Adjacent channel co-existence study between 5G NR and Wi-Fi in the 6 GHz band for indoor scenario

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***Abstract*—This study presents indoor compatibility between Wi-Fi operating in the 5925-6425 MHz band and 5G NR operating in the 6425-7125 MHz band. The study estimates interference levels between 5G NR and Wi-Fi equipment and presents the results as a performance degradation of the 5G NR. The analysis considers two scenarios, the first is a Rician channel between 5G NR and Wi-Fi equipment, and the second is when there is a Rayleigh channel.**

Keywords—5G, 6 GHz, Wi-Fi, co-existence, adjacent channel, Monte-Carlo simulations

I. Introduction

The 6 GHz band became one of the most attractive bands for broadband technology's expansion. The lower part of the band (5925-6425 MHz) today is enabled to be used on an unlicensed basis by Wi-Fi technologies for indoor applications in most countries, whereas the higher part of the band (6425-7125 MHz) is planned to be used by 5G NR in many countries and currently studies within the Radiocommunication sector of the International Telecommunication Union (ITU-R) and is planned to be identified for IMT on World Radiocommunication Conference 2023 (WRC-23). Given that 5G NR operates on a licensed basis and requires a high signal-to-noise ratio (SINR) to provide high-speed data for such applications as enhanced mobile broadband (eMBB) and ultra-reliable low-latency communication (URLLC) it is important to avoid interference with 5G NR systems so that operators would fulfill the required QoS to the users. It should be noted that 70-80% of the cellular technologies traffic is generated indoors, therefore there is a possible adjacent channel interference cases when 5G NR user equipment is located inside the same indoor premises as Wi-Fi equipment [1][2].

Today ITU-R studies the compatibility of 5G NR with incumbent services in the 6425-7125 MHz band with satellite systems and radio relay links. Many of these studies were published by the authors [3][4][5][6][7]. At the same time, the question of possible interference of Wi-Fi to 5G in the adjacent channel scenario wasn't studied yet and so far, no administration estimated how these two systems will co-existence in case of close vicinity deployment. This study intends to show how indoor deployment of Wi-Fi in the 5925-6425 MHz band may affect 5G NR user equipment that is located in the same buildings with Wi-Fi and operate in the frequency band 6425-7125 MHz. The results of this research may help administrations and operators that intend to use Wi-Fi and 5G NR in the 6 GHz bands and understand how some of the services of 5G NR may degrade in case of Wi-Fi interference. Figure 1 presents a schematic situation of interference from Wi-Fi equipment to the 5G NR user equipment located inside one building.

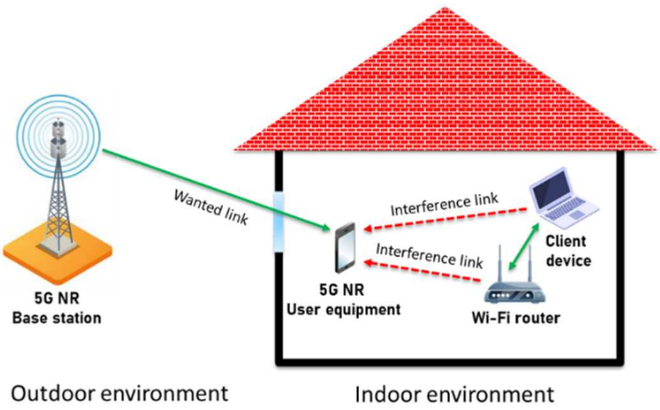

Fig. 1. Interference scenario of Wi-Fi devices to 5G NR user equipment

For indoor cases, two types of interference scenarios from Wi-Fi to 5G NR are possible, the first is when 5G NR user equipment and Wi-Fi router and/or client device are located inside the same space indoors and have close distances between each other, such a case would be the worst-case scenario since it would have the highest impact. Typical examples where such scenarios are possible include airports, railway stations, shopping malls, restaurants, and other places where 5G NR user equipment may be in the same space as Wi-Fi equipment. The second indoor scenario includes the scenario when Wi-Fi and 5G NR are located in different rooms, and there is a wall between 5G NR equipment and Wi-Fi equipment, such cases are common for residential buildings, offices, or hotels where 5G NR and Wi-Fi may be used in the neighboring rooms, this case is more interference friendly since 5G NR would be shielded by the walls from the Wi-Fi transmissions.

By analyzing possible propagation situations between the Wi-Fi transmitter and 5G NR receiver, two different path categories can be identified: paths with a strong LoS component, and obstructed paths – non-line-of-sight (NLoS).

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Because of obstacles or man-made blocking, a pure LoS situation seldom exists in indoor operating environments and the signal is received via multipath. Moreover, depending on the degree of receiver obstruction from the transmitter, additional path subcategories are considered in the indoor propagation environment: Soft-NLoS and Hard-NLoS. In the former case, there is a standard obstacle or, at least, one plasterboard between the transmitter and the receiver. In the latter case, the receiver is separated from the transmitter by a large number of obstacles or by, at least, one concrete wall [7].

This study considers three scenarios of Wi-Fi and 5G NR indoor deployment: strong LoS, Soft-NLoS with a Rician channel scenario, and Hard-NLoS with a Rayleigh channel scenario.

II. Simulation Parameters

A. *5G NR characteristics in the 6425-6125 MHz band*

To simulate the 5G NR link, characteristics of the base station for urban deployment and typical user equipment characteristics were configured. The characteristics of 5G NR for the 6425-7125 MHz frequency band used in simulation are presented in Table 1 these are the characteristics based on the 3GPP report. These parameters are also used for the studies with incumbent services in ITU-R. The channel bandwidth of 5G NR in the 6425-7125 MHz can vary from 20 MHz to 100 MHz, for this particular study the channel bandwidth was 100 MHz, the parameters derived from 3GPP TR 38.921 [9].

TABLE I. 5G NR characteristics in the 6425-7125 MHz band

Parameters	**5G NR**	
	BS	***UE***
Frequency band	6425-7125 MHz	
Channel bandwidth	100 MHz	
Type of deployment	Urban	
Cell radius	300 m	
Mechanical downtilt	10°	-
Antenna height	18 m	1.5 m
Antenna pattern	8x16 ITU-R M.2101	Omnidirectional
Antenna gain	5.5 dBi per element	-4 dB
Conducted power	22 dBm per element	23 dBm
Noise figure	6-11 dB	9-13 dB
Adjacent channel selectivity	42 dB	32 dB
Body loss	-	4 dB

The base station of 5G NR implements active antenna system with beamforming, the beamforming antenna is based on an antenna array and consists of a number of identical radiating elements located in the yz-plane with a fixed separation distance (e.g. λ/2), all elements having identical radiation patterns and "pointing" (having maximum directivity) along the x-axis. A weighting function is used to direct the beam in various directions. Total antenna gain is the sum (logarithmic scale) of the array gain and the element gain [10]. The antenna pattern in the azimuth and elevation planes that is used in simulations for 5G NR base station is presented in Figure 2.

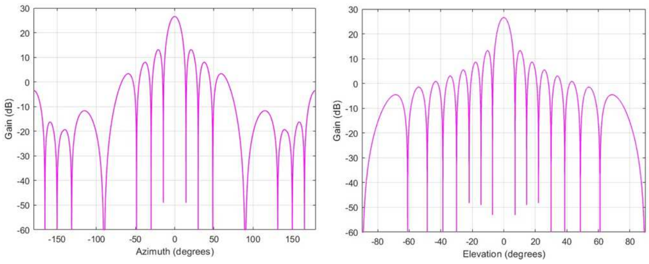

Fig. 2. 5G NR base station antenna patter in the 6425-7125 MHz band

For the case of non-co-frequency interference analysis, it is important to calculate the amount of power transmitted by a Wi-Fi on the 5925-6425 MH frequency that would be detected at the 5G NR receiver on the 6425-7125 MHz frequency. This requires the calculation of the mask integration adjustment factor and the use of ratios such as the adjacent channel selectivity (ACS), this ACS mask corresponds to the 3GPP standard for NR in the 6 GHz band [9]. Figure 3 provides 5G NR user equipment ACS mask that is used for the simulations.

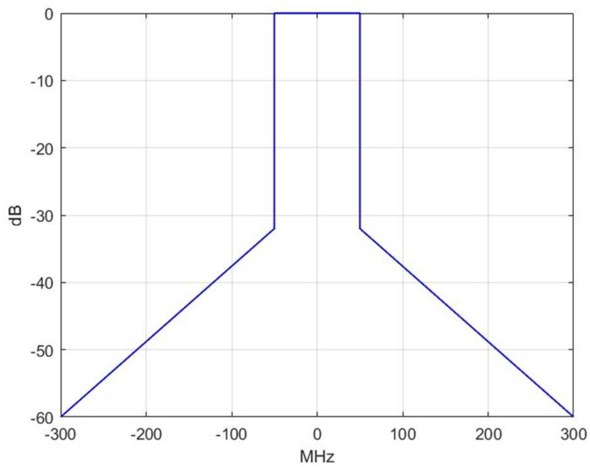

Fig. 3. Receive spectrum ACS mask of the 5G NR UE receiver

B. *Wi-Fi characteristics in the 5925-6425 MHz band*

To simulate interfering Wi-Fi equipment, typical characteristics for the 5925-6425 MHz frequency band were configured. The bandwidth of Wi-Fi in the 5925-6425 MHz band can vary from 20 MHz to 160 MHz, for this study 20 MHz channel was simulated. The interference was generated by a Wi-Fi router and a client device that operated in TDD mode. To estimate the worst case, no power control for the client device was considered. The characteristics that were used in the simulation are presented in Table 2, they can be found in Recommendation ITU-R M.1450.

TABLE II. Wi-Fi characteristics in the 5925-6425 MHz band

Parameter	**Value**
Frequency band	5925-6425 MHz
Channel bandwidth	20 MHz
Max EIRP	200 mW
Spectral EIRP	10 mW/MHz
Antenna pattern	Omnidirectional
Antenna height	1.5 m
TDD activity factor router/client device	80%/20%

The spectrum emission mask for the 20 MHz Wi-Fi channel is presented in Figure 4. This mask corresponds to the 802.11ax IEEE standard. 20 MHz channel is considered since it would be the worst-case scenario.

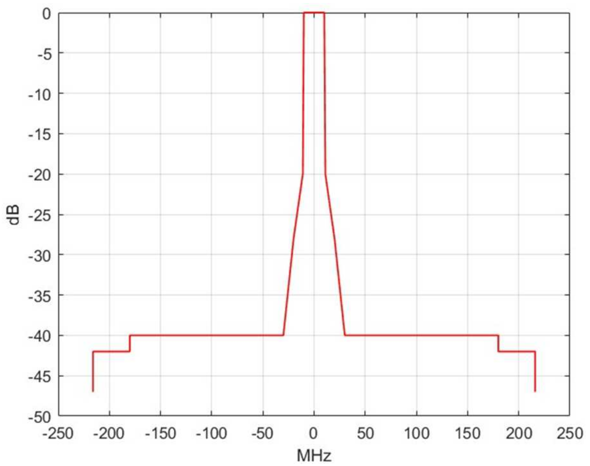

Fig. 4. Spectrum emission mask of the Wi-Fi transmitter

Both the router and client device use omnidirectional antenna since this type of antenna is the most typical for the Wi-Fi equipment.

III. Simulations Methodology

When analyzing interference from Wi-Fi to 5G NR, deterministic approaches are not suitable because of the stochastic nature of 5G NR networks where wanted links may vary depending on the beamforming factors, different building entry loss when the user equipment located indoors, and different indoor environment in every interference scenario with Wi-Fi. In order to analyze how Wi-Fi will affect 5G for the indoor scenario, a statistical approach should be used since that would allow doing calculations for all possible configurations with variations of indoor environment and 5G wanted link level fluctuations. In this study, for the simulations, the Monte-Carlo methodology was used where Wi-Fi equipment and 5G NR user equipment were randomly distributed within the indoor area of 400 m2 size. The base station of 5G NR was located in the outdoor area and the cell radius was 300 m, the building where Wi-Fi equipment and 5G NR user equipment were located was randomly distributed within the cell size of the 5G NR base station. Figure 5 presents a simulation of interference from Wi-Fi to the 5G UE and wanted link using an active antenna system with a beamforming technique in Visualyse Professional software. The number of simulation steps was 30 000, which is enough to consider possible deployment configurations within the indoor environment.

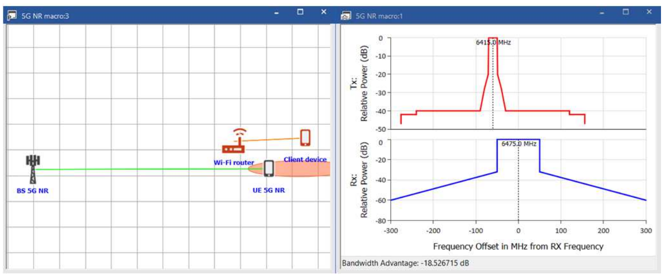

Fig. 5. Simulations of the interference from Wi-Fi to the 5G NR UE

In this study, the throughput loss of the 5G NR downlink was considered, and no throughput loss was considered for the 5G NR uplink since the interference to the outdoor base station from the Wi-Fi equipment will be negligible. Given that the wanted signal levels vary in every step of the simulation, to estimate the average throughput loss of the DL channel SINR operating range and mapping function was considered. The following equations approximate the throughput over a channel with a given SINR (dB), when using link adaptation [9]:

$$Throughput\,(SINR), bps/Hz = \begin{cases} 0 & for\ SINR < SINR_{MIN} \\ \alpha \cdot S(SINR) & for\ SINR_{MIN} \le SINR < SINR_{MAX} \\ \alpha \cdot S(SINR_{MAX}) & for\ SINR \ge SINR_{MAX} \end{cases}$$

where $S(SINR)$ is Shannon bound (bps/Hz); α is attenuation factor for modem implementations and link conditions, representing implementation losses; $SINR_{MIN}$ is minimum SINR of the code set (dB); $SINR_{MAX}$ is maximum SINR of the code set (dB). The parameters α, $SINR_{MIN}$ and $SINR_{MAX}$ can be chosen to represent different modem implementations and link conditions. The parameters proposed in Table 2 represent a baseline case, which assumes: 1:1 antenna configuration, AWGN channel model, and HARQ and link adaptation. Table 3 presents the value levels of α is attenuation factor and $SINR_{MIN}$ and $SINR_{MAX}$ values for different modulation and coding sets (MCS) the 5G NR link that are used to estimate a bitrate mapping function.

TABLE III. Parameters describing baseline Link Level performance for 5G NR

Parameter	DL	UL	Notes
α	0.6	0.4	Represents implementation losses
$SINR_{MIN}$, dB	−10	−10	QPSK, 1/8 rate (DL) & 1/5 rate (UL)
$SINR_{MAX}$, dB	30	22	256-QAM, 0.93 rate (DL) & 64-QAM, 0.93 rate (UL)

Based on the bitrate mapping presented above, channel throughput can be calculated using the following expression:

$$\text{Throughput}[Mbit/s] = \frac{N_{RB\_per\_UE}}{N_{total\_RBs}} \cdot S_{capacity}\,(SINR) \cdot B$$

where $N_{RB\_per\_UE}$ is the number of research block per user; N_{total_RBs} is the total number of resource blocks; B is the channel bandwidth of 5G NR (MHz); $S_{capacity}$ is the spectral efficiency depending on SINR (bps/Hz).

Given that the study deals with adjacent channel scenarios, to calculate the interference from Wi-Fi to the 5G NR user equipment frequency dependent rejection (FDR) which is a measure of the rejection produced by the receiver selectivity curve on an unwanted transmitter emission spectrum should be taken into account [11].

The interference level at the receiver is a function of the gains and losses the interference signal will incur between the source and the receiver and is expressed by:

$$I = EIRP_{WiFi} + G_{UE} - PL\,(d) - A_{body} - FDR\,(\Delta f)$$

where $EIRP_{WiFi}$ is the equivalent isotropic radiated power of the Wi-Fi transmitter (dBm); G_{UE} is the user equipment gain (dBi); PL (d) pathloss between a Wi-Fi transmitter and a 5G receiver (dB); A_{body} body loss of the 5G UE user (dB). The FDR (Δf) may be expressed with the following equation:

$$FDR(\Delta f) = 10 \log \frac{\int_0^\infty P(f) df}{\int_0^\infty P(f) |H(f+\Delta f)|^2 \, df}$$

To calculate PL (d) Recommendation ITU-R P.1791 was used. Indoor propagation characteristics are affected by reflection from and transmission through the building materials. The reflection and transmission characteristics of those materials depend on the complex permittivity of the materials. Site-specific propagation prediction models may need information on the complex permittivity of building materials and on building structures as basic input data.

The models described in this study are considered to be site-general as they require little path or site information. The distance power-loss coefficients given include an implicit allowance for transmission through walls and over and through obstacles, and for other loss mechanisms, like multipath, likely to be encountered in the Wi-Fi transmission. Site-specific models would have the option of explicitly accounting for the loss due to each obstacle instead of including it in the distance model [12]. The basic transmission loss $PL(d)$ experienced by Wi-Fi signals could be derived from the following model:

$$PL(d) = PL_0(d_0) + 10n \log\left(\frac{d}{d_0}\right) + X_\sigma$$

Where $PL_0(d_0)$ is the basic transmission loss (dB) at the reference distance d_0 (where d_0 is typically equal to 1 m), d is the separation distance (m) between the Wi-Fi transmitter and the receiver (where $d > 1$ m), n is the path-loss exponent, X_σ is the log-normal shadow fading, i.e. a zero mean Gaussian random variable with standard deviation σ (dB).

If the basic transmission loss at the reference distance can be approximated by:

$$PL_0(d_0) = 20 \log\left(\frac{4\pi d_0 \sqrt{f_1 \cdot f_2}}{0.3}\right)$$

where f_1 (GHz) and f_2 (GHz) are the frequencies at the −10 dB edges of the WiFi radiated spectrum.

The basic transmission loss will vary widely and will depend on how this variation interacts with the antenna characteristics of Wi-Fi and 5G NR. Typical parameters, for the basic transmission loss calculation are given in Table 4.

TABLE IV. PARAMETERS FOR THE BASIC TRANSMISSION LOSS CALCULATION

Environment	Path category	n	σ (dB)
Indoor residential	LoS	~ 1.7	1.5
	Soft-NLoS	3.5-5	2.7-4
	Hard-NLoS	~ 7	4
Indoor industrial	LoS	~ 1.5	0.3-4
	Soft-NLoS	2.1-4	0.19-4
	Hard-NLoS	4-7.5	4-4.75

This study considers only indoor residential since would be the most common interference scenario between 5G UEs and Wi-Fi equipment.

To calculate the propagation losses of the wanted link, Recommendation ITU-R P.2001 with 20% of the time was used [13]. To calculate additional building entry losses in the outdoor-indoor 5G link Recommendation ITU-R P.2109 was used with the traditional type of buildings and random percentage of locations were used [14]. This classification, of 'traditional', refers purely to the thermal efficiency of construction materials. No assumption should be made on the year of construction, type (single or multi-floors), heritage or building method. For the Hard-NLoS scenario a wall loss of 10 dB was considered since in this study, this scenario implies the room separation between a Wi-Fi transmitter and a 5G receiver.

IV. SIMULATION RESULTS

Given that Wi-Fi equipment in the study uses omnidirectional antenna patterns since it's the most common type of antenna for Wi-Fi routers and most of the client devices, it's possible to estimate the interference level around the Wi-Fi device in different types of the indoor environment. The results of such estimation are presented as an area analysis and the levels of interference in dBm are shown in different zones of the considered indoor environment. Figure 6 shows interference levels in the 400 m^2 indoor space where at every point of the room there are always LoS conditions between the Wi-Fi transmitter and the 5G NR receiver.

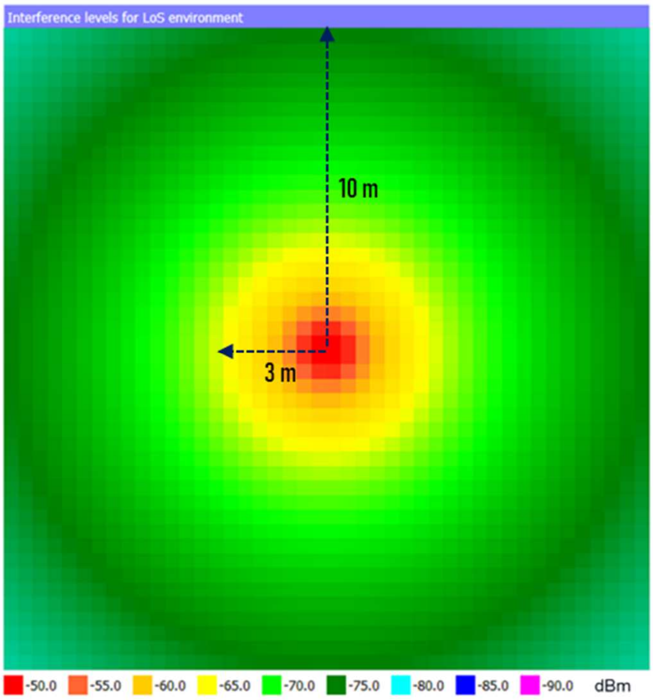

Fig. 6. Interference levels around Wi-Fi equipment in the LoS environment

As may be noted from the results for the LoS environment, in the close vicinity to the Wi-Fi router when the distance is less than 2-3 meters, the interference levels are more than -65 dBm. While for distances from 3 to 10 meters, the interference varies from -70 to -75 dBm. Figure 7 shows interference levels in the 400 m^2 indoor space where at every point of the room there are always Soft-NLoS conditions between the Wi-Fi transmitter and the 5G NR receiver.

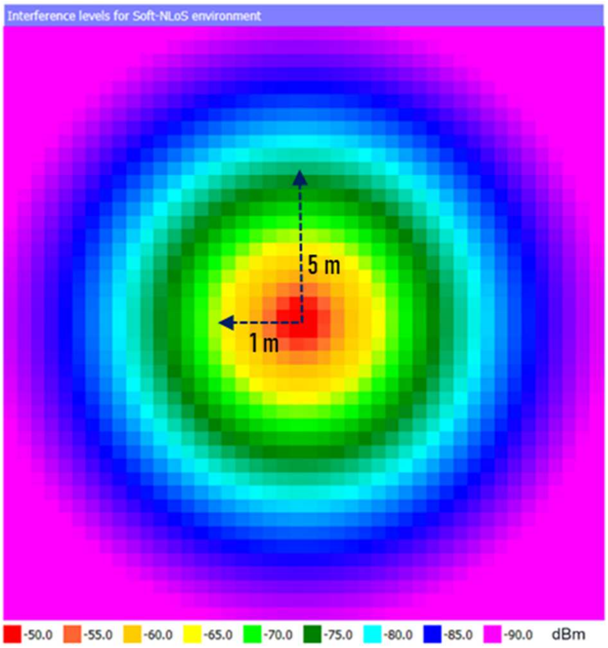

Fig. 7. Interference levels around Wi-Fi equipment in the Soft-NLoS environment

As may be noted from the results for the Soft-NLoS environment, when the distances from the Wi-Fi transmitter to the 5G NR receiver are less than 1-2 meters, the interference levels are from -50 to -55 dBm. For distances between 0.5-1 meters to 4-5 meters, the interference levels vary from -65 to -75 dBm. And for distances higher than 10 meters, the interference levels are from -80 dBm and lower. Figure 8 shows interference levels in the 400 m^2 indoor space where at every point of the room there are always Hard-NLoS conditions between the Wi-Fi transmitter and the 5G NR receiver.

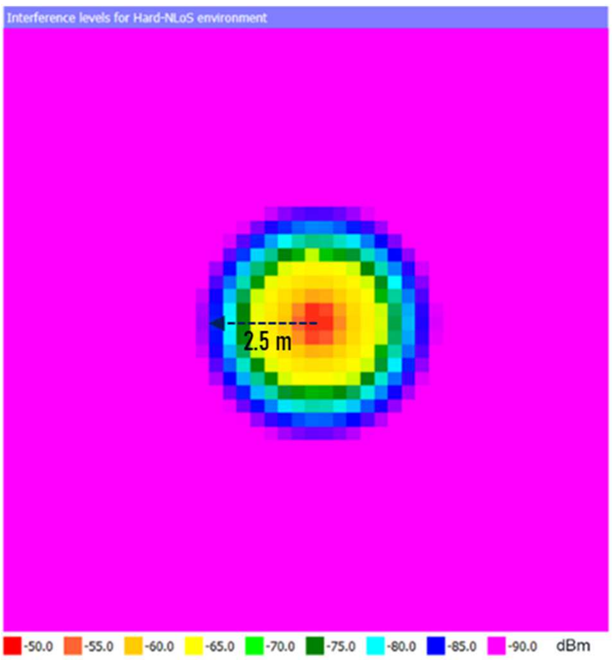

Fig. 8. Interference levels around Wi-Fi equipment in the Hard-NLoS environment

As may be noted, the Hard-NLoS scenario has the lowest interference levels. Only at distances between the Wi-Fi transmitter and 5G receiver from 2,5 meters and closer the interference levels exceed -90 dBm.

After the interference levels are calculated for each simulation step, the results are presented as 5G NR channel SINR degradations and throughput loss CDF curves for each indoor environment scenario. Figure 9 shows SINR degradation in the 5G NR downlink channel when interfered with by Wi-Fi in LoS, Soft-NLoS, and Hard-NLoS environments.

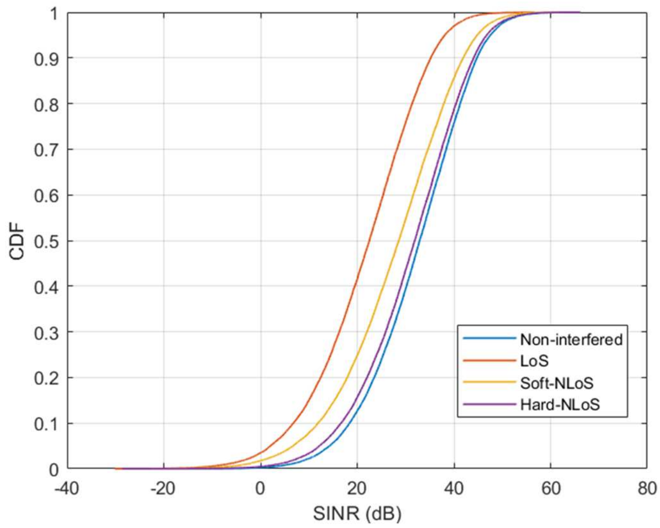

Fig. 9. SINR degradation of the 5G NR channel (DL) when interfered by Wi-Fi

The results show that for the LoS environment, the SINR degradation varies from 10 to 11 dB, for the Soft-NLoS the SINR degradation varies from 4 to 5 dB, and for Hard-NLoS the SINR degradation is around 1 dB. Figure 10 presents the throughput loss of the 5G NR downlink channel when interfered with by Wi-Fi in LoS, Soft-NLoS, and Hard-NLoS environments

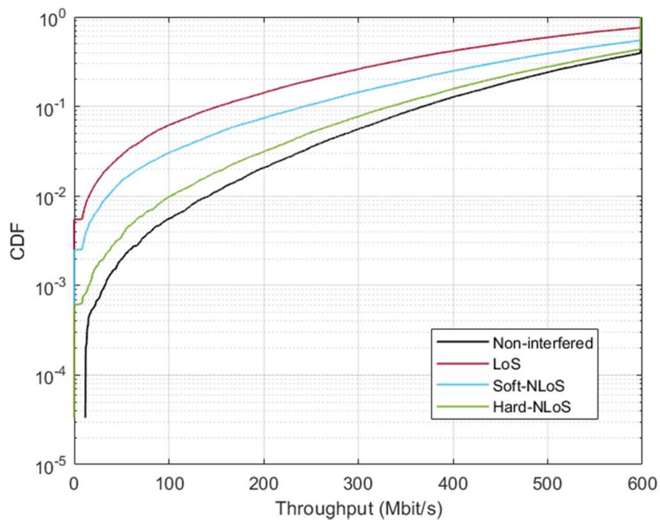

Fig. 10. Throughput loss of the 5G NR channel (DL) when interfered by Wi-Fi

To estimate the overall throughput loss, the average throughput was determined for the non-interfered, LoS, Soft-NLoS and Hard-NLoS scenarios. Then the average throughput for the LoS, Sof-NLoS and Hard-NLoS scenarios was compared with the average throughput for the non-interfered case. The results indicate that throughput loss of the 5G NR downlink channel is 22.48% for LoS conditions, 9.56% for Soft-NLoS, and 2.29% for Hard-NLoS.

V. Conclusions

Rolling out different broadband technologies with massive usage in the 6GHz band may lead to scenarios where the interference collisions between Wi-Fi and 5G NR may occur in the adjacent channel in the indoor environment where the distances between Wi-Fi transmitters and 5G NR receivers might be very short. Given the site-specific difference of the indoor environments, deterministic approaches of interference analysis are not applicable. Additionally, when performing channel degradation of 5G NR wanted link budget varies given that base stations implement active antenna systems where beamforming technology allows electronic steer of the antenna pattern. Therefore, only a statistical approach that analyses all possible location configurations and wanted link levels needs to be used.

The study performed simulations for several indoor scenarios, in particular for the scenarios when there is LoS and NLoS between the Wi-Fi transmitter and 5G NR receiver. The NLoS was also divided into two types where the first type was for the situations when there is only partial NLoS which was labeled as Soft-NLoS and for the situations where the was full NLoS which was labeled as Hard-NLoS. The results indicate that for the LoS conditions, there might be 10 dB SINR degradation which results in a 22.48% throughput loss of the 5G downlink channel. For the Soft-NLoS conditions, the SINR degradation is 5 dB which results in a 9.56% throughput loss of the 5G downlink channel. For the Hard-NLoS conditions, the SINR degradation is only 1 dB which results in a 2.29% throughput loss of the 5G downlink channel.

It should be noted that LoS conditions in an indoor environment between a Wi-Fi transmitter and a 5G receiver will occur very rarely and therefore will not affect the overall performance of 5G. On the contrary, Soft-NLoS and Hard-NLoS will be pretty common scenarios once 5G will be fully deployed in the 6425-7125 MHz band. While the Hard-NLoS scenario leads to minor throughput loss of the 5G downlink channel, the Soft-NLoS scenario leads to significant degradation of the 5G performance. One of the most possible solutions to avoid such interference would be creating a guard band between the edges of the 5925-6425 MHz and 6425-7125 MHz bands. However, the creation of guard bands in practice may result in a decrease in spectrum efficiency utilization. In this regard, it is likely that 5G operators will have to accept such throughput losses and take them into account when designing networks in accordance with the needs of users in various locations.

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