Methods for Cellular Network's Operation in Unlicensed mmWave Bands

BhanuPrakash Ramisetti and Abhinav Kumar
Department of Electrical Engineering, Indian Institute of Technology Hyderabad, Telangana, 502285 India
Email: {ee18mtech11004, abhinavkumar}@iith.ac.in

***Abstract*—The 5G New Radio (NR) specifications by 3GPP include millimeter wave (mmWave) based operations for high data rates. To further satisfy the ever increasing demand for data rates, 5G NR can also be operated on the unlicensed mmWave bands. In this direction, various channel access schemes that consider Listen Before Talk (LBT) and Listen Before Receive (LBR) have been proposed in the literature. However, a thorough comparison of these schemes for fair coexistence with 60 GHz WiFi, also termed as WiGig, in different scenarios is needed. Hence, in this paper, we compare the performance of a combination of omni-directional and directional channel access schemes with LBT/LBR/both in the presence of a realistic mmWave array antenna pattern, 3GPP mmWave Indoor path loss model, and fixed backoff mechanism for collision avoidance. Through extensive simulations, we show that the directional LBT combined with directional LBR and omni-directional LBT schemes perform better than other schemes in terms of sum rate, mean rate, and minimum rate in the system. Moreover, directional LBT performs better in terms of number of channel access and proportional fairness in the system as compared to other channel access schemes.**

***Index Terms*—Channel access, coexistence, Listen Before Talk (LBT), Listen Before Receive (LBR), mmWave, unlicensed band, WiGig.**

I. Introduction

To handle the phenomenal growth in cellular data demand, the wireless communication industry has come up with a solution to combine licensed and unlicensed bands as primary and secondary carriers, which provides a significant increase in capacity for cellular systems [1]. This has been explored in the 5 GHz unlicensed band with LTE-LAA (Licensed Assisted Access) scheme [2]. Recently unlicensed spectrum has been proposed in the 60 GHz bands that has attracted the attention of the wireless community [3]. This spectrum is being considered as a work item by 3GPP for the standardization of 5G NR in the unlicensed bands, which is termed as 5G NR-U [4].

Despite the availability of significant contiguous bandwidth in unlicensed mmWave 60 GHz bands, ensuring the fair coexistence with other technologies in these bands such as 60 GHz WiFi (WiGig) is a critical issue [5]. This issue has been addressed in LTE-LAA using LBT technique for coexistence with WiFi devices in the 5GHz unlicensed band [2]. The LBT adopts physical carrier sense using energy detection, assuming omni-directional transmission/reception, and Clear Channel Assessment (CCA). In CCA, the transmitter that has data to

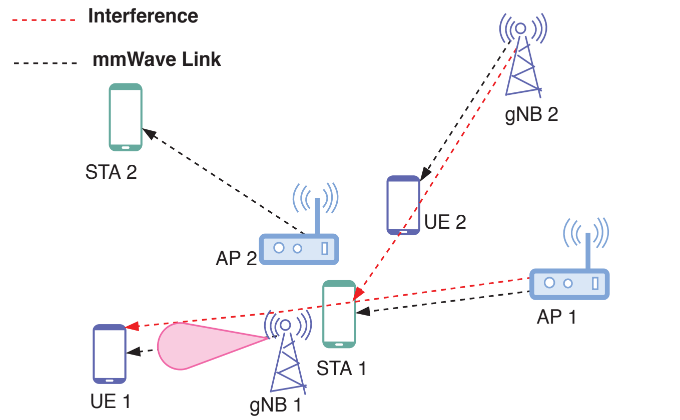

Fig. 1. Interference scenario in mmWave NR/WiGig coexistence.

transmit first senses the channel before data transmission (i.e., performs an assessment of channel being free) and initiates the transmission only if it detects tolerable interference, otherwise, it does not transmit. Unlike the coexistence of LTE and WiFi in 5 GHz band, the coexistence of NR-U and WiGig in 60 GHz bands is significantly affected by the mmWave channel propagation characteristics along with high directionality due to beamforming [7]. The transmission in mmWave bands utilizes narrow beams to compensate for the poor channel characteristics resulting in high directionality in mmWave. However, this results in the novel issue of directional coexistence between NR-U and WiGig devices. In this direction, two solutions have been considered based on carrier sense for operation of NR-U in unlicensed mmWave bands: directional LBT (dirLBT) and omni-directional LBT (omniLBT) [8]. The dirLBT senses the medium directionally, whereas, omniLBT senses the medium omni-directionally. Existing WiGig devices use omniLBT [9]. In mmWave directional transmission/reception, the dirLBT enhances the spatial reuse but suffers from hidden node problem because it will not sense the interference coming from other directions. In contrast, the omniLBT reduces the spatial reuse and is overprotective because it prevents the transmission even if there is a signal detected that will not create significant interference to the intended receiver [10]. An LAT (Listen After Talk) scheme has been proposed in [11] to address the coexistence issue of NR-U and WiGig

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devices in unlicensed mmWave bands. However, this method violates the LBT regulations and requirements in 60 GHz. The dirLBT and omniLBT schemes might not always be suitable in 60 GHz unlicensed bands because of potentially asymmetric interference observed from transmitter and receiver perspective as shown in Fig. 1. Therefore, LBR along with LBT has been proposed and, omni/dir LBT and LBR combination methods have been evaluated with few performance metrics (sum rate, mean rate) using a simple antenna gain model in [10]. However, the coexistence of 5G NR-U and WiGig has not been evaluated in the presence of a more realistic channel model. Further, other important performance metrics like minimum rate, proportional fairness along with number of channel access should be considered while evaluating this coexistence. This is the motivation of this work.

In this paper, we analyze the performance of the channel access schemes with a fixed backoff mechanism for NR-U in coexistence with WiGig. Further, we consider a combination of omni-directional and directional channel access schemes along with sensing at the receiver, transmitter, or both. We perform a detailed numerical comparison between the existing schemes using a realistic mmWave antenna and channel model for various performance metrics.

The organization of this paper is as follows. The system model is discussed in Section II. The channel access schemes for 5G NR-U along with various performance metrics are discussed in Section III. The numerical analysis is presented in Section IV. Finally, some concluding remarks along with future works are discussed in Section V.

II. System Model

We consider 5G NR gNodeBs (gNBs) along with their corresponding User Equipments (UEs) coexisting with WiGig access points (APs) and their WiGig Stations (STAs). We assume that all transmitter and receiver pairs are equipped with multiple antennas and operate in the 60 GHz unlicensed bands. All of the gNBs and APs use directional transmission and reception to overcome the propagation losses. Further, we focus only on the downlink transmissions, i.e., each gNB communicates with NR UEs, and each AP communicates with WiGig STAs. We consider the indoor dense network deployment with K Tx/Rx pairs that attempt to access the unlicensed spectrum in which K/2 are gNB-UE pairs, and the remaining K/2 are WiGig AP-STA pairs as illustrated in Fig. 2. We assume that each gNB/AP has an array of M antennas and each UE/STA has an array of N antennas. Although we focus only on the Downlink (DL) transmissions, similar kind of analysis can be applied to Uplink (UL) transmissions.

For the setup and analysis, we consider that the direction of transmit beams from gNBs/APs to their corresponding UEs/STAs have been established during the beam training by changing the phases of the antennas. Thus, each of the gNBs/APs has the transmission beam directed towards their respective UEs/STAs, and at the receiver, each of the UEs/STAs has the receive beam directed towards their respective gNBs/APs.

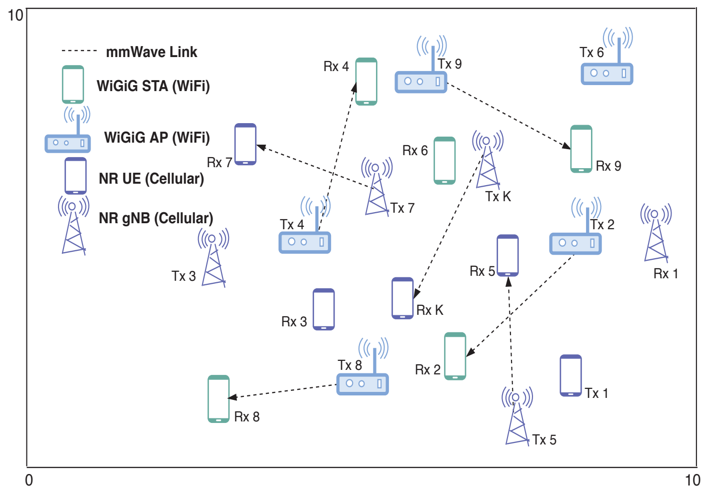

Fig. 2. System model.

We consider the 3GPP mmWave array antenna radiation patterns for both transmit and receive beams under directional transmission/reception [12]. The radiation pattern of a single antenna in an antenna array is defined as A_E (dB) and it is the amount of power radiated for any set of vertical and horizontal angles (θ, ϕ), $\forall \theta \in [0, 180^o]$, $\forall \phi \in [-180^o, 180^o]$. The radiation pattern of each antenna in an antenna array consists of horizontal and vertical patterns. The horizontal radiation pattern denoted by $A_{E,H}$ is defined as

$$A_{E,H}(\phi) = -min\left[12\left(\frac{\phi}{\phi_{3dB}}\right)^2, A_m\right] dB, \qquad (1)$$

where, ϕ is the horizontal angle, ϕ_{3dB} is the horizontal 3 dB beamwidth taken as 65^o, and A_m is the front to back ratio taken as 30 dB. Likewise, the vertical radiation pattern for the antenna, denoted by $A_{E,V}$, is given by

$$A_{E,V}(\theta) = -min\left[12\left(\frac{\theta - 90^o}{\theta_{3dB}}\right)^2, SLA_V\right] dB, \qquad (2)$$

where, θ is the vertical angle, θ_{3dB} is the vertical 3 dB beamwidth taken as 65^o, and SLA_v is the side lobe level limit taken as 30 dB. Combining both the horizontal and vertical radiation patterns in (1) and (2), we obtain the 3D single antenna gain as follows

$$A_E^{(3GPP)}(\theta,\phi) = G_{max} - min\Big[-[A_{E,V}(\theta) + A_{E,H}(\phi)], A_m\Big] dB,$$

where, G_{max} = 8 dBi is the maximal direction gain of single antenna in an array antenna [13], $A_{E,H}(\phi)$ and $A_{E,V}(\theta)$ are as in (1) and (2), respectively.

To obtain the array pattern we consider the responses of all the antennas in the antenna array. The entire radiation pattern can be computed by the combination of single antenna pattern and its array factor (AF). The AF gives the directivity

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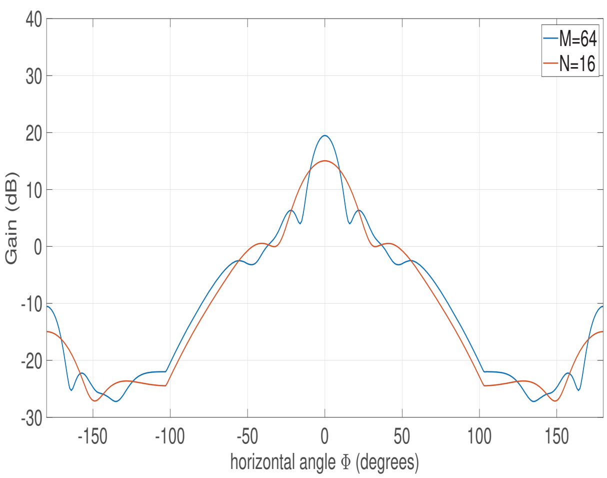

Fig. 3. Array antenna radiation pattern.

information about the array antenna.The relation is given in [14] as

$$A_A^{(3GPP)}(\theta,\phi) = A_E^{(3GPP)}(\theta,\phi) + AF(\theta,\phi), \tag{3}$$

where, $A_A^{(3GPP)}(\theta,\phi)(dB)$ is the array antenna gain and the $AF(\theta,\phi)$ for an array antenna of $n \in (M,N)$ antennas is given as

$$AF(\theta,\phi) = 10log_{10}[1+\rho(|\mathbf{b}.\mathbf{y}^{\mathbf{T}}|^2-1)],$$

where, ρ is the correlation coefficient taken as 1, $\mathbf{b} \in \mathbb{C}^n$, $\mathbf{y} \in \mathbb{C}^n$ are the amplitude and beamforming vectors respectively. We have taken the equal and constant amplitude value for all the antennas in the antenna array so that $\mathbf{b}$ is a normalized vector with each value equal to $\frac{1}{\sqrt{n}}$. The $\mathbf{y}$ which has the information about the beam steering angles (θ_s,ϕ_s) is obtained as

$$\begin{aligned}
\mathbf{y} &= [y_{1,1}, y_{1,2}, ..., y_{m,m}], \quad m=\sqrt{n}, \\
y_{p,r} &= e^{j2\pi\left((p-1)\frac{\Delta_V}{\lambda}\psi_p+(r-1)\frac{\Delta_H}{\lambda}\psi_r\right)}, \\
\psi_p &= cos(\theta)-cos(\theta_s), \\
\psi_r &= sin(\theta)sin(\phi)-sin(\theta_s)sin(\phi_s),
\end{aligned}$$

where, Δ_H is the horizontal, Δ_V is the vertical separation distance among the antennas of the array taken as $\frac{\lambda}{2}$ for both, and λ is the wavelength. We emphasize that the angles (θ,ϕ) can be any vertical and horizontal angles and the angles (θ_s,ϕ_s) are main beam steering angles due to beamforming. We have taken the vertical angles θ and θ_s to be 90^o. The array radiation pattern for $\phi_s=0$, $\theta=90^o$, and θ_s = 90^o with respect to horizontal angle ϕ is shown in Fig. 3.

The 3GPP path loss $L_{k,j}$(dB) between the Tx-Rx pairs that are separated by $d_{k,j}$ meters in indoor scenario [15] is given by

$$L_{k,j} = 32.4 + 17.3log_{10}(d_{k,j}) + 20log_{10}(f_c), \tag{4}$$

where, f_c is the carrier frequency. The power at the kth UE/STA from the jth gNB/AP at a distance $d_{k,j}$ in terms of propagation path loss and Tx/Rx antenna gains is given as

$$P_{rx}^{k,j} = L_{k,j}G_{tx}^{j,k}G_{rx}^{k,j}P_{tx}^{j},$$

where, $G_{tx}^{j,k}$ is the Tx array antenna gain at jth gNB/AP towards the kth UE/STA, $G_{rx}^{k,j}$ is the Rx array antenna gain at kth UE/STA in the direction of jth gNB/AP, and P_{tx}^{j} is the gNB/AP transmit signal power at jth gNB/AP. Notice that $G_{tx}^{j,k}$, $G_{rx}^{k,j}$ have to be computed from (3) which depends on the number of antennas (M or N) in array antenna and the steering angles (θ_s,ϕ_s) of the Tx beam at the jth gNB/AP (Rx beam at the kth UE/STA) with respect to the position of the kth UE/STA (jth gNB/AP). Note that the $L_{k,j}$, $G_{tx}^{j,k}$, $G_{rx}^{k,j}$, and P_{tx}^{j} values are converted to linear scale for computing $P_{rx}^{k,j}$. Then, the attainable data rate for the kth gNB-UE or AP-STA pair is given as

$$R_k = B\log_2\left(1+\frac{P_{rx}^{k,k}}{N_0B+\sum_{j\neq k}P_{rx}^{k,j}}\right) \quad bits/s, \tag{5}$$

where, N_0 is the power spectral density of noise, B is the channel bandwidth and $\sum$ term is the interference received. Note that the gNBs/APs which do not get the channel access will be given the power P_{tx}^{j}=0 (so $P_{rx}^{k,j}$=0, $\forall k$ that does not get channel access). We consider that LBT is performed at gNBs/APs and LBR is performed at UEs/STAs. We rely on the physical carrier sense of the channel using Energy Detection (ED), considering the fixed backoff mechanism. According to the WiGig standard [5], we assume that omniLBT is always performed for AP-STA pairs. Next, we define the various channel access schemes and performance metrics considered in this work.

III. Channel Access Schemes for 5G NR-U

A. Channel Access Schemes

We assume that omniLBT is performed for AP-STA pairs from WiGig standard [5], and we evaluate the following channel access schemes for gNB-UE pairs.

- **omniLBT:** In this scheme only the gNBs sense the channel in an omni-directional fashion.
- **dirLBT:** In dirLBT, the gNBs sense the channel in the direction of the corresponding UEs.
- **omniLBT-omniLBR:** In this scheme, the gNBs as well as the UEs sense the channel in an omni-directional fashion before deciding about channel access. In case both gNB and UE in a Tx/Rx pair find the channel to be free, a channel access attempt is made.
- **omniLBT-dirLBR:** The gNBs sense the channel in an omni-directional fashion, whereas, the UE senses the channel in the direction of the gNB from which transmission is expected. Based on both the UE and the gNB sensing the channel to be free, a transmission attempt is made.

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- **dirLBT-omniLBR:** In this scheme, gNBs sense the channel directionally, whereas, the UEs sense the channel omni-directionally.
- **dirLBT-dirLBR:** In this scheme, based on both the gNB and the UE directional sensing of the channel to be free, the gNB transmits.

We believe that the DL interference is best computed at the receiver, i.e., the UE. Thus, we consider a novel scheme **dirLBR** that senses the channel only at the UE towards the direction of transmission. This differs from the traditional schemes in that the channel sensing is not performed at gNB at all. Next, we present the performance metrics considered in this work.

B. Performance Metrics

To evaluate the performance of channel access methods, we consider the following performance metrics.

- **Sum-Rate:** It is the sum of all the data rates $\sum_{\forall k} R_k$, where, R_k is defined in (5), which measures the sum of data rates of all pairs that access the channel simultaneously.
- **Mean-Rate:** It is the average of those $R_k{}^{'}s$ that have $R_k > 0$, which means the average rate obtained by the Tx-Rx pairs that gets the channel access.
- **Min-Rate:** It is the minimum data rate of those $R_k{}^{'}s$ that have $R_k > 0$, which measures the achievable minimum data rate by the pairs that gets the channel access.
- **Proportional Fairness:** The proportional fairness is considered as expressed in [6]. It is a function of product of data rates of all Tx-Rx pairs getting channel access and equivalently also computed as $\sum_{\forall k} log(R_k)$, which measures the fairness between the pairs that gets the channel access.
- **Number of Channel Access:** It is the sum of pairs that have $R_k > 0$ which measures the simultaneous number of pairs that get the channel access.

Next, we present the numerical analysis considered in this work.

IV. Numerical Analysis

We consider an indoor dense network layout with random deployment of K Tx-Rx pairs in a 10×10 m^2 area and the distance between Tx-Rx pair is $d_{k,k}$= 4, $\forall k$. The DL performance is evaluated assuming Line of Sight (LOS) among Tx-Rx pairs and considering the path loss in (4), transmit and receive antenna gains using (3), uneven number of antennas at Tx-Rx side, and other simulation parameters mentioned in Table 1. We have not considered any other physical layer impairments like fading for this study. We consider 50% of the Tx-Rx pairs are gNB-UE pairs and the remaining 50% are AP-STA pairs. We perform the simulation for the duration of 1000 time slots. For each time slot, we have taken the number of nodes that have data to transmit with probability p. We assume that the WiGig APs always apply omniLBT. We evaluate the performance of the considered 5G NR-U channel access methods for NR gNBs based on ED threshold. The gNB/AP transmits data if the channel is sensed idle, otherwise, it undergoes backoff with fixed Contention Window (CW). The backoff value will be uniformly selected from the range [0, CW-1]. Backoff value does not change if the channel is detected to be busy and it is decremented if it senses the channel as idle for each time slot. When the backoff value reaches zero then that gNB/AP again tries to transmit data at the beginning of the next time slot based on its corresponding channel access scheme. The collision occurrence in each time slot is decided based on the SINR threshold at the UE/STA with respect to gNBs/APs that succeed in the channel access. The Tx-Rx pairs that gets the channel access and transmit data for each slot are as depicted in Fig. 2 with mmWave links. We assume that the gNB/AP that get the channel access will transmit data for R number of time slots. The data rates are computed for all the pairs that succeed in the channel access and do not undergo collision for each of those time slots. The data rates are calculated separately for each of the channel access method and are averaged over all the time slots. The total Tx-Rx pairs (K) deployed in the area are varied from 10 to 50 through simulations. The results of the simulation are averaged over 1000 channel realizations for each Tx-Rx pair. All the simulations are performed using MATLAB.

TABLE I
Simulation Parameters

Parameter	Value
B	1 GHz
CW	16
dirLBT/dirLBR ED Threshold	-64 dBm
f_c	60 GHz
M	64
N	16
Noise Power Spectral Density (N0)	-174 dBm/Hz
omniLBT/omniLBR ED Threshold	-72 dBm
p	0.5
R	4
SINR Threshold	-6.5 dB
Transmit Power (P_{tx})	10 dBm

A. Simulation Results

The variation of sum-rate with respect to the number of Tx-Rx pairs for the various channel access schemes considered in this work are shown in Fig. 4. The directional LBT combined with directional LBR scheme outperforms all the other schemes as it better avoids the hidden node problems. Fig. 5 presents the variation of number of channel access with respect to K. It is observed from Fig. 5 that the directional LBT results in the most number of channel access as compared to the other schemes because it performs directional sense only at gNB, whereas, other schemes sense both at gNB and UE. The variation of minimum rate with respect to number of Tx-Rx pairs (K) in the system is presented in Fig. 6. It is seen from Fig. 6 that the omni-directional LBT gives a better achievable minimum rate, and the minimum rate for all other schemes is decreasing due to the increase of interference with increasing K. Variation of mean rate with respect to number

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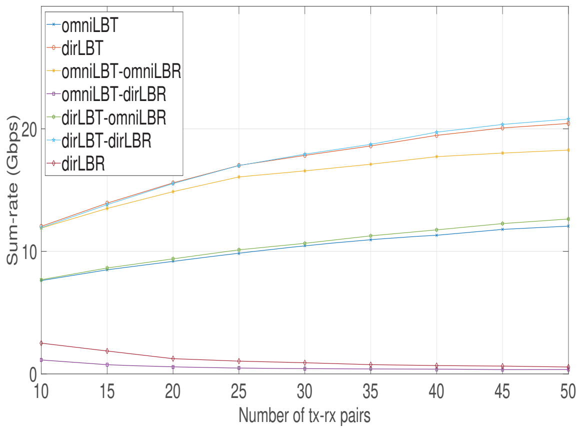

Fig. 4. Variation of sum rate (in Gbps) with respect to the number of Tx-Rx pairs (K) in the system.

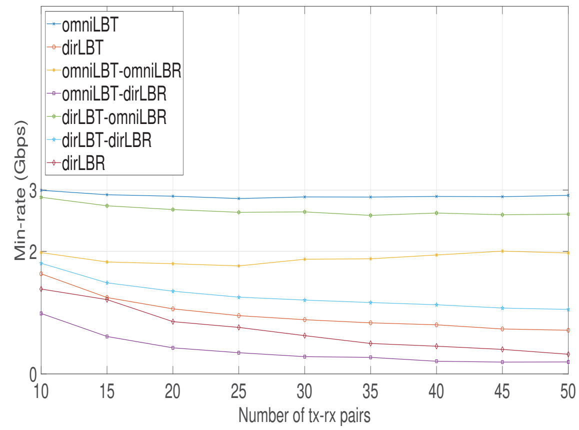

Fig. 6. Variation of minimum rate (in Gbps) with respect to the number of Tx-Rx pairs (K) in the system.

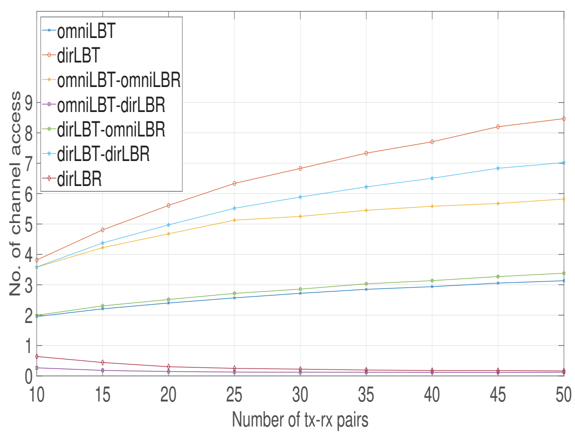

Fig. 5. Variation of number of channel access with respect to the number of Tx-Rx pairs (K) in the system.

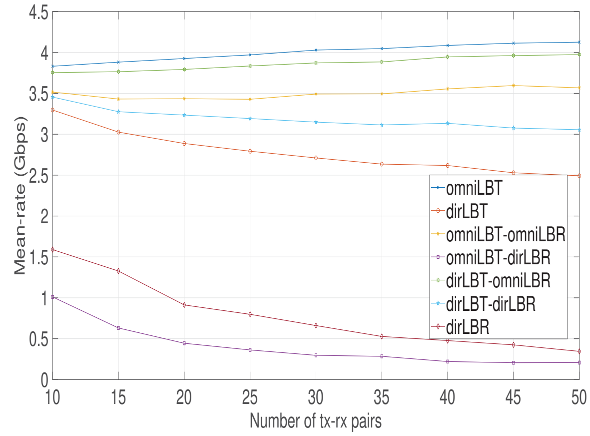

Fig. 7. Variation of mean rate (in Gbps) with respect to the number of Tx-Rx pairs (K) in the system.

of Tx-Rx pairs (K) in the system is shown in Fig. 7. The omni-directional LBT performs better in terms of the mean rate as observed in Fig. 7. Fig. 8 presents the variation of proportional fairness with respect to K. The directional LBT and directional LBT combined with directional LBR result in most fairness as compared to the other schemes because they sense the channel directionally in the direction of transmission and better reduce the interference.

V. Conclusion

In this paper, we have performed a detailed comparison between the various channel access schemes for NR-U in mmWave bands, considering a realistic channel model. Based on the results, it is observed that dirLBT-dirLBR performs better in terms of sum rate. OmniLBT performs best in terms of minimum rate and mean rate. Whereas, dirLBT performs best in terms of number of channel access and proportional fairness. Motivated by these simulation results, we will perform a testbed based evaluation of the discussed schemes in the future. We also try to analytically model the NR-U and WiGig coexistence. In future, we will also consider the error in direction estimation between the Tx-Rx pairs.

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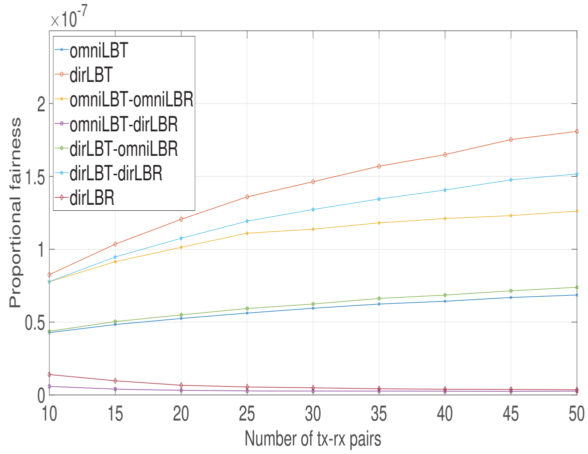

Fig. 8. Variation of proportional fairness with respect to the number of Tx-Rx pairs (K) in the system.

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