Downlink Data Rate Analysis of 5G-U (5G on Unlicensed Band): Coexistence for 3GPP 5G and IEEE802.11ad WiGig

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Abstract—**The enormous proliferation of mobile and personal telecommunications data traffic has brought severe challenges to the current mobile telecommunications system. Regarding the perspectives of both users and operators, the main obstacle is the licensing cost and scarcity of available spectrum. According to recent industrial and academic works, millimetre-wave (mmW) is a potential solution for next fifth generation (5G) mobile telecommunications. 5G on Unlicensed band (5G-U) technology, is an extension of the long-term evolution (LTE) on unlicensed band (LTE-U), which opportunistically transmits LTE signals in the unlicensed spectrum, a viable solution to deal with spectrum scarcity and increased data rates. In particular, 5G-U will aggregate carriers in the mmW band, 28 GHz or 38 GHz licensed spectrum, both candidates of 5G frequency band, and 60 GHz unlicensed spectrum, namely Wireless Gigabit (WiGig). Both systems, 5G and WiGig need to coexist without jeopardising each other. In this work, we study the coexistence of both systems in terms of downlink data rate, comparing three different scenarios: WiGig only, the coexistence of WiGig and 5G-U and 5G-U only. Results show, it is practical to operate 28 GHz licensed signal on the 60 GHz unlicensed frequency band, 5G-U can be coexisted with WiGig, and it is a good neighbourhood to current networks.**

I. INTRODUCTION

Due to the exponential boosting of telecommunications data around the world, the cost and scarcity of available spectrum became one of the most emerging and important research topics. As a result, a variety of techniques that ensure an efficient use of spectrum have been widely investigated. Notably, the two most important techniques are: the use of cognitive radio introduced the idea of accessing opportunistically poorly used spectrum [1], and spectrum aggregation, such as the Third Generation Partnership Project (3GPP) carrier aggregation (CA), that allows for simultaneous transmission of data in two different pieces of spectrum [2]. Given the rare availability of large portions of spectrum, CA facilitates an efficient use of the the fragmented parts and so allows the operator to make the most of its usable bandwidth.

Since the availability of licensed spectrum is limited and expensive, innovative solutions have been studied in the context of long term evolution (LTE) on unlicensed band (LTE-U), or Licensed Assisted Access(LAA) introduced by the 3GPP in Release 13 [3]. In particular, the standardisation body has standardised the complementary access using the unlicensed band(always supported by licensed operation), and has defined the possible deployments focused on the use of CA. Also, latest 3GPP efforts have been placed in the study of coexistence in the 5 GHz frequency band. On the other hand, LAA has been widely studied in the research community [4]. Recent research in [1] uses stochastic geometry to develop a framework for a multi-RAT(radio access technologies), to reduce both intra- and inter- RAT interferences. Research efforts are focused on creating fairness mechanism for the Wi-Fi and LTE-U coexistence, for example to propose a modified Wi-Fi operation mode, thereby to reduce required time for collision detection [5]. Research in [6] [7] also shows the performance of LTE-U by modelling the coexistence of LTE-U and Wi-Fi, along with [8] to prove that LTE-U is good neighbourhood to current unlicensed networks.

In a more practical scenario, mobile operators' deployments in China, India, Korea, and the US, a fair sharing of LTE-U and Wi-Fi are achieved by using channel selection and Carrier Sensing and Adaptive Duty Cycle Based Transmission (CSAT). Various techniques have studied use of Wi-Fi in offloading traffic from LTE network [9] [10]. A Non-Listen before talk (LBT) strategy fits the coexistence of LTE-U and other incumbent network systems; on the other hand, regarding different regulations in other regions such as Europe, Japan and UK, where specific access features including LBT are mandatory, these transmission behaviours are achieved by Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocols [8] [11], which are defined in Release 13 [3].

Moreover, recent research shows that millimetre-wave (mmW) is a potential frequency band, as a candidate for the next generation of mobile communications [12] [13], therefore it is naturally to extend LTE-U or LAA into mmW frequency bands, and upgrading LTE-U or LAA to 5G-U to achieve even higher data rates.

For the deployment of 5G licensed spectrum, there are over 1 GHz of available spectrum bandwidth are allocating in 28 GHz and 38 GHz [13] respectively. Notably, comparing the current LTE channel bandwidth is of 20 MHz [14]; free spectrum in 5G bands is over 50 times wider than that of LTE. Specifically, for the unlicensed spectrum in 60 GHz frequency range [15], there are over 2 GHz of the spectrum is free to use in most nations and regions [16]. And the Wi-Fi operating

in this frequency band is standardised by IEEE 802.11ad as Wireless Gigabit Alliance(WiGig) [16].

5G-U is an extension of LTE-U/LAA in the licensed bands of 28 GHz or 38 GHz and 60 GHz unlicensed WiGig frequency band. To coexist 5G-U and incumbent Wi-Fi system, for example, WiGig, a fair coexistence mechanism is mandatory in mobile operator's deployments.

This article is organised as follows: Chapter II outlines the concept overview of LTE-U/LAA and other key technologies. Chapter III extends LTE-U/LAA to mmW and provides path loss calculation of mmW in LOS (Line of Sight) scenario. Chapter IV explains three cases: to discuss 5G-U technology in a system model, expand this model to a complex network to show a more realistic simulation, coexist 5G-U with other unlicensed networks, for example WiGig. Next chapter display the analysis and simulation results. Conclusions are given in the final chapter and followed by relevant and future works.

II. CONCEPT OVERVIEW

A. LTE-U and LAA

Motivated by a more seamless, higher data rate and spectrally efficient way of offloading, LTE-U or LAA is aggregating both licensed spectrum and unlicensed spectrum. Specifically, the primary carrier on licensed spectrum is for combining both data, signalling and controlling information including access, authentication, mobility management, paging, registration, system acquisition information, and the secondary carrier on unlicensed spectrum is mainly for offloading and downlink traffic.

An effort in extending LTE to unlicensed spectrum in where Listen-Before-Talk (LBT) is not required, has been specified in the LTE-U Forum, which discuss the minimum base station and UE, and the coexistence with Wi-Fi [17].

A similar technology LAA has been standardized by 3GPP in Release 13, which deploys LTE itself in unlicensed spectrum. LAA-LTE uses a contention based protocol known as LBT, to coexist with other unlicensed network for example Wi-Fi.

B. Carrier Aggregation

Carrier aggregation is a key technology for both LTE-U or LAA and 5G-U see Fig. 1, which provides a bandwidth extension by aggregating multiple fragmented carriers into a virtual but wider frequency band [12]. Unlike dual connectivity, carrier aggregation aggregates multiple carriers from the same location, or from the same small cell.

C. Coexistence Mechanism

Another unneglectable notion is the coexistence between 5G-U and other mobile telecommunications systems. In Non-Listen before talk (Non-LBT) regions like China, India, Korea, and the US, it is essential for mobile operators to design a CSAT (Carrier Sensing and Adaptive Duty Cycle Based Transmission) strategy to build an on/off duty cycle. Thereby to coexist with other mobile telecommunications systems such as other 5G-U and Wi-Fi including WiGig.
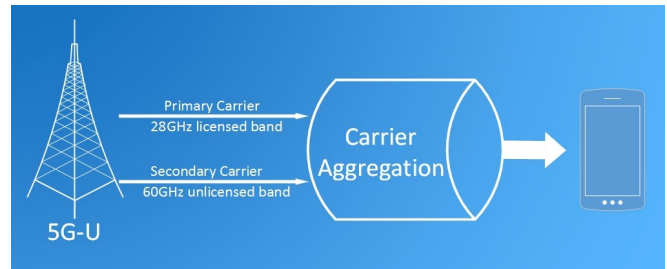

Fig. 1: 5G-U and carrier aggregation overview.

In other areas with LBT requirements, such as Europe, Japan and the UK, Wi-Fi transceiver listens to channels and to see if there is energy detected or all channels are idle. And if there is energy detected, the transmitter will keep listening; and if all channels are idle, the transmission will be processed.

III. TRANSMISSION IN MMW

A. Use of mmW in WiGig and 5G

The frequency bands in the range from approximately 30 GHz to 300 GHz are called millimetre-wave, where more than 90% of available bandwidths are in these frequency bands. However, generally, industry has a loose definition, referring to any frequencies above 10GHz [13].

Currently, one of the unlicensed frequency bands, the 60GHz frequency band is for both academic and industrial use for it capturing a wider bandwidth than that of all other unlicensed bands combined. Federal Communications Commission (FCC) initially sets up an unlicensed frequency band around 60 GHz, in 2013, IEEE802.11ad has been standardised as WiGig.

More recent research [13] [18] shows that millimetre-wave bands, for example, 28 GHz, 38 GHz and 73 GHz, are potential candidates as licensed bands for the 5G cellular network. And with the rapid developing of next generation telecommunications, it is predictable that any of these millimetre-wave bands will be licensed soon for providing higher data rate [19].

However, there are number of key challenges remain, due to the smaller wavelength at millimetre frequency bands. For example: range and directional transmission, severe shadowing includes materials and human body, and rapid channel fluctuations and intermittent connectivity.

B. Propagation in mmW

Path loss refers to the power reduction when signal propagates from transmitter to receiver through space. Works in [20] shows the equation after the measurement of path loss at lower frequencies; however at higher frequencies for example millimetre-wave, due to stronger penetration ability and foliage loss, path loss are measured in different ways [21], these millimetre-wave includes 60 GHz frequency unlicensed band and 28 GHz frequency licensed band,

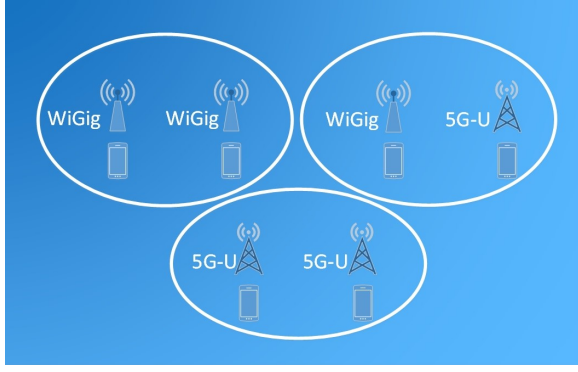$$PL(d)[dB] = PL_{FS}(d_0)[dB] + 10\beta \log_{10}(\frac{d}{d_0}), \ d > d_0,$$
$$(1)$$

Fig. 2: Theoretical downlink data rate in simple network with two pairs of transceivers.

$$PL_{FS}(d_0)[dB] = 20 \log_{10}(\frac{4\pi d_0}{\omega}), \qquad (2)$$

Equation 1 estimates that the path loss consists of three parts: path loss at reference distance are calculated in Equation 2. d is the transmitter to receiver (Tx-Rx) separation distance, $d > d_0$, and d_0 is the reference Tx-Rx separation distance.

$PL_{FS}(d_0)$ is the free space path loss at the reference distance of d_0; β is the path loss exponent (PLE); ω is the wavelength at the measured frequency.

Notably, the current stage of this research is focused on LOS indoor cases, for example, stadiums, venues, offices and conference rooms. According to the researches of path loss on 60 GHz channel [22] and 28 GHz channel [23], the values of PLEs of generic LOS path loss models are set in Table I.

IV. System Model Description

A. Simple Network

Consider an elementary network which is constructed by two pairs of transmitters and receivers are: each transmitter is serving only one corresponding receiver, thereby to simulate a coexistence of 5G-U network with other RANs (Radio Access Networks), for example, other 5G-U or WiGig networks. According to recent research on LTE-U, it is possible to calculate total throughput of each transceiver and stimulate a SISO transmission [7].

Base on the model from [7], assuming three occasions as Fig. 2 shows: firstly, both pairs of transceivers are simulated as WiGig transmissions. To calculate the downlink data rate of each transceiver, they can be achieved as Equation 3,

$$R_W = \alpha B_U \log_2(1 + SNR_1), \qquad (3)$$

where R_W is the theoretical downlink data rate from WiGig AP to its receiver; α denotes the fraction of time while WiGig AP and its receiver are occupying the air link, it is depending on time parameter settings in each WiGig AP; B_U is the unlicensed bandwidth; SNR_1 is the signal to noise ratio on the receiver in this subcase.

Secondly, consider one pair of transceiver is a WiGig transmission, the other pair is a 5G-U transmission, therefore to simulate the simplest coexistence of WiGig network and 5G-U network. Particularly, to simulate CSMA or CSAT feature, assuming WiGig AP cannot detect any signal from 5G-U eNB, but 5G-U eNB is capable of detecting whether the WiGig AP is occupying the air link. The theoretical downlink data rate from WiGig AP and 5G-U eNB are illustrated in Equation 4 and Equation 5,

$$R_{WM} = \alpha B_U \log_2(1+SNR_2)+(1-\alpha)B_U \log_2(1+SINR_1), \qquad (4)$$

$$R_{FM} = B_L \log_2(1+SNR_2)+(1-\alpha)\rho B_U \log_2(1+SINR_2), \qquad (5)$$

where R_{WM} and R_{FM} are the theoretical downlink data rate from WiGig AP and 5G-U eNB in this multi-RAN, respectively; B_U and B_L are bandwidths of unlicensed the component and licensed carriers individually; SNR_2 is the signal to noise ratio on WiGig receiver in this sub-case; $SINR_1$ is the signal to interference plus noise ratio on WiGig receiver, interferences are from an unlicensed component of an 5G-U transmitter; $SINR_2$ is the signal to interference plus noise ratio on 5G-U receiver, thereby interferences are from licensed component of 5G-U transmitter(only one 5G-U transmitter, interference free here); $SINR_3$ is the signal to interference plus noise ratio on WiGig receiver in, interferences are from unlicensed component of WiGig transmitter(similarly, interference free here); a resource allocation parameter ρ is defined to describe the portion of bandwidth used by 5G-U eNB.

Finally, both pairs of transceivers are 5G-U transceivers, which illustrates a most basic coexistence of 5G-U network and another 5G-U network. In this subcase, both 5G-U eNB can hear from each other, consequently, there is no interference between their unlicensed bands, as the CSMA or CSAT feature is performed.

$$R_F = B_L \log_2(1 + SINR_4) + \alpha\rho B_U \log_2(1 + SNR_3), \quad (6)$$

where R_F is the theoretical downlink data rate of any 5G-U eNB in this case; $SINR_4$ is the signal to interference plus noise ratio on 5G-U receiver in here, interferences are from licensed component of other 5G-U transmitter; SNR_3 is the signal to noise ratio on 5G-U receiver.

B. Coexistence of Multi-RAN and Data Rate Improvements

With larger number of pairs, when N>2, assuming they are all dropped with Poisson Point Distribution in an indoor area of A, and the locations of two sets of nodes are independently simulated as Poisson Point Process with parameter λ:

$$P(N|\lambda) = \frac{\lambda^N}{N!}e^{-\lambda}, \quad N = 0, 1, 2, ..., \infty \qquad (7)$$

where λ is the intensity of the Poisson Point Process, presents the number of transceivers per unit area; N is a nonnegative integer random value, represents the number of transceivers in study area A, defined as $N = \lambda \cdot A$; When network reaches to its saturation level, $N_S = \lambda_s \cdot A$.

Firstly, all transceivers are WiGig transceivers, to stimulate a WiGig only network. And in this case, each WiGig transceiver

ensures to transmit $1/N$ th time, and its corresponding receiver will not receive interference from other WiGig transmitters during this time, therefore the average downlink data rate on a random WiGig transceiver is calculated in Equation 8,

$$R_W = \frac{1}{f(N)} B_U \log_2(1 + SNR_1), \qquad (8)$$

where R_W denotes the downlink data rate of a random WiGig transceiver; $f(N)$ is a function of transmitters density which illustrates the number of transmitters N; SNR_1 is the signal to noise ratio on a WiGig receiver in this sub-case.

Additionally, half transceivers are WiGig transceivers, the other half of transceivers are 5G-U transceivers, consequently to establish a Multi-RAT network which simulates the co-existence of 5G-U network and incumbent WiGig network. Therefore, it is possible to calculate the average downlink data rate on each transceiver in Equation 9 and 10,

$$R_{WM} = \frac{2}{f(N)} B_U \log_2(1 + SNR_2) + \frac{2}{f(N)} B_U \log_2(1 + SINR_1), \qquad (9)$$

$$R_{FM} = \frac{N/2}{f(N)} B_L \log_2(1 + SINR_2) + \frac{1}{f(N)} B_U \rho \log_2(1 + SINR_3), \qquad (10)$$

where R_{WM} and R_{FM} represent an average downlink data rate on any WiGig transceivers, and an average downlink data rate of any 5G-U nodes in this multi-RAN, respectively; SNR_2 is the signal to noise ratio on a WiGig receiver; $SINR_1$ is the average signal to interference plus noise ratio on a WiGig receiver, interferences are from unlicensed components of 5G-U transmitters; $SINR_2$ is the average signal to interference plus noise ratio on a 5G-U receiver, interferences are from licensed components of other 5G-U transmitters; $SINR_3$ is the average signal to interference plus noise ratio on a 5G-U receiver, interferences are from unlicensed components of 5G-U transmitters.

Finally, assuming all transceivers are 5G-U transceivers, thereby to simulate a network formed by 5G-U transceivers only. And the theoretical average downlink data rate on each 5G-U transceivers is illustrated as Equation 11

$$R_F = \frac{N}{f(N)} B_L \log_2(1 + SINR_4) + \frac{1}{f(N)} B_U \rho \log_2(1 + SNR_3), \qquad (11)$$

where R_F denotes an average theoretical downlink data rate on any 5G-U transceiver; $SINR_4$ is the average signal to interference plus noise ratio on a 5G-U receiver, interferences are from licensed components of other 5G-U transmitters; SNR_3 is the average signal to noise ratio on a 5G-U receiver.

The distributions of $SINR_1$ is calculated in Equation 12,

$$SINR_1 = \frac{P_U \cdot PL_1^{-1}}{P_L \sum_1^{N/2} PL_n^{-1} + N_0}, \qquad (12)$$

where P_U and P_L are transmit power from WiGig transmitters and 5G-U transmitters, respectively; PL_n is a variable which represent the path loss from nth nearest transmitter to its receiver in the corresponding network; and N_0 is the noise floor in terms of power density with respect to the bandwidth.

To calculate the noise floor at the receiver, first is to calculate the minimum equivalent noise as the receiver according to Equation 13,

$$P = K \cdot T \cdot B, \qquad (13)$$

where P is the power in watt, K is Boltzmann constant with $1.38 \times 10^{-23}\ J/K$, T is the temperature in kelvins of 290, B is the bandwidth in Hertz. Therefore, the minimum equivalent noise is $-174\ dBm/Hz$ at a room temperature of 290 kelvins.

The noise floor N_0 at the receiver can be obtained by Equation 14.

$$N_0 = -174 + NF + 10 \log_{10} BW, \qquad (14)$$

where NF is the noise figure of 1.5 dB, and BW are the bandwidths on different frequency bands, and is equal to B_L and B_U. Similarly, the values of other SNR and $SINR$ can be calculated according to the descriptions of their independent occasions.

C. Coexistence Impact on Data Rate of WiGig

Consider two following sub-cases: firstly, WiGig A and WiGig B are two geographically overlapped unlicensed systems, and they belong to two autonomous systems individually. Assuming the total number of WiGig A transceivers plus WiGig B is fixed at the saturation level, and the density of WiGig A transceivers is the independent variable.

Secondly, assuming a multi-RAN which consists of WiGig A and 5G-U network. Again, the total number of WiGig A plus 5G-U transceivers is fixed at the saturation level, and the density of WiGig A transceivers is the independent variable.

This is to calculate the DL rate where a WiGig network coexists with other WiGig, and to see how this DL rate changes when then same WiGig network coexists with 5G-U, thereby to determine whether 5G-U is a good neighbourhood.

V. RESULTS AND DISCUSSION

Simulation parameters are detailed in Table I, based on [7] [22] [23].

A. Simple Network

The calculations of downlink data rate in a simple network with two pairs of transceivers are shown in Fig. 3. α is an independent variable increasing from 0 to 1, denotes the time fraction when a WiGig or 5G-U transceiver is occupying the link.

In the WiGig only sub-case, with the increasing of time fraction from 0 to 1: data rate on a WiGig receiver is increasing from 0 to maximum value.

In the WiGig+5G-U, with the increasing of time fraction from 0 to 1: data rate on the WiGig receiver is increasing from minimum to maximum value, 5G-U receiver is in the opposite trend.
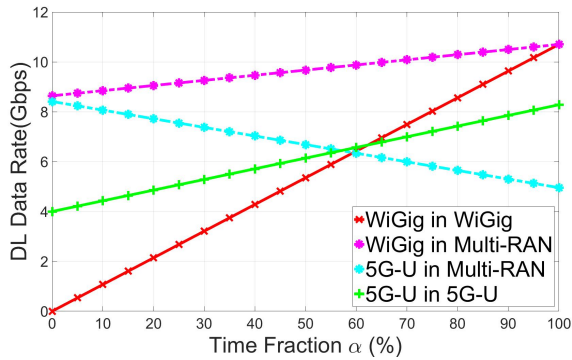
Fig. 3: Downlink data rate of WiGig and 5G-U receivers in WiGig, WiGig+5G-U multi-RAN, and 5G-U networks, with two pairs of transceivers

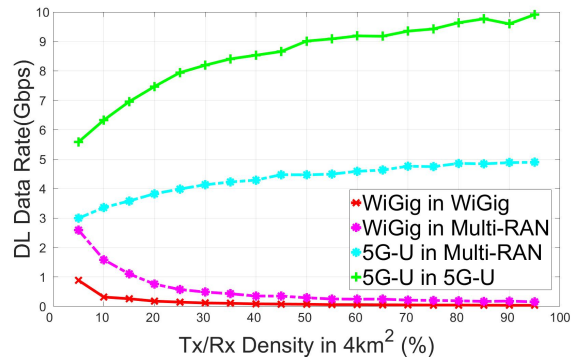Fig. 4: Downlink data rate of WiGig and 5G-U receivers in WiGig, WiGig+5G-U multi-RAN, and 5G-U networks, with more than two pairs of transceivers.

Conspicuously, when α is 0, the rate of WiGig receiver is minimum as 0, the rate of 5G-U Receiver is maximum, which means, for WiGig receiver, there is interference from 5G-U transmitter for all the time; and for 5G-U receiver, there is carrier aggregation for all time.

When α is 1, the rate of WiGig receiver is maximum, the rate of 5G-U receiver is minimum, which means; for WiGig receiver, there is no 5G-U coexistence or no interference from 5G-U transmitter, for 5G-U receiver, there is no carrier aggregation for all time.

In 5G-U only sub-case, with the increasing of time fraction from 0 to 1: data rate on one 5G-U receiver is increasing from minimum to maximum value.

Notably, the minimum rate in the last sub-case is not zero, this is due to the aggregation of unlicensed spectrum; however, the slope and the maximum value in 5G-U only network are lower than those of in WiGig only, this is because of the interferences from licensed component and a resource allocation parameter when two 5G-U transceivers coexist.

TABLE I: Simulation Parameters

Parameters	Values
time fraction, α	$0\sim1$
path loss exponent(LOS), β	1.7(60 GHz), 1.1(28 GHz)
resource allocation parameter, ρ	0.4
Tx/Rx intensity, λ	N/A
Tx/Rx saturation intensity, λ_S	4e-4
wavelength, ω	$1\sim10$ mm
Tx/Rx separation distance, d	$0\sim2828$ m
Tx/Rx separation reference distance, d_0	1 m
study area, A	$4\ km^2$
licensed bandwidth, B_L	1.008 GHz
Boltzmann constant, K	1.38×10^{-23} (J/K)
transmit power on 5G-U eNB, P_L	45 dBm
transmit power on 5G-U eNB, P_L	45 dBm
transmit power on WiGig AP, P_U	20 dBm
number of transceivers, N	$\lambda \cdot A$
Noise figure, NF	1.5 dB
number of transceivers at saturation, N_S	1600
height of receivers	1.5 m
height of WiGig AP	7.5 m
height of 5G-U eNB	12 m

B. Coexistence of Multi-RAN and Data Rate Improvements

Assuming an LOS scenario in a study area of A. All transmitters and receivers are dropped in this area with Poison Point Distributions, consider three networks: a WiGig network, a Multi-RAT network coexists with equal number of WiGig 5G-U transceivers and a 5G-U network.

Simulation results of downlink data rate of the multi-RAN are as shown in Fig. 4. The density of transceivers is an independent variable, means the density of WiGig transceivers, the density of WiGig plus 5G-U transceiver or the density of 5G-U transceiver in three subcase, individually.

In WiGig only network, with the growing of the density of WiGig transceivers: there are stronger interferences from other WiGig transmitters, therefore, the data rate on a WiGig receiver is decreasing from maximum to minimum.

In WiGig+5G-U multi-RAN, with the growing of the density of WiGig+5G-U transceivers: for a WiGig receiver, there are stronger interferences from 5G-U Transmitters. Therefore, the data rate on a 5G-U receiver is decreasing dramatically; for a 5G-U receiver, there are stronger interferences from WiGig transmitters and other 5G-U transmitters, but more carrier aggregation has compensated the loss of interferences and contribute extra data boost. Therefore, the data rate on a 5G-U receiver is boosting slightly.

In 5G-U only network, with the growing of the density of 5G-U transceivers: there are weaker interferences from other 5-U transmitters, but again, more carrier aggregations have compensated the loss from interferences and contribute extra rate increasing. Therefore, the data rate on 5G-U receiver is rising, and with no more interferences from WiGig transmitters, the slope of this rate is higher than that of 5G-U receiver in multi-RAN.

Notably, when the density of transceivers reaches at around 10%, the data rate on 5G-U receivers and WiGig receivers in a multi-RAN almost equal. However, with the increasing of the transceivers density to 50%, the data rate on 5G-U transceivers is more than 8 times of that on WiGig transceivers.
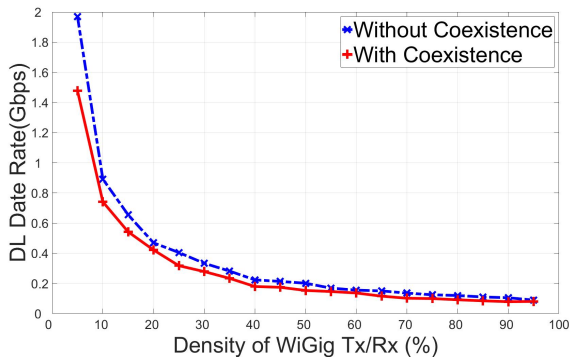
Fig. 5: Downlink data rate on the same WiGig receiver with and without coexistence of 5G-U.
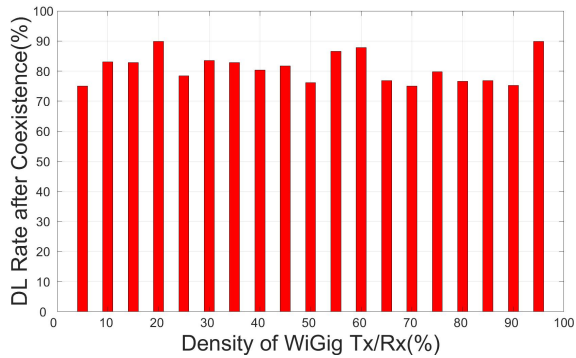

Fig. 6: Negative impact on WiGig downlink data rate after coexistence of 5G-U.

C. Coexistence Impact on Data Rate of WiGig

Although the data rate on 5G-U is improved tremendously, the negative impact on WiGig after it coexists with 5G-U always exists. Simulation results are displayed in Fig. 5 and Fig. 6 to show an accurate estimation of the data rate loss on WiGig transceivers.

Fig. 5 compares with the downlink data rate on a WiGig A receiver before and after coexistence with 5G-U. Fig. 6 shows the downlink data rate is affected by coexistence at any point, but it is transceivers density independent and with less than 30% of losses at any point.

However, this level of negative effected on WiGig data rate will be compensated by coexisting with 5G-U, compared with more then 8 times increasing on data rate of 5G-U. Therefore, 5G-U is a good neighbourhood.

VI. CONCLUSIONS

One analysis calculation and two groups of simulations are conducted to evaluate the performance of the 5G-U network and its coexistence with other unlicensed networks.

The analysis calculation shows an elementary network system model with two pairs of transceivers.

The first simulation expands the elementary network to a complex multi-RAN. The results illustrate that by coexisting

with other unlicensed networks, it is practical to operate 28GHz licensed signal on the 60GHz unlicensed band.

The last simulation indicates that incumbent WiGig will be slightly affected by the coexistence of 5G-U. In terms of downlink data rate, with no more than 30% of loss, 5G-U can coexist with other unlicensed networks and it is also a good neighbourhood to current networks.

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