On Operating 5G New Radio Indoor Small Cells in the 60 GHz Unlicensed Band

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***Abstract*—In this paper, we present a time-domain coexistence technique to operate small cells of a Fifth-Generation (5G) New Radio (NR) operator in the 60 GHz band with the access points (APs) of an IEEE 802.11ad/ay, also termed as Wireless Gigabit (WiGig), operator located within a multistory building. Small cells are dual-band enabled operating in the 60 GHz unlicensed and 28 GHz licensed bands. Moreover, we assume that small cells are not Listen-Before-Talk (LBT) feature enabled. Hence, to avoid blocking the transmission of APs of the WiGig operator, an interference avoidance scheme is developed in the time-domain that divides the air time in the 60 GHz band between the incumbent WiGig APs (WiAPs) and 5G NR Unlicensed (NR-U) small cells. We derive average capacity, Spectral Efficiency (SE), and Energy Efficiency (EE) metrics for 5G NR-U small cells. With system-level simulation results, the average capacity, SE, and EE responses for three variants of the 5G NR, namely 5G NR Standalone, 5G NR-U Standalone, and 5G NR-U Anchored are evaluated. It has been shown that NR-U Anchored can achieve the maximum average capacity and EE, whereas NR-U Standalone can achieve the maximum SE when coexisting with a WiGig operator. Because the 60 GHz unlicensed band is present in both schemes, this signifies the importance of operating a 5G NR operator in the unlicensed bands.**

Keywords—5G; 28 GHz; 60 GHz; millimeter-wave; unlicensed band; new radio; small cell; coexistence.

I. INTRODUCTION

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 of a Mobile Network Operator (MNO) [1]. An effective solution to address this problem is to serve data traffic in the unlicensed bands along with the existing licensed bands. The 3rd Generation Partnership Project (3GPP) has recently taken initiatives to operate cellular networks in the unlicensed bands with the Long-Term Evolution (LTE) [2]. However, technologies such as the IEEE 802.11 based WiFi have already been in operation globally over a wide range of unlicensed bands, including 2.4 GHz, 5 GHz, and 60 GHz bands [3]. This necessitates developing a technique that can allow both cellular networks and incumbent WiFi networks to coexist.

So far now, several research studies have addressed WiFi and cellular network coexistence such as LTE and 5G NR. For example, the authors in [4] addressed the coexistence of 5G NR Unlicensed (NR-U) and WiFi in the 6 GHz band, and in [5], the authors addressed the coexistence of WiFi with the beam based 5G NR-U in the millimeter-wave (mmW) bands. Moreover, in [1], by implementing a mode selection procedure in 5G NR, the authors investigated the coexistence performance of the 5G NR-U and WiFi networks. Moreover, to address the coexistence between WiFi and cellular systems, several studies proposed to apply the Almost Blank Subframe (ABS) based Enhanced Intercell Interference Coordination (eICIC) technique. For example, using the concept of ABS, the authors in [6] proposed a scheme to coexist LTE with WiFi systems in an unlicensed band. Similarly, the authors in [7] proposed the LTE muting mechanism to mute the transmission of LTE in *a* certain number of subframes of every 5 subframes during which the channel can be used by WiFi users. Furthermore, an ABS-based coexistence scheme to avoid co-channel interference between small cells and WiFi systems was presented by the authors in [8].

However, to operate in unlicensed bands, certain regulatory requirements, for example, using Listen-Before-Talk (LBT) and transmission power limits, are needed to be maintained [3]. Hence, to address the transmission power requirement in the unlicensed bands, 5G NR-U is expected to be operated in the small cells deployed indoors. In this regard, 60 GHz unlicensed band is considered an attractive unlicensed band for NR-U [5] [9] due to its wider contiguous bandwidth availability. This implies that NR-U will aggregate the licensed 28 GHz or 38 GHz spectrum and the 60 GHz unlicensed spectrum [9]. However, studies on the NR-U operating in both the licensed and unlicensed mmW spectra for in-building small cells are in the early stage, and detailed analysis and evaluation of major performance metrics, including capacity, Spectral Efficiency (SE), and Energy Efficiency (EE), for NR-U is yet to be addressed, which we aim to contribute in this paper.

In line with so, we derive and evaluate average capacity, SE, and EE responses of in-building 5G NR-U small cells that are considered coexisting with the IEEE 802.11ad/ay, also termed as Wireless Gigabit (WiGig), where each small cell operates in both the 28 GHz licensed and the 60 GHz unlicensed bands. In doing so, we present a time-domain coexistence technique to avoid co-channel interference by modifying the concept of ABS. A system-level performance analysis is carried out for a number of variants of 5G NR, including 5G NR Standalone operating only in the 28 GHz band, 5G NR-U Standalone operating only in the 60 GHz band, and 5G NR-U Anchored operating in both the 28 GHz and 60 GHz bands.

We organize the paper as follows. in Section II, system architecture and time-domain coexistence techniques are discussed. In Section III, we derive average capacity, SE, and EE metrics for each variant of 5G NR-U. In Section IV, we

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carry out system-level performance analysis in terms of average capacity, SE and EE by varying the amount of transmission time of small cells under each variant of 5G NR-U. We conclude the paper in Section V. A list of notations is given in Table I.

TABLE I. A LIST OF NOTATIONS.

Notation	Description
T_1 and T_2	The optimum value of the number of FBSs for NR-U and WiGig, respectively
λ_1 and λ_2	The average rate of arrival of NR-U and WiGig, respectively
T_{FPP}	An FBS Pattern Period
t and i	Index of a transmission time interval and a resource block, respectively
T	Simulation run time
σ_{MB}	Total capacity served by transceiver 1 and transceiver 2 of all SBSs in the building of operator NR-U
$\sigma_{\text{cap}}^{\text{NR-U,Anch}}$, $\sigma_{\text{SE}}^{\text{NR-U,Anch}}$, and $\sigma_{\text{EE}}^{\text{NR-U,Anch}}$	The system-level aggregate capacity, SE, and EE for NR-U Anchored, respectively
$\sigma_{\text{cap}}^{\text{NR,Std}}$ and $\sigma_{\text{cap}}^{\text{NR-U,Std}}$	The system-level average capacity for NR Standalone and NR-U Standalone, respectively
$P_{28\text{GHz}}$ and $P_{60\text{GHz}}$	The transmission power of transceiver 1 and transceiver 2, respectively, of each SBS
$P_{2\text{GHz,MC}}$ and $P_{2\text{GHz,PC}}$	The transmission powers of a macrocell and a picocell, respectively
$M_{2\text{GHz}}$, $M_{28\text{GHz}}$, and $M_{60\text{GHz}}$	The number of resource blocks of 2 GHz, 28 GHz, and 60 GHz spectra, respectively, of the NR-U operator
S_{F}	The number of SBSs of the NR-U operator
S_{M}	The number of macrocell base stations of the NR-U operator
S_{P}	The number of picocell base stations per macrocell of the NR-U operator

II. SYSTEM ARCHITECTURE AND TIME-DOMAIN COEXISTENCE

Figure 1 shows the system architecture consisting of a 5G NR-U operator and a WiGig operator. Each NR-U operator has three types of base stations (BSs), namely macrocell BSs (MBSs), picocell BSs (PBSs), and small cell BSs (SBSs). We assume that all SBSs and WiGig Access Points (APs) are deployed only within a building, one per apartment per operator. An SBS or a WiGig Access Point (WiAP) serves only one User Equipment (UE) at a time. Each SBS is dual-band enabled such that the 28 GHz licensed band operates at its transceiver 1, and the 60 GHz unlicensed band operates at its transceiver 2. Note that each WiAP operates at the 60 GHz band. Moreover, we assume that any MBS or any PBS of the NR-U operates in the 2 GHz band.

Since both SBSs and WiAPs operate in the 60 GHz unlicensed band, co-channel interference is generated. To coexist both SBSs and WiAPs in the 60 GHz unlicensed band, we present the following coexistence technique. An SBS can share the 60 GHz spectrum with an incumbent WiAP by allocating them in different time slots to avoid simultaneous access by either the SBS or the WiAP to the 60 GHz spectrum using the well-established concept termed as ABS in LTE. We consider modifying ABSs to avoid transmitting control signals as well during ABSs resulting in Fully Blank Subframes (FBSs) as shown in Figure 2.

An optimal amount of time to transmit data by NR-U operator in terms of Transmission Time Intervals (TTIs) can be defined by considering the average number of UEs of each operator over a certain time period T. According to [10], the arrival process of UEs of NR-U and WiGig operators can be assumed to follow the Poisson processes with a mean λ_1 and λ_2, respectively, over T. An optimum value of the number of FBSs (which is strictly a positive integer) over an FBS pattern period (FPP) T_{FPP} of 5G NR-U operator can be obtained as follows.

$$T_1 = \left\lceil \left(\lambda_1 / \left(\lambda_1 + \lambda_2\right)\right) T_{\text{FPP}} \right\rceil \tag{1}$$

Since UEs of different Radio Access Technologies (RATs) are allocated orthogonally in the time-domain, i.e., in different TTIs, no collision from simultaneous transmissions from UEs of both RATs occurs. Moreover, cellular technologies use a centralized scheduling-based approach to transmit continuously without sensing the channel status such that, based on the values of λ_1 and λ_2 over T, an effective allocation of FBSs using (1) can be performed for UEs of both NR-U and WiGig operators. Furthermore, (1) can be generalized for any arbitrary number of NR-U and WiGig operators, which we show in Appendix I. In general, an increase in the number of active operators, either NR-U or WiGig, causes a corresponding decrease in the number of subframes allocated to each operator for a given T_{FPP} and vice versa.

Remark 1: The value of T_{FPP} plays a significant role in the allocation of subframes to each operator. If T_{FPP} is less than the total number of NR-U and WiGig operators, there would be a high probability that one or more operators might not get scheduled over each T_{FPP}. This problem would get worsen if all operators are active over any T_{FPP}, particularly, for delay-sensitive traffic. Hence, to ensure that each active NR-U, as well as WiGig, operator is scheduled in every T_{FPP} to address the delay-sensitive traffic, it is recommended that the value of T_{FPP} should be chosen such that each active operator is scheduled at least once per T_{FPP}, i.e., T_{FPP} (in terms of TTIs) should be at least equal to the sum of the number of NR-U and WiGig operators. As a general rule, a higher value of T_{FPP} with respect to the total number of operators results in a better performance in subframe allocations to NR-U and WiGig operators.

III. PERFORMANCE METRICS ESTIMATION

Let S_{F} denote the maximum number of SBSs of the NR-U operator in the building. Assume that there are S_{M} macrocells and S_{P} picocells per macrocell. Let $M_{2\text{GHz}}$, $M_{28\text{GHz}}$, and $M_{60\text{GHz}}$ denote, respectively, the number of Resource Blocks (RBs) of 2 GHz, 28 GHz, and 60 GHz spectra of NR-U operator where an RB is equal to 180 kHz. Let transceiver 1 and transceiver 2 of each SBS operate at the transmission power of $P_{28\text{GHz}}$ and $P_{60\text{GHz}}$, respectively, whereas the transmission powers of a macrocell and a picocell are denoted as $P_{2\text{GHz,MC}}$ and $P_{2\text{GHz,PC}}$, respectively.

Let $\boldsymbol{T}$ denote simulation run time with the maximum time of Q (in time step each lasting 1 ms) such that $\boldsymbol{T}=\{1, 2, 3, \ldots, Q\}$ and hence $|\boldsymbol{T}| = Q$. Let $\boldsymbol{T_1}$ denote the number of FBSs of NR-U operator over $\boldsymbol{T}$. Let t_1 denote an FBS of NR-U operator such that $t_1 \in \boldsymbol{T_1}$. Using Shannon's capacity formula, a link throughput at RB=i in TTI=t for NR-U operator in bps per Hz for the Signal-to-Noise-Plus-Interference Ratio (SINR) $\rho_{t,i}$ is given by [11],

$$\sigma_{t,i}\left(\rho_{t,i}\right)=\begin{cases}0, & \rho_{t,i}<-10\,\text{dB}\\ \beta\log_2\left(1+10^{\left(\rho_{t,i}(\text{dB})/10\right)}\right), & -10\,\text{dB}\le\rho_{t,i}\le 22\,\text{dB}\\ 4.4, & \rho_{t,i}>22\,\text{dB}\end{cases} \quad (2)$$

where β=0.6 denotes the implementation loss factor that takes into account modulation and coding schemes, for example.

The capacity of macrocell UEs of NR-U operator can be expressed as

$$\sigma_{2\text{GHz}} = \sum_{t=1}^{Q}\sum_{i=1}^{M_{2\text{GHz}}} \sigma_{t,i}\left(\rho_{t,i}\right) \quad (3)$$

where σ and ρ are the throughput and the corresponding SINR responses over $M_{2\text{GHz}}$ RBs of all macro UEs in $t \in \boldsymbol{T}$ for NR-U operator.

Now, transceiver 1 of all SBSs in the building operates at the 28 GHz spectrum in $t \in \boldsymbol{T}$ such that the capacity served by transceiver 1 of all SBSs in the building is given by,

$$\sigma_{28\text{GHz}}^{\text{Trans 1}} = \sum_{s=1}^{S_F}\sum_{t\in\boldsymbol{T}}\sum_{i=1}^{M_{28\text{GHz}}} \sigma_{s,t,i}\left(\rho_{s,t,i}\right) \quad (4)$$

Similarly, transceiver 2 of all SBSs in the building operates at the 60 GHz spectrum in $t_1 \in \boldsymbol{T_1}$ such that the capacity served by transceiver 2 of all SBSs of NR-U is given by,

$$\sigma_{60\text{GHz}}^{\text{Trans 2}} = \sum_{s=1}^{S_F}\sum_{t_1\in\boldsymbol{T}_1}\sum_{i=1}^{M_{60\text{GHz}}} \sigma_{s,t,i}\left(\rho_{s,t,i}\right) \quad (5)$$

So, the total capacity served by transceiver 1 and transceiver 2 of all SBSs in the building of operator NR-U is given by,

$$\sigma_{\text{MB}} = \sigma_{28\text{GHz}}^{\text{Trans 1}} + \sigma_{60\text{GHz}}^{\text{Trans 2}} \quad (6)$$

Due to a short distance between a UE and its SBS and a low transmission power of an SBS, we assume similar indoor signal propagation characteristics for both mmWs of the NR-U operator. So, by linear approximation, the system-level average aggregate capacity for the 5G NR-U Anchored is given by,

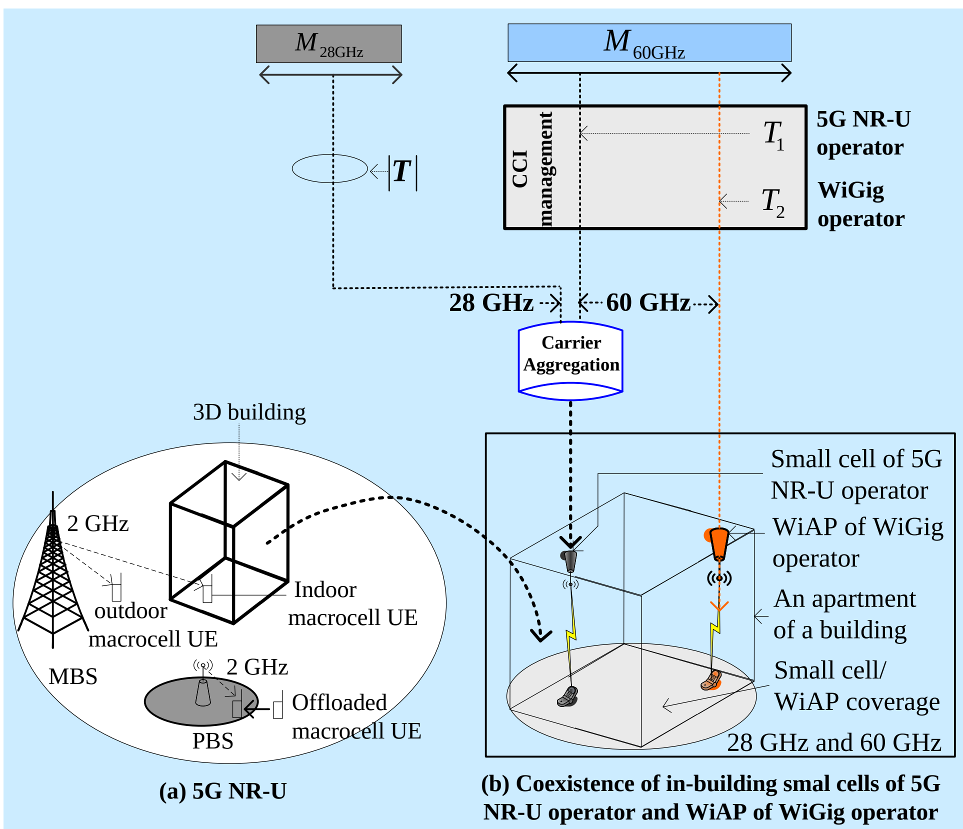

Figure 1. System architecture for the coexistence of small cells of a 5G NR-U operator with WiAPs of a WiGig operator.

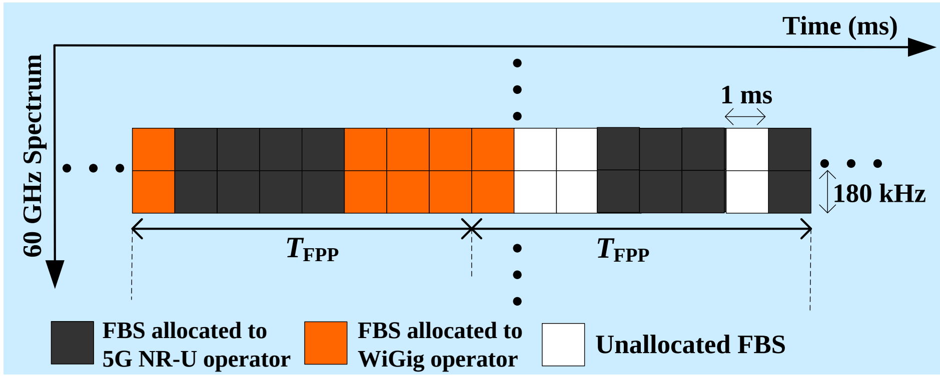

Figure 2. CCI avoidance in time-domain using FBSs.

$$\sigma_{\text{cap}}^{\text{NR-U,Anch}} = \sigma_{\text{2GHz}} + \sigma_{\text{MB}} \tag{7}$$

The SE is then given by,

$$\sigma_{\text{SE}}^{\text{NR-U,Anch}} = \sigma_{\text{cap}}^{\text{NR-U,Anch}} \Big/ \left(\left(M_{\text{2GHz}} + M_{\text{28GHz}}\right) \times Q\right) \tag{8}$$

Similarly, the EE (i.e., the energy required per bit transmission) is given by,

$$\sigma_{\text{EE}}^{\text{NR-U,Anch}} = \left(\begin{array}{l} \left(L \times S_{\text{F}} \times \left(P_{\text{28GHz}} + P_{\text{60GHz}}\right)\right) + \\ \left(S_{\text{P}} \times P_{\text{2GHz,PC}}\right) + \left(S_{\text{M}} \times P_{\text{2GHz,MC}}\right) \end{array} \right) \Big/ \left(\sigma_{\text{cap}}^{\text{NR-U,Anch}} / Q\right) \tag{9}$$

It is to be noted that for the SE estimation, only the licensed spectra, i.e., 2 GHz and 28 GHz spectra, of the NR-U operator are considered due to paying the licensing fee by the respective operator to use these bands. Now, 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.

$$\sigma_{\text{cap}}^{\text{NR,Std}} = \sigma_{\text{2GHz}} + \sigma_{\text{28GHz}}^{\text{Trans 1}} \tag{10}$$

$$\sigma_{\text{cap}}^{\text{NR-U,Std}} = \sigma_{\text{2GHz}} + \sigma_{\text{60GHz}}^{\text{Trans 2}} \tag{11}$$

Now, following (8) and (9), SE and EE can be expressed using (10) for NR Standalone and (11) for NR-U Standalone.

IV. Performance Result and Evaluation

Table II shows selected simulation parameters and assumptions. Detailed parameters and assumptions can be found in [12] [13]. Transmission time is varied to evaluate the performance of 5G NR-U small cells when applying the proposed technique as given below.

TABLE II. SIMULATION PARAMETERS AND ASSUMPTIONS

Parameters and Assumptions			**Value**
Number of 5G NR-U and WiGig operators, respectively			1, 1
Spectrum bandwidth of 5G NR-U operator		2 GHz	10 MHz (for an MBS and PBSs)
		28 GHz	50 MHz (for transceiver 1 of all SBSs)
		60 GHz	100 MHz (for transceiver 2 of all SBSs and WiAPs)
Number of cells	Macrocells, picocells, and small cells		1, 2, and 48
Path loss	MBS and a UE[1]	Outdoor macrocell UE	PL(dB)=15.3 + 37.6 $\log_{10}R$, R is in m
		Indoor macrocell UE	PL(dB)=15.3 + 37.6 $\log_{10}R$ + L_{ow}, R is in m and L_{ow}=20 dB
	PBS and a UE[1]		PL(dB)=140.7+36.7 $\log_{10}R$, R is in km
	SBS and a UE[1,2]	28 GHz	PL(dB)=61.38+17.97 $\log_{10}R$, R is in m
		60 GHz	PL(dB)=68+21.7$\log_{10}(R)$, R in m
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
3D multistory building and SBS models (square-grid apartments)			A single building, 6 floors, 8 apartments per floor, 1 SBS and 1 WiAP per apartment, and 10×10 m^2 area of an apartment
Scheduler, traffic model[2], Type of SBSs			Proportional Fair, full buffer, and 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 [12], [2]from [13].

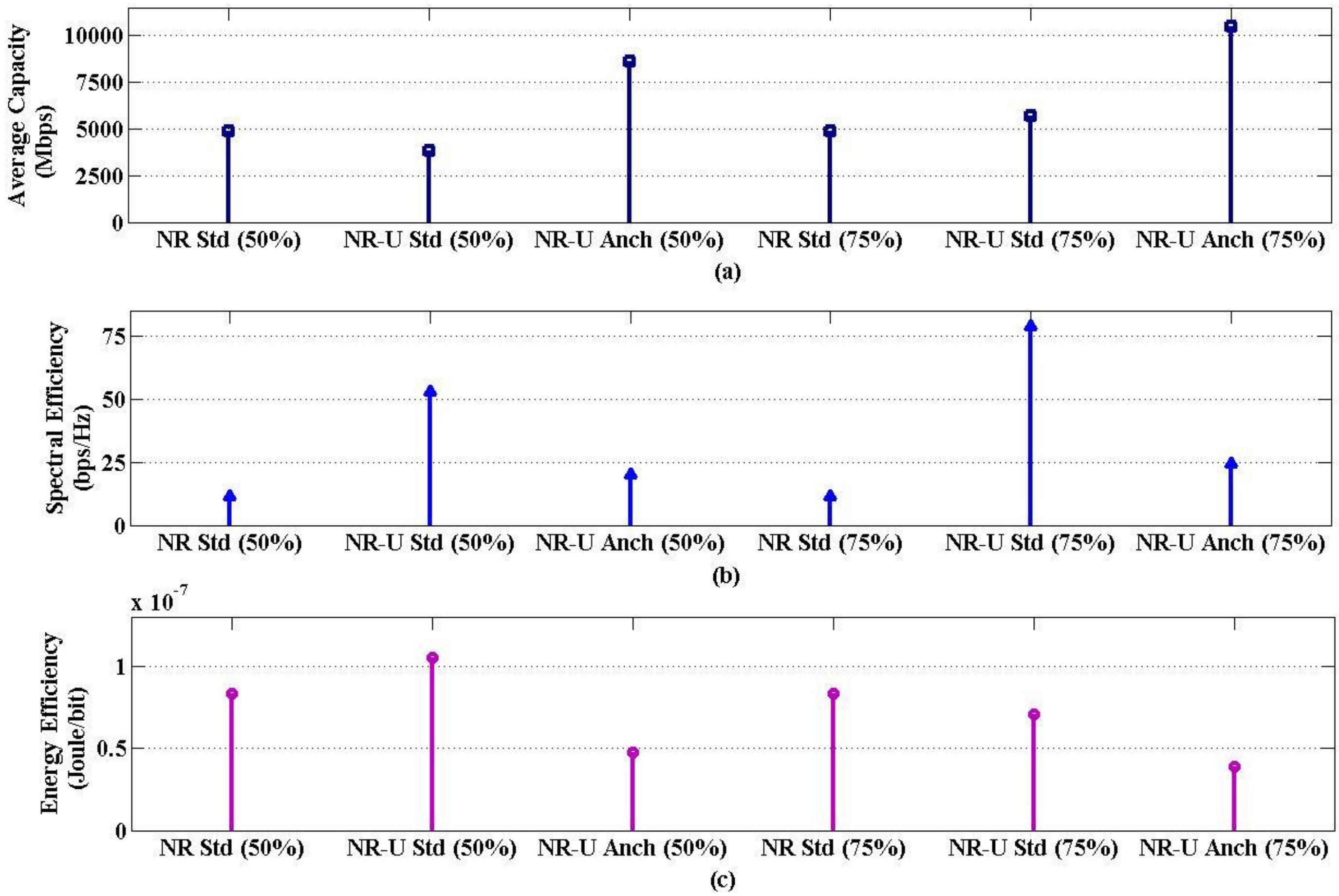

Figure 3. Average capacity, spectral efficiency and, energy efficiency responses of small cells of a single operator of 5G NR Standalone (Std), 5G NR-U Std, and 5G NR-U Anchored (Anch) with the variation of the number of FBSs (i.e., its transmission time) per FPP, including 50% and 75% of FPP, which coexists with a single WiGig operator in a building of small cells. (a) average capacity, (b) spectral efficiency, and (c) energy efficiency.

We vary the transmission time (i.e., the number of allocated FBSs) per FPP (including 50% and 75% of FPP) of small cells of a 5G NR operator coexisting with a single WiGig operator within a building. Figure 3 shows the average capacity, SE, and EE responses for three variants of the 5G NR operator, namely 5G NR Standalone, 5G NR-U Standalone, and 5G NR-U Anchored (Anch), which can be summarized as follows.

- Since 5G NR Standalone operates only in the 28 GHz licensed spectrum, which is allocated exclusively to it only, no changes in capacity, SE, and EE occur with a change in the number of FBSs over an FPP.
- Since 5G NR-U Standalone operates only in the 60 GHz unlicensed spectrum, which is shared as well by the WiGig operator, the capacity, SE, and EE responses increase with an increase in the transmission time from 50% FPP to 75% FPP due to having more time to transmit by the small cells.
- Since 5G NR-U Anchored operates both in the 28 GHz licensed spectrum, as well as in the 60 GHz unlicensed spectrum, with an increase in the transmission time, the average capacity response increases more than that of NR Standalone, as well as NR-U Standalone, operators due to operating in both the 28 GHz licensed and the 60 GHz unlicensed spectra. However, SE is a function of both achievable capacity and system bandwidth. Particularly, though SE is directly proportional to the achievable capacity, it is also inversely proportional to the effective licensed spectrum as given by (8). Due to this reason, SE for the 5G NR-U Anchored does not improve proportionately with its achievable capacity as the transmission time increases from 50% FPP to 75% FPP. Rather, 5G NR-U Standalone achieves the maximum SE due to requiring the least amount of the effective licensed spectrum. However, since EE is a function of transmission energy (Joule/bit), as well as achievable capacity (bits/s), the increase in the achievable capacity due to increasing the transmission time from 50% FPP to 75% FPP is significant enough to exceed the increase in the transmission energy for the NR-U Anchored as given by (9) in the same duration. This results in the minimum average energy required per bit transmission for the NR-U Anchored.

Overall, NR-U Anchored can achieve the maximum average capacity and EE, whereas NR-U Standalone can achieve the maximum SE when coexisting with a WiGig operator. Because in NR-U standalone, as well as NR-U Anchored, the 60 GHz unlicensed spectrum plays a role, this implies the importance of operating the 5G NR operator in the unlicensed bands.

V. CONCLUSION

In this paper, we have presented a time-domain coexistence technique for small cells of a 5G NR located within a building to coexist with a WiGig operator in the 60 GHz band. Each small cell has been considered dual-band enabled, operating in both the 60 GHz unlicensed and 28 GHz licensed bands. Because each small cell has not been considered Listen-Before-Talk (LBT) feature enabled, to avoid complete blockage of the transmission of WiGig Access Points (APs), an interference avoidance scheme has been proposed in the time-domain to divide the air time in the 60 GHz band between the incumbent WiGig APs (WiAPs) and small cells. We have derived average capacity, Spectral Efficiency (SE), and Energy Efficiency (EE) performance metrics for in-building small cells of the NR-U. With system-level simulation results, by varying the number of allocated FBSs per FPP the 5G NR operator, the average capacity, SE, and EE responses for three variants of the 5G NR, namely 5G NR Standalone, 5G NR-U Standalone, and 5G NR-U Anchored (Anch) have been evaluated. It has been shown that NR-U Anchored can achieve the maximum average capacity and EE, whereas NR-U Standalone can achieve the maximum SE when coexisting with a WiGig operator. Because the 60 GHz unlicensed band is present in both schemes, this signifies the importance of operating a 5G NR operator in the unlicensed bands.

APPENDIX I

Let X_1 and X_2 be the maximum number of NR-U operators and WiGig operators, respectively, such that $x_1 \in \{0,1,...,X_1\}$ with a corresponding average rate of arrivals $\lambda_{n,x_1} \in \{0,\lambda_{n,1},...,\lambda_{n,X_1}\}$, whereas $x_2 \in \{0,1,...,X_2\}$ corresponding to $\lambda_{w,x_2} \in \{0,\lambda_{w,1},...,\lambda_{w,X_2}\}$. Then, (1) can be expressed for NR-U operators as follows.

$$T_{n,x_1} = \left\lceil \left(\lambda_{n,x_1} \Big/ \left(\sum_{x_1=0}^{X_1} \lambda_{n,x_1} + \sum_{x_2=0}^{X_2} \lambda_{w,x_2} \right) \right) T_{\text{FPP}} \right\rceil$$

Similarly, for WiGig operators, (1) can be expressed as follows.

$$T_{w,x_2} = \left\lceil \left(\lambda_{w,x_2} \Big/ \left(\sum_{x_1=0}^{X_1} \lambda_{n,x_1} + \sum_{x_2=0}^{X_2} \lambda_{w,x_2} \right) \right) T_{\text{FPP}} \right\rceil$$

where $T_{\text{FPP}} = \left(\sum_{x_1=0}^{X_1} T_{n,x_1} + \sum_{x_2=0}^{X_2} T_{w,x_2} \right)$. ■

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