$, R is in m
		Indoor macrocell UE	$\text{PL}\,(\text{dB}) = 15.3 + 37.6\log_{10}R + L_{\text{ow}}$, R is in m and $L_{\text{ow}} = 20\,\text{dB}$
	PBS and a UE[1]		$\text{PL}\,(\text{dB}) = 140.7 + 36.7\log_{10}R$, R is in km
	SBS and a UE[1,2,3,5]	28 GHz	$\text{PL}\,(\text{dB}) = 61.38 + 17.97\log_{10}R$, R is in m
		60 GHz	$\text{PL}\,(\text{dB}) = 68 + 21.7\log_{10}(R)$, R in m
Lognormal shadowing standard deviation (dB)		MBS[2] and PBS[1]	8 and 10
		SBS in 28 GHz and 60 GHz[2,3,5]	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 omnidirectional Biconical horn SBS[1,3]
Antenna gain plus connector loss (dBi)			MBS[2], PBS[1], and SBS[1,3,6] 14, 5, and 5
UE antenna gain[2,3,6]		2 GHz, 28 GHz, and 60 GHz (biconical horn)	0 dBi, 5 dBi, and 5 dBi
UE noise figure[2,6], 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, number of floors per building	L, 6
		Number of apartments per floor, number of SBSs per apartment	8, 1
		Area of an apartment	$10 \times 10\,\text{m}^2$
Scheduler, traffic model[2], and type of SBSs			Proportional fair, full buffer, and closed subscriber group femtocell BSs
TTI[1], FPP, PF scheduler time constant (t_c), and total simulation run time			1 ms, 8 ms, 100 ms, and 8 ms

Taken [1]from [37], [2]from [43], [3]from [40], [4]from [44], from [5] [45], and from [6] [46].

Because of the favorable signal propagation, coverage, and hand-off characteristics, we consider the 2 GHz band outdoors, whereas both the 28 GHz and 60 GHz bands indoors. Even though the available bandwidth in the 28 GHz band can be large enough, e.g., 400 MHz [41] or more, for an operator in a country, we consider only 50 MHz per operator for simplicity to evaluate the performance. Likewise, the number of operators in a country can be more than three, and the simulator can be applied to any number of operators in a country.

Due to the less multipath fading effect of high-frequency signals in indoor environments, we consider the Line-Of-Sight (LOS) large-scale path loss model for the mmW signals within buildings. Similarly, because of a small coverage and less multipath fading effect of an indoor small cell operating in the mmW bands, we assume a similar mmW signal propagation characteristic within each adjacent building. Moreover, due to the high external wall and floor penetration losses of a building, low transmission power of a small cell, and high attenuation experienced by high-frequency signals, both the 28 GHz and 60 GHz spectrum bands can be reused in small cells within the same building, as well as adjacent buildings. Since information is transmitted in every discrete TTI in mobile systems, we consider the discrete-event type simulation at TTI of 1 ms to execute simulation results. We limit evaluating the performance of only cellular networks (i.e., for 5G NR-U networks only) in the unlicensed bands for a number of evaluation scenarios. WiGig-related performance evaluations are out of the scope of this paper, and hence, no results and analyses for WiGig networks are presented.

5.1.2. The Operating Mechanism of the Simulator. In the following, we describe in brief how the simulator works. For each operator, the total number of macrocell UEs are first disjointed into three groups to estimate indoor, outdoor, and offloaded (to picocells) macrocell UEs randomly. The realization of macrocell UEs served by the macrocell and picocells is not mutually independent since macrocell UEs served by picocells are macrocell UEs offloaded from the macrocell, and the schedulers have complete knowledge when a macrocell UE is offloaded [42]. The number of small cell buildings and picocells is located randomly and uniformly in the macrocell area of each operator. The indoor macrocell UEs are distributed randomly and nonuniformly within each building. All outdoor macrocell UEs, offloaded macrocell UEs, and small cell UEs are distributed randomly and uniformly within their respective BSs' coverage area.

All macrocell UEs are then scheduled by a frequency-domain proportional fair scheduler at the MBS. Likewise, for each operator, a frequency-domain proportional fair scheduler for all small cells per floor per mmW band in a building schedules small cell UEs of the respective floor. The same process repeats for all RBs of each spectrum band per operator in each TTI and continues for all operators for all TTIs of the simulation run time. The aggregate throughput is then estimated for all macrocell UEs using (9), whereas for all small cell UEs per operator per building using (15). The aggregate throughput of small cell UEs for all buildings per operator is then estimated and summed with that of macrocell UEs using (17) for NR-U anchored. Likewise, the system-level average SE and EE are estimated using (18) and (19), respectively, for NR-U anchored. The same process repeats for all operators.

Now, following the same procedure, the average capacity for NR standalone and NR-U standalone for all operators can be estimated using (20) and (21), respectively. Similarly, following (18) and (19), SE and EE for NR standalone and NR-U standalone can be estimated. Note that we have explained the calculation of throughput in Section 4.2. Moreover, the shadow fading and small-scale fading of all UEs are estimated and updated in each TTI per realization.

5.2. Performance Evaluation Scenario. We consider three 5G NR-U operators and one WiGig operator. The following two scenarios are evaluated for 5G NR-U operators:

(i) A single 5G NR-U operator and a single WiGig operator

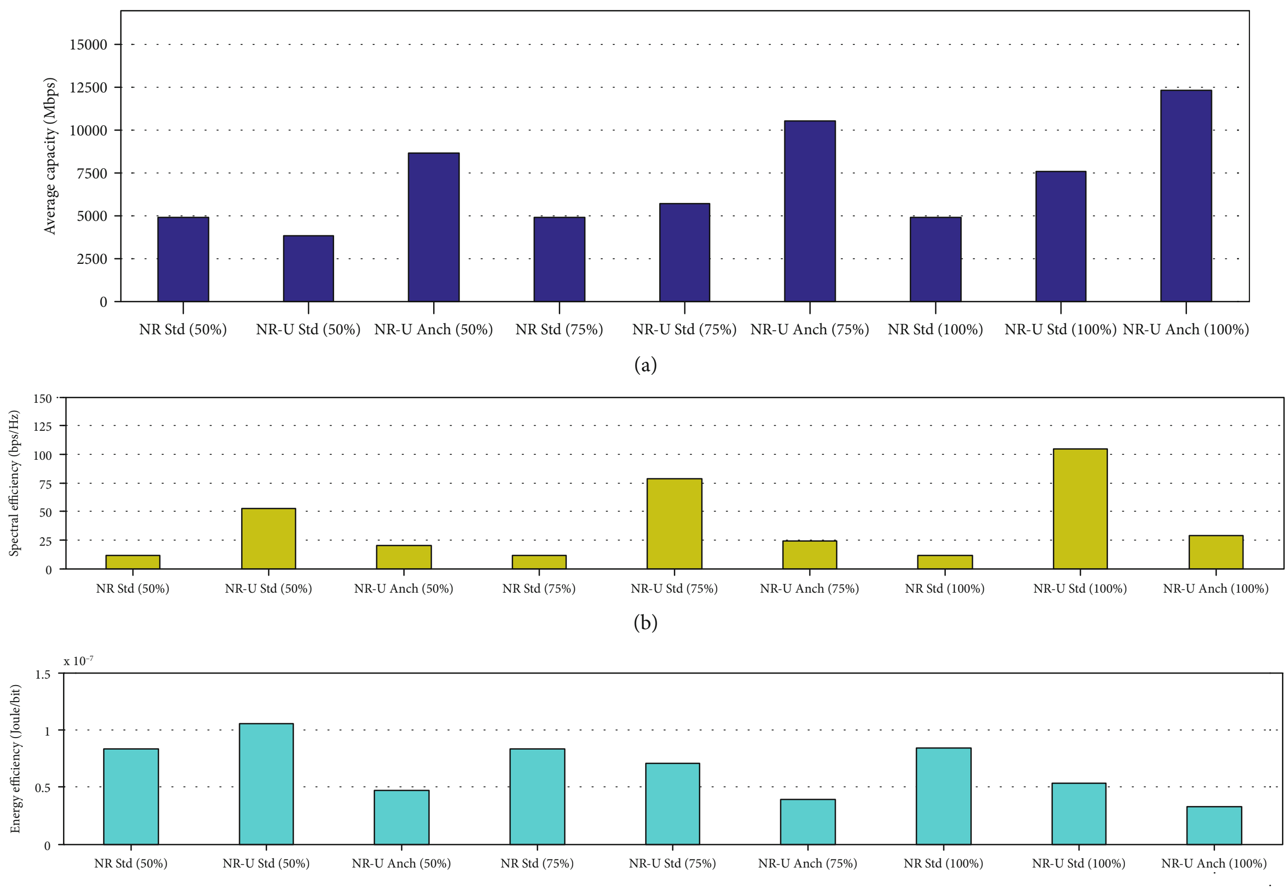
(ii) Multiple 5G NR-U operators and a single WiGig operator

In the former scenario, performance metrics are evaluated by varying the transmission time per FPP of a 5G NR-U operator for 50%, 75%, and 100% of FPP by changing its average number of small cell UEs on each floor of a building. For the latter scenario, three 5G NR-U operators (i.e., 5G NR-U operator 1, 5G NR-U operator 2, and 5G NR-U operator 3) are considered without changing the number of WiGig operators to evaluate the SE and EE performances of 5G NR-U operators for an arbitrary average number of small cell UEs of 1/8, 2/8, and 3/8 per FPP, respectively.

For the worst-case evaluation, we consider the maximum amount of interference that any NR-U node (i.e., small cell) or the AP of the WiGig operator (i.e., WiAP) may get experienced in the presence of others in each apartment of a building. Hence, theoretically, each 5G NR-U operator has the maximum number of one node, as well as the WiGig operator has the maximum number of one AP, in each apartment of a building. However, in practice, a node of any 5G NR-U operator and the AP of the WiGig operator may not be deployed in an apartment such that the distribution of the total number of nodes and APs per apartment of a building is random. Hence, the average interference experienced by a node or the AP is upper limited by the amount of interference it experienced in the worst-case scenario. Moreover, a node of any 5G NR-U operator, or the AP of the WiGig operator, could be deployed and run by either the corresponding operator or the customer without any explicit coordination between the 5G NR-U operator and the WiGig operator due to the disparity in the development of their MAC layers' protocols, mentioned earlier.

5.3. Performance Result and Analysis

5.3.1. Coexistence of a Single 5G NR-U Operator and a Single WiGig Operator. Figure 3 shows the average capacity, SE, and EE responses of small cells of a single operator of 5G NR standalone (Std), 5G NR-U Std, and 5G NR-U anchored (Anch) systems with the variation in its transmission time (i.e., the number of FBSs allocated to it) per FPP, including 50%, 75%, and 100% of FPP, of the respective operator of each system. The operator of each 5G NR system is considered coexisting with a single WiGig operator within a multistory building for the vertical reuse factor $(\mathrm{vRF}) = 1$ and horizontal RF $(\mathrm{hRF}) = 1$. Note that the SE of an operator is influenced by its effective licensed spectrum, as well as its achievable capacity. However, the achievable capacity is affected mainly by the transmission time over an FPP and the available licensed and unlicensed spectra of an operator. Like SE, EE is influenced by the capacity, as well as the transmission power of SBSs of an operator.



(a)

(b)

(c)

Figure 3: Average capacity, SE, and EE responses of small cells of a single operator of 5G NR standalone (Std), 5G NR-U Std, and 5G NR-U anchored (Anch) systems with the variation in its transmission time per FPP, including 50%, 75%, and 100% of FPP, which coexists with a single WiGig operator in a building for vRF = 1 and hRF = 1. (a) average capacity, (b) SE, and (c) EE.

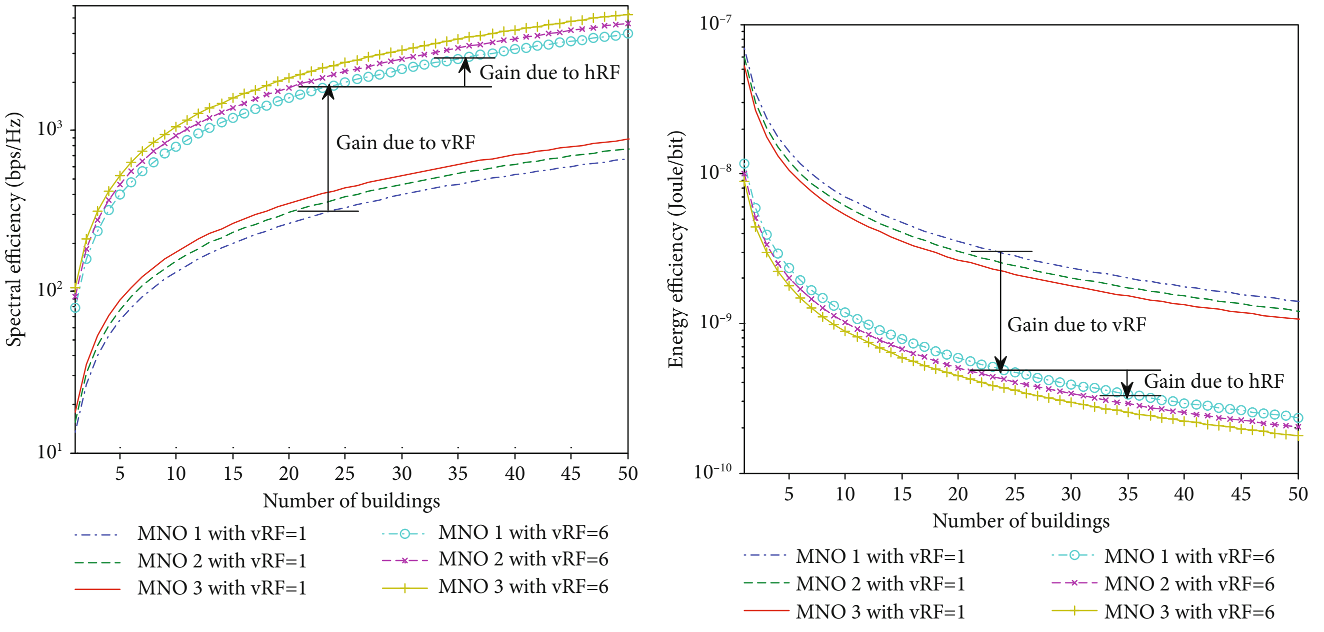
Since the 28 GHz licensed spectrum is allocated exclusively to an NR operator, no changes in capacity, SE, and EE due to the licensed band can occur with a change in the number of FBSs over an FPP. This can be observed for NR standalone since in-building small cells of the NR standalone operator operate only in the 28 GHz licensed spectrum. This causes NR standalone small cells to be independent of the transmission time, the available licensed spectrum, and the overall transmission power of all small cells. However, as small cells of the NR-U are allowed more time to transmit (e.g., increasing the transmission time from 50% FPP to 100% FPP) only in the 60 GHz unlicensed spectrum, the capacity, SE, and EE of the NR-U operator are increased.

Further, with an increase in the transmission time, the NR-U anchored operator provides the best responses in average capacity and EE. The average capacity of NR-U anchored operator is increased due to operating in both the 28 GHz licensed and the 60 GHz unlicensed spectra, as compared to only the 28 GHz for the NR standalone and the 60 GHz for the NR-U standalone operators. The increase in capacity is significant enough to exceed the corresponding increase in the transmission energy with a high margin due to increasing the transmission time from 50% FPP to 100% FPP such that the required average energy per bit transmission is the least.

Furthermore, though the SE of the NR-U anchored operator increases with an increase in the transmission time, the best SE response is achieved when small cells of the NR-U operator are operating only in the 60 GHz unlicensed spectrum due to requiring the least amount of the effective licensed spectrum by the NR-U operator. Overall, NR-U anchored provides the best capacity and EE responses, whereas NR-U standalone provides the best SE response. Since the unlicensed spectrum is common to both schemes, this implies the importance of operating the 5G NR in the unlicensed bands.

5.3.2. *Coexistence of Multiple 5G NR-U Operators and a Single WiGig Operator and the Impact of Spectrum Reuse Factors.*

Figure 4 shows SE and EE responses when multiple NR-U anchored operators coexist with a single WiGig operator for the vRF of 1 and 6 with the variation of the hRF from 1 to $L = 50$. vRF is obtained by reusing both the 28 GHz and 60 GHz mmW spectra of the NR-U anchored operator to its small cells located on each floor of a six-story building, for example, whereas hRF is obtained by



(a)

(b)

Figure 4: SE and EE responses of three 5G NR-U anchored operators when coexisting with a single WiGig operator by varying the transmission time of 12.5% FPP, 25% FPP, 37.5%FPP, and 25%FPP, respectively, per FPP for the vRF of 1 and 6 and the hRF of 1 to $L = 50$.

reusing these spectra to L number of six-story buildings over a macrocell coverage. From Figure 4, it can be observed that an NR-U anchored operator (i.e., NR-U operator 3) allocated to more FBSs per FPP can provide better SE and EE performances than others (i.e., NR-U operator 1 and NR-U operator 2). Also, due to allocating less number of FBSs per FPP to an NR-U anchored operator, SE and EE per NR-U operators decrease with an increase in the number of NR-Us. The above explanation is applicable for multiple WiGig operators coexisting with other NR-U schemes.

5.4. Performance Comparison. Assume that the future 6G systems would require 10 times average SE (i.e., 270-370 bps/Hz) and 10 to 100 times average EE (i.e., 0.3×10^{-6} to 0.03×10^{-6} Joules/bit) of 5G systems [47–50]. Considering 370 bps/Hz SE and 0.03 μJ/bit EE requirements for 6G, from Figure 3, it can be found that without reusing the mmW spectra spatially, it is difficult to satisfy these requirements for 6G with any 5G NR schemes. However, from Figure 4, it can be found that by choosing an appropriate value of vRF, as well as hRF, the expected SE and EE requirements for 6G mobile systems mentioned above can be satisfied. For example, considering the worst-case analysis, NR-U anchored (5G NR-U operator 1) with the minimum number of FBSs for the transmission per FPP can achieve both the expected SE and EE requirements for 6G for either vRF = 1 and hRF = 28 or vRF = 6 and hRF = 5.

6. Conclusion and Future Research Direction

The cost and scarcity of the available licensed spectrum are major concerns toward addressing the continuing demand for high capacity and data rate at a low cost per bit transmission in cellular networks. Due to the license-free access to unlicensed bands and wide spectrum availability in both unlicensed and licensed bands, the operation in mmW bands is considered as a potential solution to minimize spectrum scarcity and licensing cost for 5G NR and beyond mobile networks. In this regard, due to wider contiguous bandwidth availability, the 60 GHz unlicensed mmW band is considered an attractive candidate to operate 5G NR-U. However, the IEEE 802.11-based WiGig is in operation in the 60 GHz band. Hence, to operate in the 60 GHz unlicensed band, an appropriate mechanism is necessary for a 5G NR-U operator to *coexist* with an incumbent WiGig operator without causing interference to each other.

Accordingly, in this paper, we have given an overview, including issues, challenges, and possible solution alternatives, for the fair coexistence of cellular and incumbent WiFi networks in the unlicensed bands. We then have presented a coexistence mechanism for 5G NR-U small cells located within buildings to coexist with WiGig operators. Each small cell is dual-band enabled operating in the 60 GHz unlicensed and 28 GHz licensed mmW bands. Following several research studies that proposed to use the ABS-based eICIC technique in LTE to address the coexistence issue between WiFi and cellular operators in the unlicensed band, we have developed an interference avoidance scheme that considers FBSs by modifying the concept of ABS to avoid CCI between small cells of the 5G NR-U operator and the incumbent WiGig operator. We have then derived average capacity, SE, and EE responses of in-building 5G NR-U small cells. The system-level performance analysis has been carried out for a number of variants of 5G NR-U, including 5G NR standalone, 5G NR-U standalone, and 5G NR-U anchored. In addition, we have analyzed the impact of reusing mmW spectra by varying both the vertical and horizontal spatial spectrum reuse factors, as well as the coexistence of multiple 5G NR-U operators with a WiGig operator.

It has been shown that 5G NR-U anchored provides the best capacity and EE performances, whereas 5G NR-U standalone provides the best SE performances, which implies explicitly the importance of operating the 5G NR on unlicensed bands as the 60 GHz unlicensed spectrum is common to both schemes. For the coexistence of multiple 5G NR-U anchored operators, it has been found that any 5G NR-U allocated to more FBSs per FPP can provide better SE and EE performances than others. Moreover, due to allocating less number of FBSs to serve traffic per FPP to a 5G NR-U, the SE and EE per 5G NR-U decrease with an increase in the number of 5G NR-U operators. For the impact of spatial spectrum reuse factors, it has been shown that regardless of the number of 5G NR-U operators, an increase in either vertical reuse factor (vRF), or horizontal reuse factor (hRF), both SE and EE improve. Moreover, by choosing an appropriate value of vRF, as well as hRF, the expected SE and EE requirements for 6G mobile systems can be achieved.

In this paper, we limit evaluating the proposed coexistence mechanism to the performance of cellular technologies, i.e., NR-U under different deployment scenarios, in the presence of IEEE 802.11 technologies, i.e., WiGig, in the high-frequency 60 GHz mmW band. In our future studies, we will be interested in evaluating the performance of WiGig technologies as well to see the combined effect of the proposed mechanism on both technologies. Since the performance of the proposed mechanism depends on how we allocate blank subframes to cellular and IEEE 802.11 standards, other approaches than the one used in this paper (i.e., the average number of UEs per operator over a certain duration T) to define the optimal number of blank subframes to transmit data by each operator can be explored to improve the combined performance of all operators further.

Further, even though the impact of the assumption about serving multiple UEs simultaneously by each SBS/WiGig AP is insignificant over T in terms of the throughput performance, which may as well lead to the increased complexity in analysis and the difficulty in deriving closed-form expressions, it would be interesting to see the overall performance when investigating under such multiple UEs per SBS/WiGig AP scenario. Besides, though the blank subframe mechanism reduces delay in cellular users due to a small gap between transmissions, a short sensing period may lead to inaccurate channel sensing results. Hence, a tradeoff between interference detection accuracy and cellular user experience is another important research direction to carry out. Few other directions for extension may include investigating the proposed mechanism under other unlicensed spectrum bands, particularly, 6 GHz, beam-based transmissions, and distributed time resource allocations.

Data Availability

Data, primarily, in the form of numerous simulation assumptions and parameters reported previously by the standardization bodies, including 3rd Generation Partnership Project (3GPP) [42, 43] and International-Telecommunication Union-Radiocommunication Sector (ITU-R) [46], included and detailed within the article in Table 4, were used to carry out the performance evaluation of this study. Other prior studies than these above were cited as references [39, 44, 45] as well. No data other than these were used to evaluate the performance studies. Taking into account all these parameters and assumptions, performance results were generated by a simulator running on a personal computer, which was built by the author using the standard computational tool MATLAB R2012b. MATLAB codes are not publicly available. However, supports for writing MATLAB instruction codes can be provided over the emails querying directly to the author at rony107976@gmail.com.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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