Handling Overflow Traffic in Millimeter Wave 5G NR Deployments using NR-U Technology

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***Abstract*—5G millimeter wave (mmWave) New Radio (NR) base stations (BS) are expected to be deployed in areas with extremely high and drastically fluctuating traffic demands resulting in frequent quality-of-service violations in terms of the provided rate at the access interface, especially, during busy hour conditions. As a cost-efficient countermeasure we consider NR unlicensed (NR-U) technology encompassing both NR and WiGiG at a single NR-U BS. To ultimate goal of this study is to determine the required density of these NR-U BSs in an area characterized by a certain density of NR and WiGiG users, where NR users may utilize WiGiG technology as long as their rate requirements are met. Joining the tools of stochastic geometry, queuing theory and Markov chains we characterize the sought metric of interest. We then report the dependency of eventual NR UE session loss probability that can be used to deduce the sought density of NR-U BSs as a function of system parameters. Among other conclusions, we reveal that the effect of the antenna array at NR part of NR-U BS is non-uniform and needs to be taken into account planning NR-U deployments.**

***Index Terms*—NR-U technology, New Radio, WiGiG, overflow traffic, QoS, queuing theory, Markov chains**

I. Introduction

5G New Radio (NR) technology, standardized as a part of 3GPP Rel. 15 and Rel. 16 efforts, promises drastic boost in the access rate at the last mile [1]. This is specifically the case for NR operating in millimeter wave (mmWave) frequency band, where a large set of resources has been made available worldwide [2]. Operating as a part of of heterogeneous 5G technology, NR is expected to become a decisive step towards meeting increased user demands at the access interface.

At the first phase of market penetration, mmWave NR base stations are expected to be deployed in places with extreme concentration of user traffic demands, e.g., shopping malls, concerts. In these conditions, one might expect extreme fluctuations in traffic demands, i.e., number of active session over time. Recalling that commercial NR technology is expected to provide a certain level of quality-of-service in terms of achieved rate at the access interface, these fluctuations may potentially result rate degradation beyond acceptable limit. To address this challenge a number of approaches have been suggested. Deploying higher density of NR BSs, is a plausible option but leads to higher operational expenditures and may potentially requite interference management techniques [3]. The use of moving BS such as those carried by unmanned aerial vehicles (UAV, [4], [5]) or cars [6] is another approach that received considerable attention in the recent literature. However, this option is not available indoor. Furthermore, the considered approaches operate at much longer timescale and thus are incapable of efficiently smoothing traffic variations that may happen at sub-minutes timescales.

In this study, we consider another approach providing a viable option for smoothing traffic variations that happen at sub-minutes scales. Particularly, we consider a joint implementation of NR and WiGiG technologies occupying spectrum at 60 GHz at a single BS. With both technologies operating in mmWave band these systems are characterized by inherently matched rates at the access interface and also are expected to be widely supported by modern and future UEs. Relying upon carrier aggregation technique standardized by 3GPP such kind of systems are expected to be a part of future 5G landscape. However, having distinctively different medium access control protocols with WiGiG utilizing random access procedure, rate guarantees may not always be provided at WiGiG interface posing natural question related to the required density of such NR-unlicensed (NR-U) BSs to support given densities of NR-U UEs and UE operating using WiGiG technology only.

In this paper, we investigate the joint service process of user traffic demands using NR-U BSs joining the NR and WiGiG technologies. By utilizing the tools of stochastic geometry, queuing theory and Markov chains as well as accounting for mmWave-specific propagation, resource allocations at NR and random access procedure at WiGiG, we develop a performance evaluation framework allowing to access the rate provided to NR-U and WiGiG UEs. This intermediate metric allows us to deduce the ultimate metric of interest – required density of NR-U BSs for a given density of NR-U and WiGiG UEs. We also perform comparison of the required NR-U BS density with that of NR only deployments reflecting economical effects of the proposed approach.

The rest of the paper is organized as follows. The system model is proposed in Section II. The mathematical framework for analysis of the considered approach is developed in Section III. Numerical results are elaborated in Section IV. Conclusions are drawn in the last section.

II. System model

In this section, we introduce the system model. First, we start with the joint operation of NR and WiGiG technology as a part of a single NR-U BS and then proceed specifying models required for analysis: propagation, blockage, traffic,

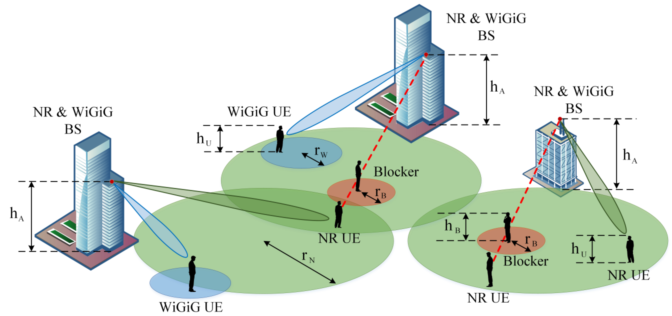

Fig. 1. Illustration of the considered NR-U deployment

resource allocation and random access models. The metrics of interest are finally introduced.

A. Deployment Model

We consider the system with the NR and WiGiG technologies physically co-located at the same NR-U BS. NR technology uses the licensed 28 GHz band using a channel of $B_N = 200$ MHz [7]. WiGiG technology is assumed to operate in 60 GHz band using one channels having the bandwidth of $B_W = 160$ MHz [8]. We assume that NR-U BSs are deployed according to Poisson point process (PPP) in $\Re^2$ with the density of λ_A BS per squared meter, see Fig. 1. The height of NR-U BS is set to h_A.

There are two types of UEs in the considered deployment, NR-U UEs and WiGiG UEs. The former is capable of operating in both NR and WiGiG bands. WiGiG UEs utilize WiGiG technology only. Both NR-U and WiGiG UEs follow PPP in $\Re^2$ with densities of $\lambda_{B,N}$ and $\lambda_{B,W}$ per squared meter, respectively. The heights of all UEs are h_U.

The joint implementation of NR and WiGiG is achieved by using 3GPP carrier aggregation technique [9]. No additional cooperation/signalling between NR and WiGiG technologies at the NR-U BS side is assumed as all the logic is implemented at NR-U UEs. The unlicensed band is used by the NR-U BS to serve NR-U UE sessions offloaded from NR part. Particularly, if UEs rate guarantees cannot be provided at NR part of NR-U BS, UE tries unlicensed WiGiG technology. If the achieved rate is insufficient, NR-U UE leaves the system.

B. Coexistence Mechanism

All UEs using unlicensed band employ LBT approach. To enhance the rate of NR sessions we assume that the NR-U technology utilizes the CoLBT mechanism based on contention window (CW) and back-off counter concepts (LBT based on channel observation, see Fig. 2) which is similar to that recommended by 3GPP for LAA technology [10]. Initially, the CW size is set to 32 slots. $M = \Gamma + T$ denotes the maximum number of retransmissions, where Γ is the maximum number of unsuccessful transmissions when CW is doubled while T is the number of additional retransmissions when CW remains constant.

A UEs that have a packet ready for transmission choose back-off timer uniformly in $(0, CW)$. The value of the back-off counter is decremented by one at each slot, where the channel is sensed to be free. If the channel is busy, UE pauses the back-off counter and continues to listen to the channel. When the value of the back-off timer reaches one the transmission opportunity (TxOp) starts and UE transmits its packet. There are three possible outcomes: (i) successful transmission, (ii) unsuccessful transmission due to collision with another NR-U or WiGiG UE transmission, and (iii) unsuccessful transmission due to LoS blockage.

The contention resolution procedure of both the NR-U BS and WiGiG APs is affected by directivity of utilized antenna arrays. That is, a collision may only occur when UEs located in the same WiGiG sector attempt to transmit at the same time. In fact, from the modeling point of view, this implies that the effective number of UEs is limited by the WiGiG antenna array directivity.

C. Propagation, Blockage and Antennas

1) Blockage Model: We consider blockage of propagation paths by pedestrians. Pedestrians are assumed to move in $\Re^2$ according to a random direction mobility (RDM) model [11] with the speed of v m/s and an exponentially distributed run length with the mean of τ meters. Pedestrians are modeled as cylinders having height h_B and radius r_B. In practice, h_B is the average height of humans, 1.7 m.

Define the blockage probability $p_b(r)$ as the probability that UE located at distance r from the NB-U BS is blocked. Then $1 - p_b(r)$ is the probability that at the distance r there is line-of-sight (LoS). Combining the results of [11], [12], the probability that an UE is blocked at time instant t is given by

$$p_b(r) = 1 - e^{-2\lambda_B r_B (r \frac{h_B - h_U}{h_A - h_U} + r_B)}, \quad (1)$$

where λ_B is the density of pedestrians.

2) Propagation Model: Since both considered technologies operate in mmWave band we employ similar propagation model. Using NR part of NR-U BS as an example, the signal-to-noise plus interference ratio (SINR) at the receiver located at the distance of y is

$$S(y) = \frac{P_{N,U} G_{N,A} G_{N,U}}{N_0 W L(y) M_I M_S}, \quad (2)$$

where $P_{N,U}$ is the UE transmit power, $G_{N,A}$ and $G_{N,U}$ are the antenna array gains at the NR and the UE ends, respectively, N_0 is the power spectral density of noise, W is the operating bandwidth, $L(y)$ is the linear path loss, M_I is the interference margin, and M_S is the shadow fading margin.

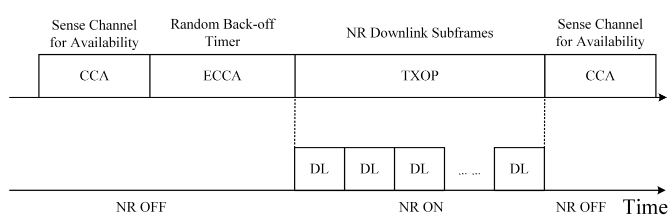

Fig. 2. The considered CoLBT mechanism for NR-U.

We capture interference from the adjacent NR-U BSs via an interference margin M_I in (2). For a given NR-U BS deployment density, one may estimate it by employing stochastic geometry based models [3], [13], [14]. Similarly, the effect of shadow fading is accounted for by using the shadow fading margins, $M_{S,B}$ and $M_{S,nB}$, for the LoS blocked and non-blocked states provided in [15].

Following [15], the path loss measured in dB is given by

$$L_{dB}(y) = \begin{cases} 32.4 + 21\log_{10} y + 20\log_{10} f_c, \text{ non-bl.}, \\ 47.4 + 21\log_{10} y + 20\log_{10} f_c, \text{ blocked}, \end{cases} \quad (3)$$

where f_c is the carrier frequency in GHz and y is the three-dimensional (3D) distance between the NR-U BS and the UE. The path loss in the form of (3) can be represented in the linear scale by utilizing the model in the form of $A_i y^{-\zeta_i}$, where A_i and ζ_i are the propagation coefficients. Introducing the coefficients (A_1, ζ_1) and (A_2, ζ_2) that correspond to LoS non-blocked and blocked conditions, we have

$$\begin{aligned} &A_1 = 10^{2\log_{10} f_c + 3.24} M_{S,nB} M_I,\ \zeta_1 = 2.1, \\ &A_2 = 10^{2\log_{10} f_c + 4.74} M_{S,B} M_I,\ \zeta_2 = 2.1. \end{aligned} \quad (4)$$

The value of SNR at the UE can then be written as

$$S(y) = \frac{P_{N,U} G_{N,A} G_{N,U}}{N_0 W} \left[\frac{y^{-\zeta}[1 - p_b(y)]}{A_1} + \frac{y^{-\zeta} p_b(y)}{A_2} \right], \quad (5)$$

where $p_b(y)$ is the blockage probability at the 3D distance y.

Introducing the coefficients

$$C_i = P_{N,U} G_{N,A} G_{N,U} / (N_0 W A_i),\ i = 1, 2, \quad (6)$$

the propagation model finally reads as

$$S(y) = C_1 y^{-\zeta}[1 - p_b(y)] + C_2 y^{-\zeta} p_b(y). \quad (7)$$

3) Antenna Model: Similarly to [3], we assume that the array radiation pattern is represented by a conical zone with an angle of α coinciding with the HPBW of the antenna array. Using [16], the HPBW of the antenna array, α, is proportional to the number of elements as $\alpha = 2|\theta_m - \theta_{3db}|$, where θ_{3db} is the angle at which the value of the radiated power is 3dB below the maximum and θ_m is the location of the array maximum. The latter is $\theta_m = \arccos(-\beta/\pi)$, where β is the array orientation, i.e., the azimuth angle representing the physical orientation of the array, i.e., $\theta_m = \pi/2$ for $\beta = 0$.

The mean antenna gain over the HPBW can be found as [16]

$$G = \frac{1}{\theta_{3db}^{+} - \theta_{3db}^{-}} \int_{\theta_{3db}^{-}}^{\theta_{3db}^{+}} \frac{\sin(N\pi\cos(\theta)/2)}{\sin(\pi\cos(\theta)/2)} d\theta, \quad (8)$$

where $\theta_{3db}^{\pm} = \arccos[-\beta \pm 2.782/(N\pi)]$, and N is the number of antenna elements.

D. Traffic, Associations and Resource Allocation

We assume that NR-U and WiGiG UEs generate elastic traffic demands. According to this model (also known as full buffer model in 3GPP) UEs always have data for transmission. However, NR-U UEs are associated with some minimum rate demands, $r_{\min}$ which is provided as a part of QoS agreement between network operator and users.

WiGiG UEs utilize only the unlicensed band. They are assumed to be associated based on reference signal receive power (RSRP). Recalling that the path loss model is a monotonously decreasing function of the distance, we consider that these UEs are associated with the nearest NR-U BS. The association procedure for NR-U UEs is different. By default they try to associate with the nearest NR-U BS and utilize NR technology. However, if the current rate provided to other NR-U UEs currently utilizing NR technology at this BS will fall below the required minimum rate, $r_{\min}$, session is rerouted at associated WiGiG technology. If the rate provided at WiGiG interface is not sufficient to meet minimum rate requirements, $r_{\min}$ NR-U session is dropped.

E. Metrics of Interest

The main metric of interest we target in our study is the required density of NR-U BSs to be deployed in the area to maintain a minimum rate of NR-U sessions $r_{\min}$ for given densities of NR-U and WiGiG UE densities, $\lambda_{B,D}$ and $\lambda_{B,W}$, respectively. In the following section, we assess this metric by deriving the intermediate metric of interest – eventual NR-U UE session loss probability, i.e., the probability that NR-U UE session offloaded to WiGiG part of NR-U BS is not provided with the minimum rate $r_{\min}$ and thus, lost.

III. Performance Evaluation Framework

In this section, we introduce our performance evaluation framework. First, we provide a brief outlook of the proposed combined approach. Then, we proceed with the core of the framework by successively defining the resource request, queuing, and random access models. Finally, the metrics of interest are estimated.

A. Framework at the Glance

The system at hand is rather complex requiring multi-stage approach for performance assessment. We logically divide the analysis into three stages: (i) resource request characterization, (ii) analysis of the overflow process from NR part to WiGiG part of NR-U BS, and (iii) analysis of random access procedure at WiGiG interface.

At the first stage we utilize the deployment model and apply the tools of stochastic geometry to characterize the mean amount of resources required by NR-U UE at NR radio interface. Equipped with this knowledge we then proceed applying the tools of queuing theory to characterize the intensity of NR-U UEs that cannot be supported at the NR interface and needs to be offloaded to WiGiG technology. At the final stage, having intensities of NR-U overflow process and of WiGiG UEs in the coverage area of WiGiG part of NR-U BS we estimate the rate provided to individual NR-U UE session. This rate is then further used to determine the required density of NR-U BSs in the area using numerical algorithm. Particularly, if this rate is smaller than a given $r_{\min}$ then NR-U UE sessions are lost and the density of NR-U BS in the area needs to be increased.

B. Resource Request Characterization

To parameterize the service process at NR part of NR-U BS we need the following parameters: (i) resources required by a single NR-U UE session, (ii) fraction of sessions that can be offloaded to WiGiG part of NR-U BS.

To determine the sought parameters we first need the effective coverage radii of NR and WiGiG parts of NR-U BS, r_N and r_W. Since both radii are obtained similarly, below we consider r_N. In the field of NR-U BSs the effective coverage radius, r_N, is determined by the interplay between the distance between NR-U BSs, $r_{N,V}$, and the maximum coverage of NR part of NR-U BSs, $r_{N,S}$. Thus, we have $r_N = \min(r_{N,S}, r_{N,V})$. Below, we obtain these components.

The radius $r_{N,S}$ is defined as the maximum separation distance between the NR-U UE and the NR-U BS, such that the NR-U UE in the LoS blocked conditions is not in outage conditions. According to our propagation model, the SNR at the maximum 2D distance $r_{N,S}$ is given by

$$S = C_2 \left(r_{N,S}^2 + (h_A - h_U)^2\right)^{-\frac{\zeta}{2}} = S_{th}, \qquad (9)$$

where S_{th} is the SNR corresponding to the lowest feasible NR modulation and coding scheme (MCS). Solving this equation for d_N, we obtain

$$r_{N,S} = \sqrt{(C_2/S_{th})^{\frac{2}{\zeta}} - (h_A - h_U)^2}. \qquad (10)$$

Note that $r_{N,S}$ depends on C_2 from (6), which, in its turn, depends on the sector angle α according to (8). Note that usually $r_{W,S} < r_{N,S}$ due to differences in carrier frequencies and allowed emitted power.

We approximate the radius $r_{N,V}$, characterizing the half distance between NR-U BS locations, by circle approximation of the Voronoi cell induced by NR-U BS locations in $\Re^2$. Since the actual area of Voronoi cell is not known [17] we utilize computer simulations to obtain $r_{N,V}$. The radius of WiGiG part of NR-U BS, r_W, is obtained similarly.

Once radii r_N and r_W are obtained, one may proceed characterizing the amount of resources requested by NR-U UE. Observe that due to differences in r_N and r_W and also in system parameters of NR and WiGiG technologies, these rates may vary even for the same NR-U UE. Recalling that NR-U UEs are assumed to follow PPP in $\Re^2$ for NR part of NR-U BS, the mean spectral efficiency can be obtained using Shannon's formula as follows

$$E[S_e] = \int_0^{r_N} \frac{2x}{r_N} \log_2(1 + S(x))dx, \qquad (11)$$

where $S(x)$ is defined in (7) and the probability density function (pdf) of the distance from NR-U BS to the NR UE is defined in [18]

Accounting for the rate of applications and available bandwidth at NR part of NR-U BS, B_N, one may now use the mean spectral efficiency to determine the mean amount of minimum resources requested by UE as $b_{\min} = r_{\min}/E[S_e]$, where $r_{\min}$ is the minimum rate requirement.

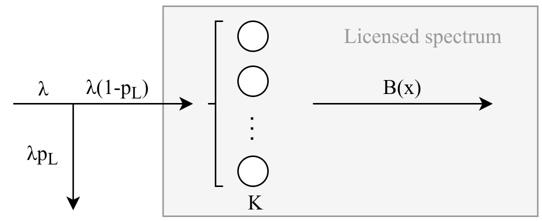

Fig. 3. Illustration of the employed queuing model.

Recall that the capacity of WiGiG part of NR-U BS and the associated amount of requested resources by NR-U UE is estimated similarly. Observe that that the NR-U UE offloaded from NR to WiGiG requests different amount of resources at the latter technology to maintain the minimum data rate $r_{\min}$.

C. Overflow Process Characterization

We model the service process of NR-U UE sessions at NR part of NR-U BS using the $M/G/K/K$ queuing system, see Fig. 3. Observe that for a given density of deployment of NR-U BSs, a certain arrival rate of NR-U UE sessions, $\lambda_{B,N}$, and the mean minimum resource requirements, $b_{\min}$, estimated in the previous section, we can determine the fraction of load that NR-U cannot handle in the licensed spectrum using NR part of NR-U BS. In fact, the overflow arrival rate to the unlicensed part of NR-U BS can be calculated as λp_L, where p_L is the session loss probability in $M/G/K/K$.

Denote by K the maximum number of NR-U UEs in the system, i.e., the average number of sessions that can be simultaneously served at the NR part of NR-U BS. For $M/G/K$ type of queuing systems, the stationary probabilities of having i active NR-U UE sessions in the system are [19],

$$p_i = \frac{\rho^i}{i!} p_0,\, p_0 = \left(\sum_{i=0}^{K} \frac{\rho_N^i}{i!} p_i\right)^{-1},\, i = 1, 2, \dots, n. \qquad (12)$$

The loss probability in $M/G/K$ system is known to be

$$p_L = \frac{\rho_N^K}{K!} \Big/ \sum_{i=0}^{K} \frac{\rho_N^i}{i!}. \qquad (13)$$

where the offered load $\rho_N = \rho_N = \lambda_{B,N} r_N^2 \pi / \mu_N$, and μ_N is the mean service time of NR-U UE sessions.

Note that there is inherent technological mismatch between NR and WiGiG. Particularly, simpler antenna arrays employed in WiGiG systems as well as higher carrier frequency often lead to $r_W < r_N$. Thus, only the following fraction of NR UEs lost at NR part of NR-U BS can compete for resources at WiGiG part of NR-U BS

$$\lambda_N^\star = p_L \lambda_{B,N} r_W^2 \pi / r_N^2 \pi, \qquad (14)$$

where $p_L \lambda_{B,N} r_N^2 \pi$ is the overflow intensity at NR part of NR-U BS. Note that $1 - \lambda_N^\star$ NR-U UE sessions are lost and these losses can only be minimized by increasing the density of NR-U BSs.

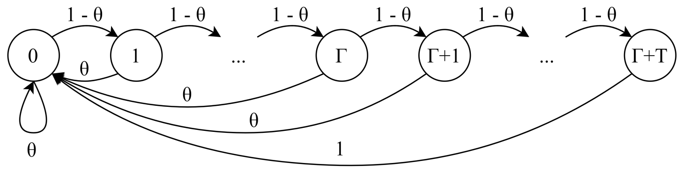

Fig. 4. State transition diagram of the Markov model.

D. Service Process in Unlicensed Spectrum

NR-U UE sessions offloaded to WiGiG part of NR-U BS compete for transmission resources with WiGiG UEs. In this section, we proceed to derive the successful transmission probability of both UE types that is used further to determine the rate obtained by NR UE at WiGiG part of NR-U BS.

Let p_c be the collision probability and p_b denote the probability that the LoS path is blocked. Then, the probability of successful transmission can be expressed as

$$\theta = (1 - p_c)(1 - p_b). \tag{15}$$

The behavior of system can be described by a Markov chain $\{X_n,\ n \geq 0\}$, where $X_n = i$ for $i = 1, ..., \Gamma + T$ denotes transmission attempt when back-off counter is in $\left[0, 2^i W - 1\right]$, and W is the minimum value of CW. Using the state transition diagram shown in Fig. 4, the system of equilibrium equations can be written as

$$\begin{cases} q_0(\theta + (1-\theta)) = q_0\theta + q_1\theta + \cdots + q_{\Gamma+T}1, \\ q_i(\theta + (1-\theta)) = q_{i-1}(1-\theta), i = 1, .., \Gamma + T - 1, \\ q_{\Gamma+T}(1) = q_{\Gamma+T-1}(1-\theta). \end{cases} \tag{16}$$

where q_i is the stationary probability

$$q_i = \lim_{n\to\infty} P\{X_n = i\},\ i = 0, 1,\ \ldots\ \Gamma + T. \tag{17}$$

Solving the system (16) we obtain

$$q_0 = \frac{1}{\sum_{j=0}^{\Gamma+T}(1-\theta)^i} = \frac{\theta}{1-(1-\theta)^{\Gamma+T+1}}. \tag{18}$$

Substituting the result for q_0 (18) into the system (16), we obtain the expression for calculating the stationary probability q_i in the following form

$$q_i = \frac{\theta}{1-(1-\theta)^{\Gamma+T+1}}(1-\theta)^i,\ i = 0, 1, .. \tag{19}$$

Since UEs transmit only in states $X_n = j$, the transmission probability π_N can be calculated as a fraction of slot time divided by the mean number of time slots UE spends in any state. Thus, to find the probability that UE performs the transmission attempt, we need to sum up the mean number of time slots b_j that UE spends in state j, multiplied by probability q_j that UE is in the state j, i.e.,

$$\pi_N = \left[\sum_{i=0}^{\Gamma+T} q_j b_j\right]^{-1}, \tag{20}$$

where the mean number of slots b_j in state j is

$$b_j = \sum_{i=1}^{2^j W} \frac{1}{2^j W} i = \frac{2^j W + 1}{2}, j = 0, 1, .., \Gamma + T. \tag{21}$$

Finally, substituting (19), (21) into (20), and using simple algebraic manipulations, the transmission probability π_N can be written in the following form

$$\pi_N = \left[\frac{\theta W\left(1 - 2^{\Gamma+T+1}(1-\theta)^{\Gamma+T+1}\right)}{2\left(1-(1-\theta)^{\Gamma+T+1}\right)(2\theta - 1)} + \frac{1}{2}\right]^{-1}. \tag{22}$$

Having obtained the probability of transmission π_W (22), we can determine the average successful transmission probability as a function of the number of NR and WiGiG UEs competing for transmission, respectively, i.e.,

$$\Pi_N = \sum_{i=1}^{\infty} \frac{(\lambda_N^\star)^i}{i!} e^{-\lambda_N^\star} \sum_{j=0}^{\infty} \frac{\lambda_W^j}{j!} e^{-\lambda_W} \pi_N(i,j)\theta(i,j) \tag{23}$$

The transmission and successful transmission probabilities for WiGiG UE are calculated similarly. The mean rate achieved by NR UE over WiGiG technology is now given by

$$E[R_{N,U}] = \Pi_N B_W E[\log_2(1 + S(x))], \tag{24}$$

where $S(x)$ is the SNR at the separation x. This component is obtained by applying the law of unconscious statistician as follows

$$E[\log_2(1 + S(x))] = \int_0^{r_W} \log_2(1 + S(x)) f_W(x) dx, \tag{25}$$

where $f_W(x)$ is the probability density function (pdf) of the distance from NR-UBS to the NR UE. This pdf is [18]

$$f_W(x) = 2x/r_W^2,\ 0 < x < r_W, \tag{26}$$

where r_W is the coverage radius of WiGiG.

The rate achieved by WiGiG UEs is obtained similarly. Define q_L to be eventual NR UE session loss probability, i.e., the probability that NR UE session lost at NR part of NR-U

TABLE I
DEFAULT SYSTEM PARAMETERS.

Parameter	Value
NR/WiGiG operating frequencies	28/60 GHz
NR/WiGiG bandwidths	200/160 MHz
Height of NR-U BS	10 m
Blocker radius	0.2 m
Height of blockers and UE	1.7/1.5 m
WiGiG transmit power	23 dBm
NR transmit power	33 dBm
Thermal noise	-174 dBm/Hz
Interference margin	3 dB
Cable losses	0.5 dB
Outage threshold	-9 dB
Blockers intensity	0.3
WiGiG AP/UE antenna arrays	16x4, 8x4
NR-U BS/UE antenna	64x4, 8x4
Active NR UE session probability	0.1
Active WiGiG UE session probability	0.1
Contention window	128

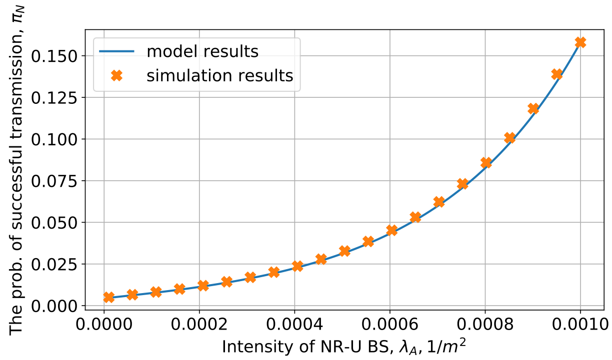

Fig. 5. Comparison the successful transmission probability.

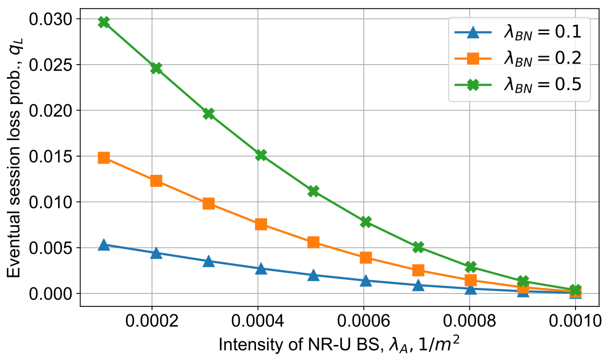

Fig. 6. Eventual NR UE drop probability as a function of NR-U density.

BS will also be eventually lost at WiGiG part of NR-U BS due to insufficient rate. Using $E[R_{N,U}]$ it is given by

$$q_L = p_L I\left(E[R_{N,U}]\right), \; I(x) = \begin{cases} 1 & x < R_{min}, \\ 1 - \frac{r_W^2}{r_N^2} & x \geq R_{min}. \end{cases} \quad (27)$$

IV. Numerical Results

In this section, we present our numerical results. We start assessing the accuracy of our model. Then, we proceed analyzing the metrics of interest and finally report on the density of NR-U BS required to support a given traffic demands in the area. The default parameters are provided in Table I.

A. Accuracy Assessment

The probability of successful transmission is the most complex part of the developed model that may affect its overall accuracy. Thus, we first assess the accuracy of this part by comparing the successful transmission probability obtained using the developed model and the one calculated using the computer simulations of the random access procedure in Fig. 5. As one may observe, the model results approximate the ones obtained using the computer simulation very well. Thus, in what follows, we will rely on the developed model to assess the required density of NR-U BSs.

B. Required NR-U BS Density

We now proceed assessing the response of the system to the input parameters by concentrating on the eventual NR-U

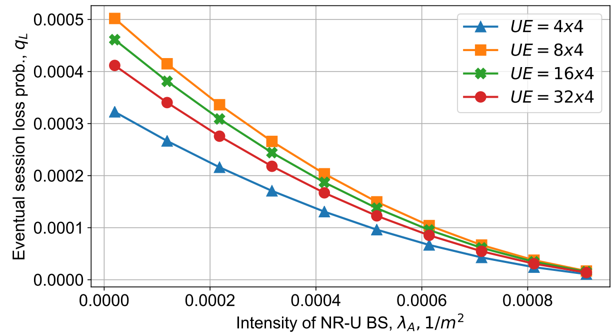

Fig. 7. Eventual NR UE drop probability as a function of NR-U array.

UE session loss probability, q_L. Note that this probability can then be used the decide upon the minimal NR-U BS density required to achieve a given q_L.

The eventual session loss probability, q_L, is shown in Fig. 6 as a function of NR-U BS density for several values of NR-U UE sessions intensity, $\lambda_{B,N}$. Expectedly, the increase in the NR-U BS density decreases the value of q_L that reaches zero for extremely high values of λ_A. As one may observe, the increase in the NR-U UE session intensity negatively affects the considered metric. Fig. 7 complements this discussion showing q_L as function of NR-U BS density for several values of NR-U BS antenna configurations. Here, one may deduce that the the increase in the number of antenna elements does not always lead to better offloading performance. Worse performance is observed improving the array from 4×4 to 8×4. However, using even better arrays, i.e., 16×4 and 32×4, starts to lead to better performance. This effect is explained by different coverage of NR part of NR-U BS that is limited by both outage probability and density of NR-U BS.

Further, Fig. 8 shows the effect of the minimum NR-U UE session rate, $r_{\min}$ on the eventual NR-U UE session loss probability, q_L, for several values of external density of blockers. Recall that the overall density of blockers is joint density obtained by summing density of WiGiG UEs, NR-U UEs and external blockers. Expectedly, the minimum rate negatively affects the eventual session loss probability as for a given density of NR-U BSs, WiGiG and NR UEs the achieved rate decreases with the increase of $r_{\min}$. Furthermore, observe

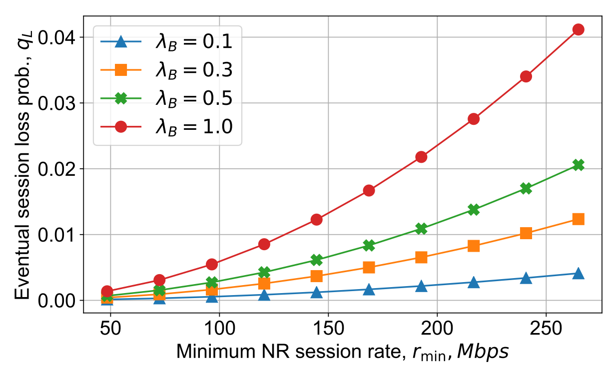

Fig. 8. Eventual NR UE drop probability as a function of minimum rate.

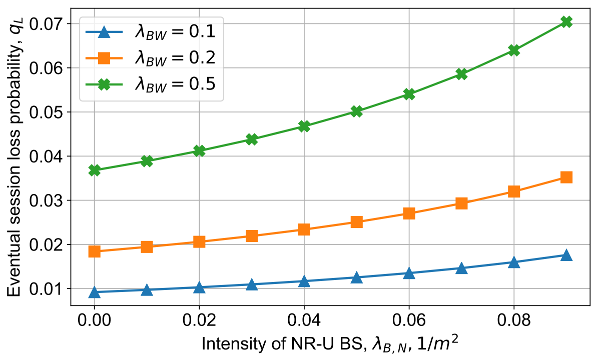

Fig. 9. Eventual NR UE drop probability as a function of NR UEs.

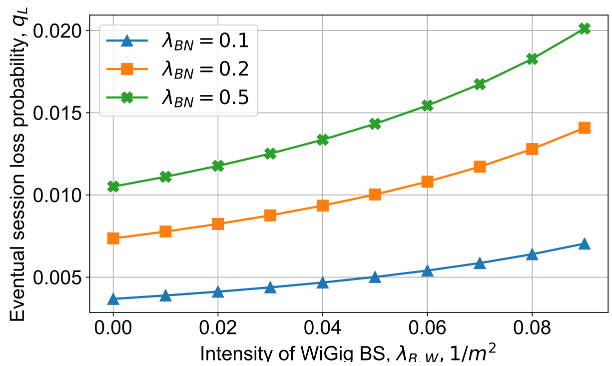

Fig. 10. Eventual NR UE drop probability as a function of WiGiG UEs.

that the increase in the density of blockers negatively affects the eventual NR UE session drop probability.

Finally, we illustrate the effect of NR-U and WiGiG UE densities, $\lambda_{B,W}$ and $\lambda_{B,N}$, on the eventual NR-U UE session loss probability, q_L in Fig. 9 and Fig. 10. As one may observe, the effect is straightforward, i.e., the increase in NR or WiGiG UE densities leads to worse performance. In both cases the rationale is that the competition for resources at WiGiG part of NR-U BS increases reducing the rate achieved by NR UEs.

V. Conclusions

In this paper, by utilizing the tools of stochastic geometry, queuing theory and renewal theory we proposed a performance evaluation framework for joint use of NR and WiGiG mmWave technologies, known as NR-U. According to the considered model we assume that those NR-U UEs that cannot receive service with a given throughput at NR part of NR-U BS are offloaded to WiGiG part, where they compete with single band WiGiG UEs for transmission resources using conventional LBT scheme with multi-stage back-off. Although the proposed model assumes co-located design of NR and WiGiG systems no internal information is exchanged between them implying that the developed framework can be applied to arbitrary deployments of these technologies.

Using the NR-U UE session loss probability as a measure of interest we reported on the density of of NR-U BS required to support a given density of NR UEs with prescribed QoS guarantees in terms of ergodic throughput. We determined that in addition to NR and WiGiG UE densities it is heavily affected by NR antenna array, density of blockers and minimum required rate. These considerations need to be taken into account when planning NR-U deployments.

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