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RESEARCH ARTICLE

System-Level Performance Evaluation of 5G Use Cases for Industrial Scenarios

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ABSTRACT The Fifth Generation (5G) of mobile radio technologies represents a change of paradigm in mobile communications by serving not only users but also verticals. Given the increasing number of use cases identified for industrial scenarios, Third Generation Partnership Project (3GPP) defined a set of relevant use cases for Indoor Factory (InF) scenarios with their associated requirements and channel models to theoretically study signal propagation in these environments. In this context, this work first studies these InF scenarios by means of System-level Simulations (SLSs). By selecting the most demanding sub-scenario, we then carry out a performance evaluation of the specific 5G industrial use cases with the most stringent requirements, following 3GPP assumptions. Three use cases from the thirteen defined by the 5G Alliance for Connected Industries and Automation (5G-ACIA) have been carefully selected: massive wireless sensor networks, autonomous mobile robots, and augmented reality. The results demonstrate the fulfillment of the performance requirements in each use case, validating 5G as an enabler technology for future industry verticals.

INDEX TERMS 5G, industry 4.0, indoor factory, system-level simulations, KPI evaluation.

I. INTRODUCTION

The new generation of mobile communications (Fifth Generation (5G)) represents a change of paradigm in the way communications are conceived. While the Fourth Generation (4G)'s main focus was put on traditional communications, 5G has been designed to address the specific needs of the industry. 5G services have been classified into three main categories according to International Telecommunications Union (ITU) [1]: Enhanced Mobile Broadband (eMBB), Ultra-Reliable and Low Latency Communications (URLLC), and massive Machine Type Communications (mMTC). 5G is expected to deliver ambitious requirements such as low latency, massive device connectivity, or high network reliability [2]. Worldwide 5G deployments already started in 2020, with a first focus on human-centric use cases, i.e. eMBB services. URLLC and mMTC usage scenarios focus on Industrial Internet of Things (IIoT) applications, such as real-time communications with large amounts of data or periodic machinery monitoring processes. All these functions and specifications related to New Radio (NR) deployments can be found in Release (Rel) 15, 16, and 17 [3]. While Release (Rel)-15 focused on eMBB, Rel-16 and Rel-17 are centered on IIoT by introducing enhancements such as Time Sensitive Networks (TSN) to define the new era of connected factories.

Since there are no physical deployments for industrial scenarios, the ITU recommends theoretical studies on channel modeling. This can provide technical criteria for assessing and optimizing resources. For this purpose, the geometry-based stochastic model (GBSM) is ideal for geometrically complex scenarios, as the characterization of the channel is based on real scenarios by previously performed measurements. Thus, the channel parameters are practically predefined by the generation of stochastic distribution. Furthermore, the low computational cost of this

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model is the most widespread and widely used to evaluate mobile communication systems for various frequency bands.

Within the GBSM family, many channel models are currently available in the literature. For instance, the Third Generation Partnership Project (3GPP) TR 38.901 [4], QuaDRiGa channel model defined in [5], or those defined in European projects such as METIS [6], mmMAGIC [7], or WINNER [8]. The NYU wireless channel model [9] is another example. Even though these channel models support a wide range of scenarios (i.e. Urban Macro-cell (UMa), Urban Micro-cell (UMi), Rural Macro-cell (RMa) and Indoor Hotspot (InH)), only the 3GPP has introduced the study of the industrial scenarios in the standardization TR 38.901 version V16.0.0 [10] by request from the industry forum 5G Alliance for Connected Industries and Automation (5G-ACIA). This version includes new channel parameters categorized by their industrial interior geometric condition. Hence they have been classified into the following sub-scenarios: Indoor Factory-Sparse Low (InF-SL), Indoor Factory-Dense Low (InF-DL), Indoor Factory-Sparse High (InF-SH), Indoor Factory-Dense High (InF-DH), and Indoor Factory-High High (InF-HH). The latter has a 100% probability of Line of Sight (LoS) and has not been taken into account for this study.

In the literature, some contributions clarify the benefits of 5G for industrial verticals like in [11], where the customization of private networks is introduced as key for the industry. In [12] slicing and resource management are introduced as new features of 5G, and [13] shows the need of 5G and Mobile Edge Computing for enabling real-time collaboration. However, only few contributions considered studying the 3GPP channel model for industrial scenarios. In [14], a comprehensive survey of the standardization of the 3GPP Indoor Factory (InF) channel model is presented. The authors mainly analyze the channel characterization of all sub-scenarios by comparing them with the 3GPP InH channel model. In [15] an implementation and calibration of the InF channel model sub-scenarios is done for the system-level simulator ns-3. Although these contributions represent a first step towards the evaluation of the InF channel model, it is necessary to explore further aspects. This work provides a first study of the different InF sub-scenarios and specific industrial use cases not analyzed before, validating the InF channel model with real use cases. This will create a solid base for future studies in the industrial field. More concretely, the main contributions of this manuscript are: i) to introduce the first deep study of the new InF channel model, defined by the 3GPP ii) to clearly show how the different InF sub-scenarios, associated with different industrial conditions, impact in the Key Performance Indicators (KPIs) proposed by the 3GPP; iii) to validate the new InF channel model with the most stringent use cases from the set proposed by the 5G-ACIA for connected industries and automation. The evaluation of the instantaneous state in an industrial network, number of users, requirements, or Quality of Service (QoS) are system-level related factors not addressed in the literature so far. For this purpose, specific KPIs have been selected under technical criteria of system-level evaluation of the ITU guidelines [1].

In order to evaluate the use of industrial 5G networks in possible extreme conditions, three use cases are presented as the second topic of this project. These industrial use cases are addressed in TS 22.104 [16], which have been mainly influenced by the contributions of the 5G-ACIA [17]. The following three use cases have been selected to study whether the network performance meets the specific QoS of each factory automation process: massive wireless sensor networks (MWSN), autonomous mobile robots (AMR) and augmented reality (AR).

Both topics have been evaluated by means of System-level Simulations (SLSs) using the ns-3 [18] simulation tool. This simulator is one of the most popular open-source software within the research community, where several scenarios of the 3GPP channel model are implemented, including InF. The integration of the industrial channel model into the ns-3 simulator and the calibration, as mentioned above in [15], was published by the authors of this work. Thus, this work already has a precedent in evaluating industrial scenarios, and this paper would be the second step in our research on industries and verticals.

The rest of this article is organized as follows. Section II provides an overview of the 3GPP channel model standardization for InF, taking into account the environmental characteristic of IIoT scenarios. An analysis on the impact in channel modeling of each InF sub-scenario is also presented. Section III presents the evaluation methodology, the use cases, and KPI definitions. Section IV describes the SLSs results obtained, which in turn are compared against the requirements defined for their validation. Finally, conclusions of the work are described in Section V.

II. INDUSTRIAL CHANNEL MODEL OVERVIEW

In 2017, in the Release 14, 3GPP only included under the TR 38.901/ITU [19] framework the InH channel model as the only consideration for indoor scenarios. The InH channel model represents an office environment, classified into Indoor Mixed Office, oriented to cubicle areas, walled offices and corridors; and Indoor Open Office, mainly composed of more open spaces. However, the InH channel model cannot support the novel features required for industrial environments with large number of machines and metal structures that affect the propagation.

These new characteristics introduced the need for a new channel model: InF. 3GPP defined the specifications of the InF channel model in the Release 15 version of the TR 38.901 [20].

At the 3GPP Technical Specification Group (TSG) of Radio Access Network (RAN) #81 [21] meeting, a new study item was identified to develop an industrial channel model, as a request of the 5G-ACIA industry forum. This standardization process was carried out by 3GPP RAN working group 1 (RAN1) [22], which is the technical body in charge of the physical layer specification. In November 2018, the RAN1

TABLE 1. Indoor factory - evaluation parameters [10].

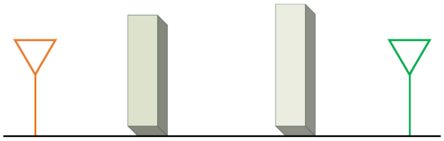
	Parameters	Indoor Factory Sub-scenarios				
		InF-SL	InF-DL	InF-SH	InF-DH	InF-HH
Layout	Room size	Rectangular: 20-160000 m^2				
	Ceiling height	5-25 m	5-15 m	5-25 m	5-15 m	5-25 m
	Effective clutter height	<Ceiling height, 0-10 m				
Test environment	Distance typical clutter size	10 m	2 m	10 m	2 m	Any
	Clutter density	$\leq$ 40 %	$\geq$ 40%	$\leq$ 40%	$\geq$ 40%	Any
	BS	Below clutter		Above clutter		Above clutter
	UE condition	LOS and NLOS				100% LOS
	UE height	Below clutter				Above clutter

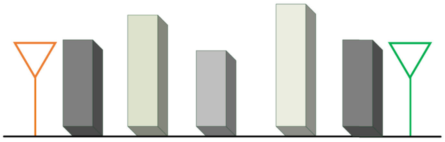
began the discussion at RAN1 #95 meeting for modeling the features that need to be modified. During 2019, at the RAN #96, #96b and #97 meetings, the electromagnetic interference and network layout, frequency bands, and reclassification for each sub-scenario of the measurement results were established, respectively. Finally, the channel model of the InF scenarios was fully established at the RAN #98 meetings and delivered in 3GPP TR 38.901 (v16.0.0, Release-16) [10]. All changes in the aforementioned version are mainly oriented to the InF channel model, in comparison to the predecessor version (Release-15) [23]. These modifications include new features in terms of the scenario description, the pathloss model, and the LoS probability model, among others. Some of these changes are described in the following subsections.

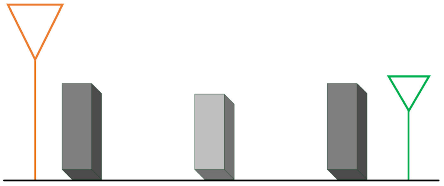
A. INDOOR FACTORY SCENARIO DESCRIPTION

An industrial scenario commonly includes warehouses, manufacturing plants, assembly halls, or production areas, where the signal propagation of any wireless communication channel is affected by its frequency fading, caused by specular reflections from metallic structures, or simply by machine and human obstruction. Therefore, for modeling the InF channel, the first aspect to consider is the detailed characteristics of the target scenario. For this purpose, the 3GPP recommends four Non Line of Sight (NLoS) sub-scenarios and only one LoS sub-scenario.

Table 1 describes in detail the parameters considered for modeling the network layout and geometry. The table provides details about key parameters such as the ceiling height or room size. The clutter height is also included, defined as the average height of the set of objects placed in the environment. Antenna height and clutter density are the main criteria for the classification of the four NLoS sub-scenarios. As illustrated in Figure 1, the InF-SH and InF-DH sub-scenarios have the antennas Base Station (BS) above the clutter height, while the InF-SL and InF-DL have them below the clutter. In addition, the clutter density parameter can vary according to the values in Table 1, referring to the quantity of machinery and other objects in the room. In Figure 1, the InF-SH and InF-SL sub-scenarios have a sparse clutter (i.e. less and more spread clutter), while the InF-DH and InF-DL sub-scenarios have a dense clutter (i.e. more and more dense clutter). For a more particular evaluation, Table 2 defines the specific parameters that have been considered to obtain the SLS results, that are within the ranges suggested by the 3GPP and shown in Table 1.


(a) InF-Sparse Low


(b) InF-Dense Low


(c) InF-Sparse High

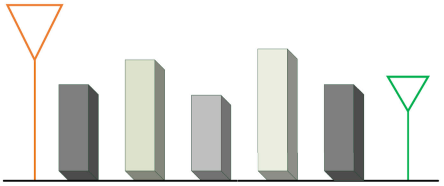

(d) InF-Dense High

FIGURE 1. NLoS sub-scenarios for InF channel model.

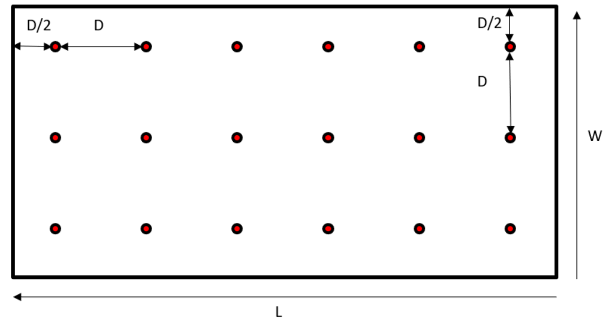
B. IMPACT OF THE ENVIRONMENT ON THE INDUSTRIAL CHANNEL MODEL

The aforementioned environmental description directly affects the pathloss and LoS probability models within the channel modeling procedure. 3GPP introduced new suitable adjustments to each InF sub-scenario, whose characteristics are analyzed as follows.

1) LoS PROBABILITY

The LoS probability determines whether receiver (Rx) nodes positions are in LoS or NLoS conditions at a given distance. Consequently, either of these selected propagation conditions will define the channel state that will later be an important

TABLE 2. **Indoor factory simulation assumptions.**

Parameter	Values
gNodeB (gNB) Deployment	
Room size	Small-hall → L = 120 m, W = 60 m (D = 20 m) Big-hall → L = 300 m, W = 150 m (D = 50 m)
Ceiling height	10 m
UE height	1.5 m
gNB height	Low sub-scenarios: 1.5 m High sub-scenarios: 8 m
UE attachment	Based on Path Loss (PL)
Carrier frequency	3.5 GHz and 30 GHz
Bandwidth	100 MHz and 400 MHz
Numerology	1 and 3
Clutter density	Low clutter density: 20% High clutter density 60%
Clutter height	Low clutter density: 2 m High clutter density: 6 m
Clutter size	Low clutter density: 10 m High clutter density: 2 m

input for the generation of the large scale parameters (LSP) and small scale parameters (SSP). Hence, the 3GPP [10] has recommended the probability function adapted for each NLoS sub-scenario as shown in (1).

$$\Pr_{LOS,subsce}(d_{2D}) = e^{-\left(\frac{d_{2D}}{k_{subsce}}\right)} \tag{1}$$

where, k_{subsce} is a constant determined for each NLoS sub-scenario, defined in (2), and d_{2D} is the 2D-distance between User Equipment (UE) and BS.

$$k_{subsce} = \begin{cases} -\dfrac{d_{clutter}}{\ln(1-r)} & \text{for InF-SL, InF-DL} \\ -\dfrac{d_{clutter}}{\ln(1-r)}\,\dfrac{h_{BS}-h_{UE}}{h_c-h_{UE}} & \text{for InF-SH, InF-DH.} \end{cases} \tag{2}$$

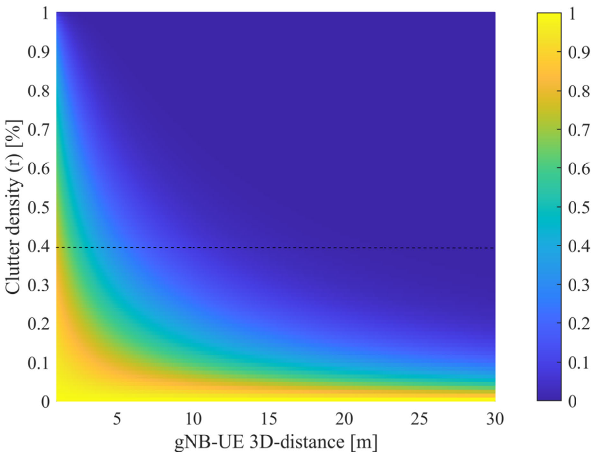
where $d_{clutter}$ is distance typical clutter size, r is clutter density, h_c is effective clutter height, h_{BS} is gNB height and h_{UE} is UE height. Note that the distance typical clutter size ($d_{clutter}$), clutter density (r) and effective clutter height (h_c) for each sub-scenario are detailed in Table 1. The distance typical clutter size and the clutter density values defined by the 3GPP are 10 m and $\leq$ 40% for sparse sub-scenarios and 2 m and $\geq$ 40% for dense sub-scenarios, respectively, while the effective clutter height is any value under the room ceiling for all sub-scenarios.

For a better understanding, Figure 2 illustrates the value of the probability function in (1) according to the clutter density (r) and the 3D-distance between the gNB and UE. The LoS probability is represented by the range 0 to 1, where yellow is the lowest probability and blue is the highest. Note that, according to 3GPP specifications in Table 1, the part above the 0.4 of clutter density in Figure 2 correspond to dense scenarios (InF-DL and InF-DH), while the part below 0.4 correspond to sparse scenarios (InF-SL and InF-SH). In Figure 2, it can be seen how the LoS probability decreases if the distance between the BS and UE or the clutter density increases, as the Equation (1) describes. Moreover, comparing sub-figures 2a and 2b, the sub-scenarios with higher antennas (InF-SH and InF-DH) have clearly higher LoS probability than the ones with lower antennas (InF-SL and InF-DL).

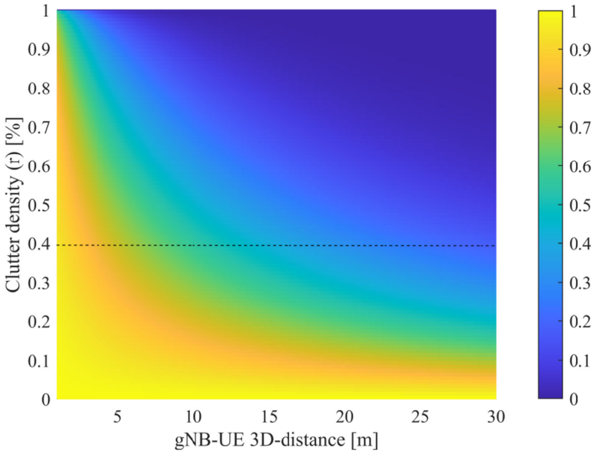
2) PATHLOSS

According to the conventional diagram of the 3GPP channel modeling procedure (Figure 7.5-1 in TR 38.901 [10]), the next step is the pathloss calculation. In general, pathloss is the attenuation of electromagnetic waves propagating through space. Nervelessness, the industrial scenarios are more complex than others due to the multiple propagation components resulting from the high reflection, diffraction or absorption caused by metallic structures, walls or machinery.

To calculate the pathloss it is necessary to previously know the channel condition since the 3GPP [10] has proposed different pathloss models for LoS and NLoS conditions. There is a single model for LoS condition (3), while there



(a) InF-SH and InF-DH



(b) InF-SL and InF-DL

FIGURE 2. **LoS Probability by varing the k_{subsce} according to (2).**

are different models for NLoS condition depending on the subscenario used: InF-SL (4), InF-DL (5), InF-SH (6), and InF-DH (7).

$$\mathrm{PL} = 31.84 + 21.50 \log_{10}(d_{3D}) + 19 \log_{10}(f_c) \tag{3}$$

$$\mathrm{PL} = 33.00 + 25.50 \log_{10}(d_{3D}) + 20 \log_{10}(f_c) \tag{4}$$

$$\mathrm{PL} = 18.6 + 35.70 \log_{10}(d_{3D}) + 20 \log_{10}(f_c) \tag{5}$$

$$\mathrm{PL} = 32.40 + 23.00 \log_{10}(d_{3D}) + 20 \log_{10}(f_c) \tag{6}$$

$$\mathrm{PL} = 33.63 + 21.9 \log_{10}(d_{3D}) + 20 \log_{10}(f_c) \tag{7}$$

where d_{3D} is the 3D distance between the transmitter (Tx) and Rx in meters and fc denotes the center frequency in GHz.

Figure 3 shows the average pathloss considering several simulation seeds for each sub-scenario for distances from 0 to 60 meters, considering the high-band frequency of 30 GHz, defined in the simulation parameters from Table 2. The impact of LoS probability on the pathloss behavior at some 3D-distance can be reflected, with InF-DL being the worst case and InF-SH being the best case. It could be concluded that the percentage of clutter density and the height of the antennas play an essential role in the channel conditions, as 3D-distance increases, the pathloss levels worsen significantly. Therefore, the pathloss models recommended by 3GPP are considered reasonable, since they may represent what the propagation signal mainly suffers in each InF sub-scenario.

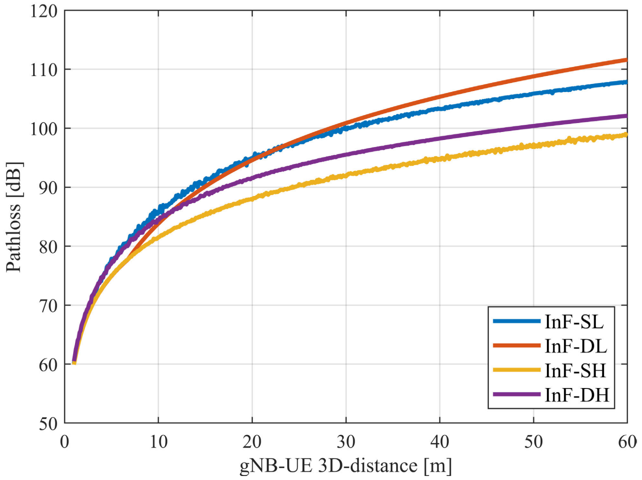


FIGURE 3. **Pathloss Model performance for each InF sub-scenarios.**

III. EVALUATION METHODOLOGY

Three use cases are defined in this manuscript from a wide set originally presented in the guidelines of 5G-ACIA [17]. The use cases were carefully selected for a complete representation of the 5G most restrictive use cases for eMBB, URLLC and mMTC. The assumptions for the use cases were extracted from 3GPP TS 22.104 [16]. A massive simulation campaign with multiple seeds was carried out for achieving a complete and comprehensive analysis. From all these results, this work summarizes and highlights the effect of the key parameters that depend on the industrial specific use case under study, e.g. user speed, packet size or frequency band. Hence, the impact of this parameters is compared against the four KPIs that represent the cornerstone of our study: latency, throughput, availability and connection density. In the following paragraphs, we discuss the use cases considered, their KPIs, the main simulation assumptions and methodology.

A. KEY PERFORMANCE INDICATORS

In this evaluation study a total of four KPIs were selected for the evaluation: latency, throughput, availability and connection density. The KPIs objective values are set in [16]. These four KPIs are defined as follows, according to [24]:

1) LATENCY

User plane latency (latency, from now on) is the contribution of the radio network to the time from when the source sends a packet to when the destination receives it (in ms). It is defined as the one-way time it takes to successfully deliver an application layer packet/message.

TABLE 3. Use case requirements.

	Massive wireless sensors networks	Mobile robots	Augmented reality
Message size	20 bytes	40 to 250 bytes	15 to 250 kbytes
Mobility	0 km/h	$\leq$ 50 km/h	$\leq$ 50 km/h
Transfer interval	100 ms to 60 s	40 to 500 ms	10 to 100 ms
Latency	$<$ 100 ms	1 to 50 ms	10 to 100 ms
Throughput	$\leq$ 1.6 kbps	0.64-50 kbps	1.2-200 Mbps
Availability	99.99%	99.9999%	99.9%
Connection density	$\leq 1\mathrm{MUEs/km^2}$	$\leq 2.000\mathrm{UEs/km^2}$	$\leq 2.000\mathrm{UEs/km^2}$

2) THROUGHPUT

The throughput, also known as data rate, is defined as the number of bits sent during a specific period of time. It is commonly measured as bits per second.

3) RELIABILITY

Reliability is calculated as the percentage of packets that successfully arrive at the destination within a time margin over the total sent packets. Note that, although the KPI defined in the use cases in [16] is availability, reliability will be considered for this manuscript as reliability is related to the network, while availability includes the end-to-end application which is out of the scope of this work. In Table 5.1-1 [16] the relation of reliability and availability is described assuming that the survival time is equal to the transfer interval for a specific application. Assuming this, the availability can be calculated from the reliability as indicated in Equation (8).

$$\text{availability} = \text{reliability} \times (1 + (1 - \text{reliability})) \qquad (8)$$

4) CONNECTION DENSITY

This KPI stands for the number of UEs connected to the network per square kilometer with a certain QoS. Depending on the physical dimensions of the scenario, the number of UEs simulated needs to be different to maintain the same density.

B. USE CASES

5G-ACIA defines 13 industrial use cases, as shown in Figure 4 [17]. The selected use cases for the evaluation represent the three most stringent and representative 5G use cases of the three families: eMBB, URLLC and mMTC. We selected augmented reality for eMBB, autonomous mobile robots for URLLC and massive wireless sensor networks for mMTC, highlighted in Figure 4 and described in the following subsections. The use cases will be evaluated with the KPIs defined in the last section, comparing them with the goal values to validate if the objectives are achieved.

1) AUGMENTED REALITY

The AR use case evaluates a communication for a video-operated robot, defined as "Use Case 2" in Table A.2.2.3 in TS 22.104 [16]. The most critical KPI is the data rate needed for a fluid and immersive video-operation. Also an optimum latency is key for a real-time experience. All KPIs explored in this use case are gathered in Table 3. Note that in this particular case, the message size must be between 15 kbytes and 250 kbytes, the transfer interval between packets from 10 ms to 100 ms, with UEs speeds lower than 50 km/h.

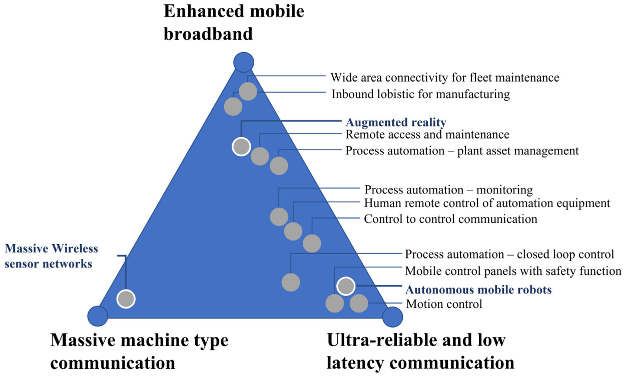


FIGURE 4. Representation of the 13 use cases defined in 5G-ACIA [17].

2) AUTONOMOUS MOBILE ROBOTS

The AMR use case is about periodic communications for the support of precise cooperative robotic motion control, machine control and cooperative driving, defined as "Use Case 1" in Table A.2.2.3 in TS 22.104 [16]. The most critical KPI is the latency required for a efficient cooperation between the robots. All KPIs are shown in Table 3. The message size here must be between 40 bytes and 250 bytes, the transfer interval between 40 ms and 500 ms, with UEs speeds lower than 50 km/h.

3) MASSIVE WIRELESS SENSOR NETWORKS

The MWSN use case consists of sensors generating periodic measurements of values like temperature or pressure, defined as "Use Case 1" in Table A.2.3.2 in TS 22.104 [16]. The most critical KPI for this use case is, therefore, the device connection density. The rest of KPIs are summarized in Table 3. The message size must be 20 bytes, the transfer interval between 100 ms and 60 s, and there is no specific requirement for use speed, so we keep it to 0 km/h.

C. SIMULATION ASSUMPTIONS

The parameters introduced in the simulator are shown in Table 2, extracted from Table 7.8-7 of 3GPP TR 38.901 [10].

Frequency band, bandwidth and numerology were treated as a unique block, considering two combinations: mid-band (carrier frequency = 3.5 GHz, bandwidth = 100 MHz, numerology = 1) and high-band (carrier frequency = 30 GHz, bandwidth = 400 MHz, numerology = 3). For mid-band, the values were extracted from Table 7.8-7 of 3GPP TR 38.901 [10], while in the case of high-band the frequency has been selected as an intermediate value from the available range (24-40 GHz) [25]. The selected bandwidth is the highest from the available ones (50, 100, 400 MHz), following the recommendation in [10] for mid-band, where 100 MHz is selected for this frequency. For the numerologies, the most typical from both frequency ranges were selected [26].

Two layouts have been selected for the evaluation also defined in the Table 7.8-7 in TR 38.901 [10]. The layouts are called big-hall and small-hall, technically defined in Table 2. They were selected assuming that the AMR use case requires a layout with a larger area due to its nature (UEs moving), while MWSN and AR use cases do not. Both Uplink (UL) and Downlink (DL) have been evaluated, although the UL is the dominant link studied, as industrial use cases usually rely on UL transmissions to send data to the network, and not the other way around. Note that a high volume of data has been gathered resulting from the simulation campaign, but just a selection will be shown in the results section. Nevertheless, the conclusions are based on all the available data.

IV. SIMULATION RESULTS

A. INDUSTRIAL CHANNEL MODEL COMPARISON

This section presents the evaluation of the four InF channel models in the big-hall and small-hall scenarios for high-band and mid-band. As shown in Section II, each InF model is related to an industrial environment that has different physical characteristics, e.g. clutter density or clutter height, and is also related to the height of gNB antenna with respect to the clutters height. As for the environment characteristics, both big-hall and small-hall are different in the room sizes and the separation between the gNBs, which are 20 and 50 meters, respectively, as shown in Table 2.

The purpose of this section is first to assess the impact on the latency of the physical dimensions of the room and the separation between gNB (big-hall and small-hall); and second to determine how the channel models affect three relevant KPIs such as latency, throughput and reliability. For this evaluation, the augmented reality use case described in Table 3 has been chosen and in order to isolate the impact of the channel model from other variables such as lack of resources, number of users, scheduling, bandwidth and others, the simulations have been performed with a single user at random positions.

Figure 5 shows the results for the high-band big-hall scenario with a symmetric TDD pattern, a packet size of 15 kbytes and a transfer interval of 10 ms. On the one hand, there is a cloud of points corresponding to the data obtained from each seed and the solid line represents the mean. It can be observed that the latency has similar values up to about 15 meters for the four channel models and for longer distances the latency is affected to a larger extent for the InF-DL channel model. One explanation for this behaviour is that the LoS probability and the propagation model is directly related to the distance between the user and the gNB, as has been shown in section II. The fact that the InF-DL sub-scenario is the worst case is due to the higher clutter density that negatively impacts on the propagation, and the lower position of the gNB, what lowers the LoS probability. Similarly, Figure 6 shows the results for the mid-band small-hall scenario. It can be observed that the latency values are similar for each sub-scenario, being slightly worse for the InF-DL, InF-SL (almost the same position as InF-DL) and InF-DH channel models. With these two figures we can notice that the latency is affected more in big-hall scenario than in small-hall due to the difference in separation between gNBs. Therefore, it is justified that in order to improve the KPIs it is necessary to have gNBs more closely spaced.

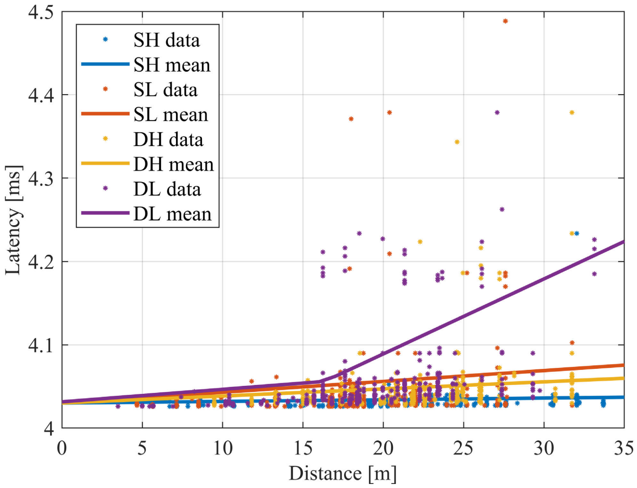


FIGURE 5. Latency vs. distance for big-hall layout.

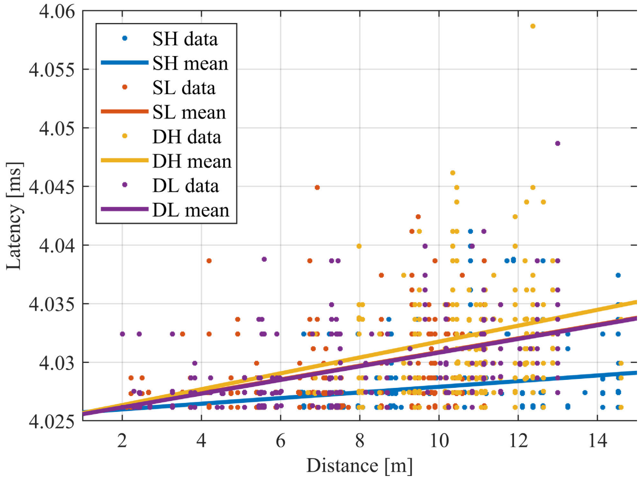


FIGURE 6. Latency vs. distance for small-hall layout.

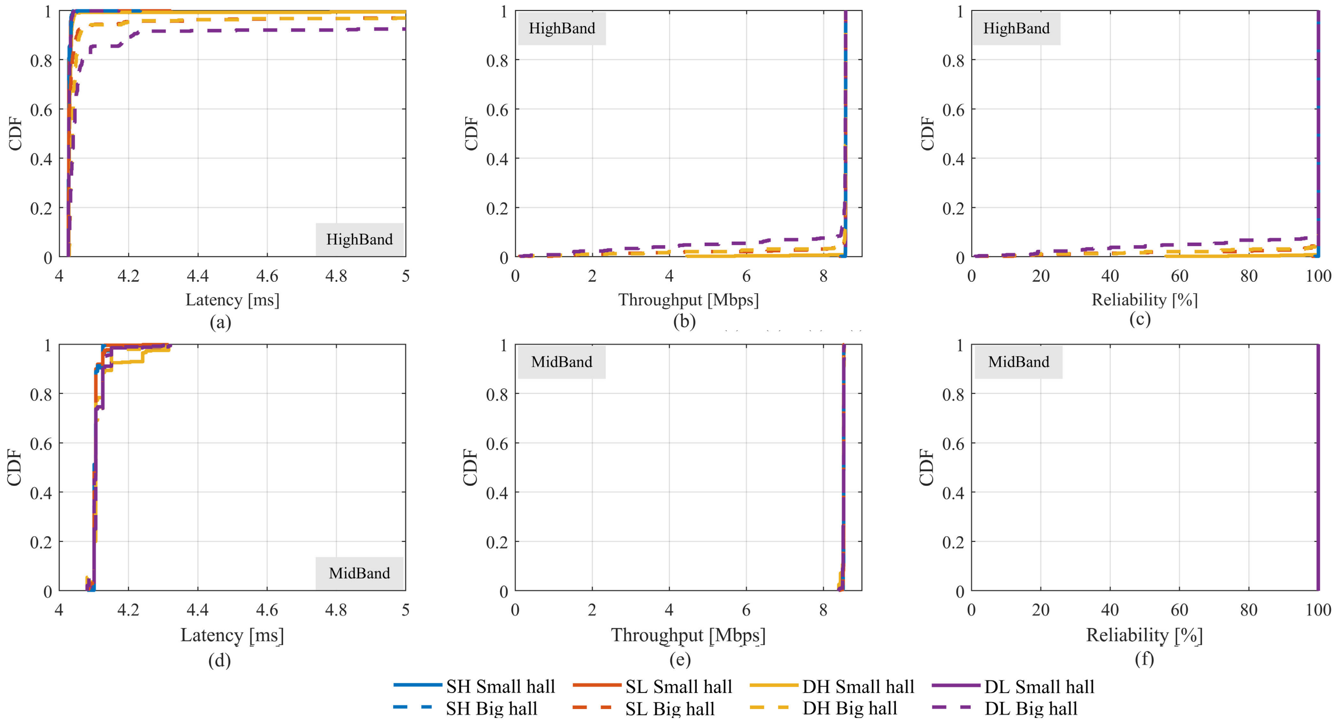
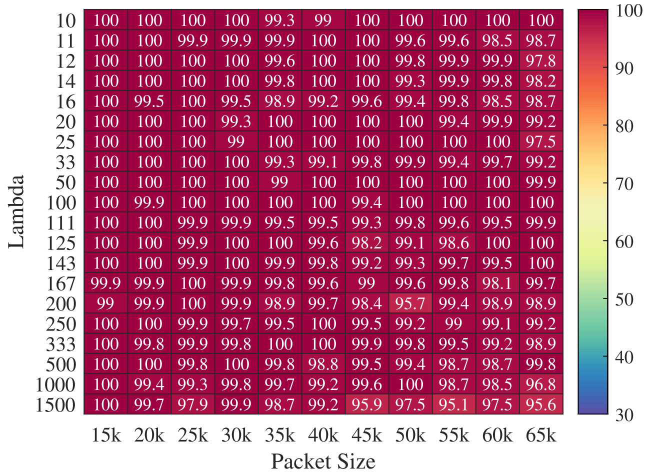
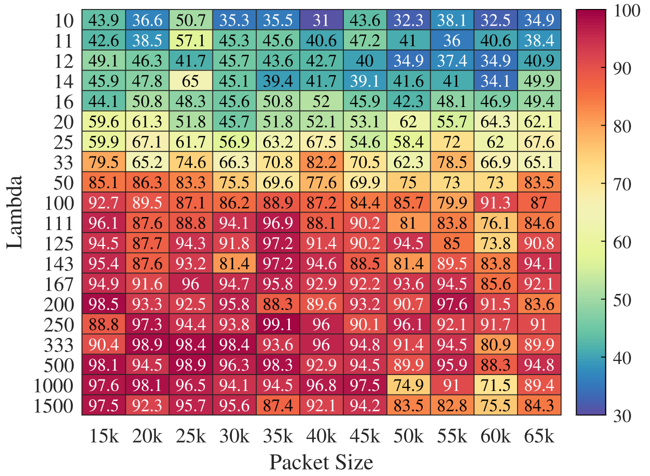


FIGURE 7. Cumulative distribution function of the KPIs for different bands (mid-band and high-band) and layouts (small-hall and big-hall).



	15k	20k	25k	30k	35k	40k	45k	50k	55k	60k	65k
10	100	100	100	100	99.3	99	100	100	100	100	100
11	100	100	99.9	99.9	99.9	100	100	99.6	99.6	98.5	98.7
12	100	100	100	100	99.6	100	100	99.8	99.9	99.9	97.8
14	100	100	100	100	99.8	100	100	99.3	99.9	99.8	98.2
16	100	99.5	100	99.5	98.9	99.2	99.6	99.4	99.8	98.5	98.7
20	100	100	100	99.3	100	100	100	100	99.4	99.9	99.2
25	100	100	100	99	100	100	100	100	100	100	97.5
33	100	100	100	100	99.3	99.1	99.8	99.9	99.4	99.7	99.2
50	100	100	100	100	99	100	100	100	100	100	99.9
100	100	99.9	100	100	100	100	99.4	100	100	100	100
111	100	100	99.9	99.9	99.5	99.5	99.3	99.8	99.6	99.5	99.9
125	100	100	99.9	100	100	99.6	98.2	99.1	98.6	100	100
143	100	100	99.9	100	99.9	99.8	99.2	99.3	99.7	99.5	100
167	99.9	99.9	100	99.9	99.8	99.6	99	99.6	99.8	98.1	99.7
200	99	99.9	100	99.9	98.9	99.7	98.4	95.7	99.4	98.9	98.9
250	100	100	99.9	99.7	99.5	100	99.5	99.2	99	99.1	99.2
333	100	99.8	99.9	99.8	100	100	99.9	99.8	99.5	99.2	98.9
500	100	100	99.8	100	99.8	98.8	99.5	99.4	98.7	98.7	99.8
1000	100	99.4	99.3	99.8	99.7	99.2	99.6	100	98.7	98.5	96.8
1500	100	99.7	97.9	99.9	98.7	99.2	95.9	97.5	95.1	97.5	95.6

FIGURE 8. Reliability for different lambda and packet size combinations at 0 km/h in AR use case.



	15k	20k	25k	30k	35k	40k	45k	50k	55k	60k	65k
10	43.9	36.6	50.7	35.3	35.5	31	43.6	32.3	38.1	32.5	34.9
11	42.6	38.5	57.1	45.3	45.6	40.6	47.2	41	36	40.6	38.4
12	49.1	46.3	41.7	45.7	43.6	42.7	40	34.9	37.4	34.9	40.9
14	45.9	47.8	65	45.1	39.4	41.7	39.1	41.6	41	34.1	49.9
16	44.1	50.8	48.3	45.6	50.8	52	45.9	42.3	48.1	46.9	49.4
20	59.6	61.3	51.8	45.7	51.8	52.1	53.1	62	55.7	64.3	62.1
25	59.9	67.1	61.7	56.9	63.2	67.5	54.6	58.4	72	62	67.6
33	79.5	65.2	74.6	66.3	70.8	82.2	70.5	62.3	78.5	66.9	65.1
50	85.1	86.3	83.3	75.5	69.6	77.6	69.9	75	73	73	83.5
100	92.7	89.5	87.1	86.2	88.9	87.2	84.4	85.7	79.9	91.3	87
111	96.1	87.6	88.8	94.1	96.9	88.1	90.2	81	83.8	76.1	84.6
125	94.5	87.7	94.3	91.8	97.2	91.4	90.2	94.5	85	73.8	90.8
143	95.4	87.6	93.2	81.4	97.2	94.6	88.5	81.4	89.5	83.8	94.1
167	94.9	91.6	96	94.7	95.8	92.9	92.2	93.6	94.5	85.6	92.1
200	98.5	93.3	92.5	95.8	88.3	89.6	93.2	90.7	97.6	91.5	83.6
250	88.8	97.3	94.4	93.8	99.1	96	90.1	96.1	92.1	91.7	91
333	90.4	98.9	98.4	98.4	93.6	96	94.8	91.4	94.5	80.9	89.9
500	98.1	94.5	98.9	96.3	98.3	92.9	94.5	89.9	95.9	88.3	94.8
1000	97.6	98.1	96.5	94.1	94.5	96.8	97.5	74.9	91	71.5	89.4
1500	97.5	92.3	95.7	95.6	87.4	92.1	94.2	83.5	82.8	75.5	84.3

FIGURE 9. Reliability for different lambda and packet size combinations at 50 km/h in AR use case.

Figure 7 shows the Cumulative Distribution Function (CDF) of latency, throughput, and reliability for the high-band and mid-band for both small-hall and big-hall scenarios. It can be observed that for mid-band (Figure 7(d),(e) and (f)) the evaluated KPIs present similar values for the four channel models. On the other hand, for high-band (Figure 7(a),(b) and (c)), it can be noted that the KPIs are affected from a greater to a lesser extent for InF-DL, InF-DH, InF-SL and InF-SH, in that order. For big-hall (dashed curves), the curves are more separate than in small-hall as the average distance between UEs and gNBs is higher. In mid-band, the results are similar for both small-hall and big-hall layouts, while in high-band the difference between the two scenarios is more noticeable because of the higher loss for this frequency band, which has a negative impact for longer distances introduced in big-hall.

B. PERFORMANCE ANALYSIS OF 5G INDUSTRIAL USE CASES

This section presents the results and the main findings of the industrial use cases analysis using the InF-DL channel model, which has been demonstrated to be the most restrictive one. Firstly, an analysis of the packet size and the transfer interval is used to select the optimum combination of these

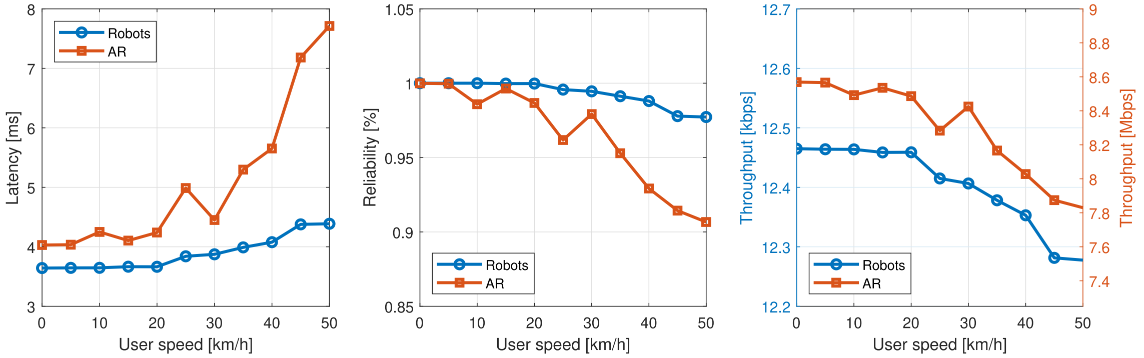


FIGURE 10. Effect of the user speed in the latency, reliability and throughput.

parameters. Once these values are selected, the KPIs are studied for each use case in a deeper way through three different evaluations, i.e., impact of the mobility, impact of different connection densities, and UL/DL analysis.

1) PACKET SIZE AND LAMBDA SELECTION

As mentioned before, it is first necessary to select a combination of packet size and transfer interval that will be used in the following studies. Instead of transfer interval, lambda will be employed in this section for simplicity. Note that lambda stands for the inverse of the transfer interval, defined as the number of packets sent per second. As defined in the use cases and shown in Table 3, the packet size and transfer interval can be selected from a specific range. This range is wider and with higher values for AR use case, as it is the use case with more stringent throughput requirements. For this reason, we selected this use case for showing the procedure for selecting these values. The other two use cases follow a similar procedure, but for the sake of simplicity, we will just simply show the results.

The simulations for AR use case were run with lambdas (λ) from 10 to 1500, corresponding to transfer intervals from 100 to 10 ms and an extra range from 10 ms to 0.67 ms, and with packet sizes (ps) from 15 to 65 kbytes. Note that the extra range is not in the Table 3, but will be also simulated to study the behaviour beyond this limits. Due to simulator constraints, the packet size selected is not higher than 65 kbytes. These combinations make a total of 220 possible combinations. Moreover, this process was repeated for the two extreme mobility scenarios, i.e. 0 km/h and 50 km/h, resulting in 440 results. The results can be seen in the two heatmaps shown in Figures 8 (0 km/h) and 9 (50 km/h), showing the reliability values for each combination.

When there is no mobility, almost all lambda-packet size combinations are above 99% of reliability. However, when the UE is moving at 50 km/h, the reliability drops radically. The optimum values in this case correspond to high lambda values and small packet sizes. With these results, the selected combination was $\lambda = 100$ and packet size $= 15$ kbytes, which has the best results while satisfying the throughput requirement and the use case ranges from Table 3. The latency behaves in a similar way, achieving better values for higher lambdas. The values for the optimum combination of lambda and packet size are 4.03 and 6.74 ms for 0 km/h and 50 km/h, respectively. The selected values for the other two use cases are $\lambda = 10$ and $ps = 20$ for MWSN and $\lambda = 25$ and $ps = 40$ for AMR, as it was demonstrated to be the most optimal ones.

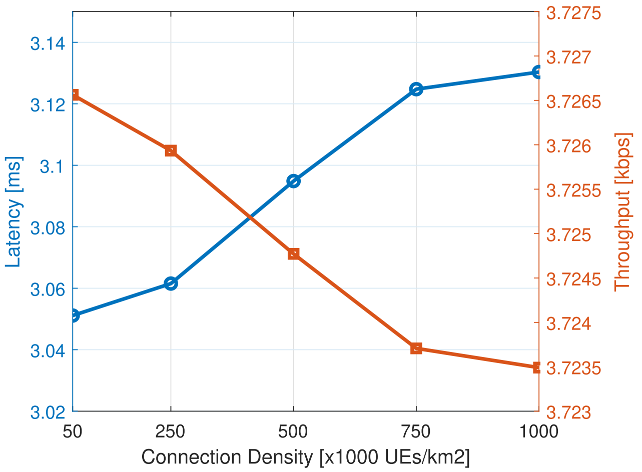


FIGURE 11. Latency and throughput vs. connection density for MWSN use case.

TABLE 4. KPI values for different connection densities for AMR and AR.

	Mobile robots		Augmented reality	
UEs/km^2	2000	16000	2000	16000
	0 km/h			
Latency	3.64 ms	3.65 ms	4.03 ms	4.04 ms
Reliability	100%	100%	100%	99.99%
Throughput	12.464 kbps	12.462 kbps	8.57 Mbps	8.56 Mbps
	50 km/h			
Latency	4.43 ms	4.57 ms	4.53 ms	10.02 ms
Reliability	97.00%	96.54%	96.60%	75.19%
Throughput	12.165 kbps	12.219 kbps	8.31 Mbps	6.79 Mbps

2) MOBILITY ANALYSIS

When analyzing mobility, two out of the three use cases need to be studied, i.e., AMR and AR. Figure 10 shows the impact of the mobility in the latency, reliability and throughput KPIs for both use cases. User speed values from 0 to 50 km/h with

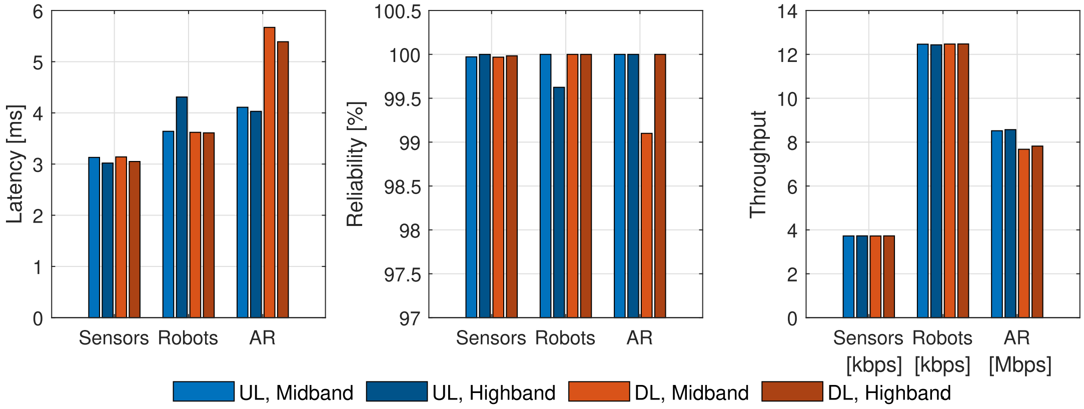


FIGURE 12. Mid-band vs. High-band and UL vs. DL impact in the latency, reliability and throughput.

TABLE 5. Summary KPIs for all use cases (UL/DL).

	Massive wireless sensors networks	**Mobile robots**		**Augmented reality**	
Midband	0 km/h	0 km/h	50 km/h	0 km/h	50 km/h
Latency [ms]	3.13 / 3.14	3.64 / 3.62	4.37 / 5.07	4.11 / 5.67	5.79 / 5.25
Throughput [kbps]	3.72 / 3.72	12.46 / 12.47	12.28 / 12.14	8518.53 / 7675.23	8294.09 / 7900.27
Reliability	99.97% / 99.97%	100% / 100%	97.47% / 97.47%	100% / 99.10%	96.13% / 99.18%
Availability	99.99999% / 99.99999%	100% / 100%	99.94% / 99.94%	100% / 99.992%	99.85% / 99.993%
Connection density [UEs/km^2]	1M	2000	2000	2500	2500
Highband	0 km/h	0 km/h	50 km/h	0 km/h	50 km/h
Latency [ms]	3.02 / 3.05	4.31 / 3.61	10.79 / 4.44	4.03 / 5.39	6.74 / 5.05
Throughput [kbps]	3.73 / 3.73	12.43 / 12.48	11.23 / 12.28	8569.09 / 7820.33	7673.99 / 7990.59
Reliability	99.9998% / 99.98%	99.62% / 100%	64.67% / 98.56%	100% / 100%	87.88% / 99.84%
Availability	100% / 99.99999%	99.99% / 100%	87.52% / 99.98%	100% / 100%	98.53% / 99.999%
Connection density [UEs/km^2]	1M	2000	2000	2500	2500

step 5 km/h were simulated. In both use cases, as Figure 10 shows, all analyzed KPIs reduce their performance when increasing the user speed: the latency increases and the reliability and throughput decrease. In AMR, the latency increases from 3.64 to 4.38 ms, the reliability decreases from 100% to 98.56% and the throughput decreases from 12.46 to 12.27 kbps, while in AR the latency increases from 4.03 to 7.71 ms, the reliability decreases from 100% to 89.28% and the throughput decreases from 8.56 to 7.82 Mbps.

3) CONNECTION DENSITY

This study is key for the MWSN use case, as it is the crucial KPI representing the mMTC extreme case. For the AMR and AR use cases the connection density is not as restrictive but needs to be studied as well. This section will, therefore, cover the three use cases. In AMR and AR, the density goal is 2000 UEs/km^2, and values from 2000 to 16000 were simulated. In the particular case of MWSN use case, the connection density goal is one million UEs per square kilometer, and densities from 50000 to 1 million were simulated.

In MWSN use case, for higher densities the latency increases while the reliability and throughput decrease, although the study shows the performance is almost the same from 50000 up to 1 million devices per square kilometer. Figure 11 shows the values of the latency and the throughput for the different densities. The reliability follows a trend directly proportional to the throughput values, from a value of 99.9947% to 99.972% for 50000 and 1 million UEs/km^2, respectively.

For AMR and AR use cases the KPIs get worst with higher user densities, but depending on the case the impact may vary, that is, the worst results are obtained when the mobility is higher, and the impact of the connection density is higher for AR use case.

Results for AMR and AR are summarized in Table 4, where the KPIs for densities of 2000 and 16000 UEs/km^2 and user speeds of 0 km/h and 50 km/h are shown. The values are similar for both densities, being the AR use case with 50 km/h where the impact is more noticeable.

4) EFFECT OF DL/UL AND FREQUENCY BANDS

Up to this point, the analysis has focused on UL transmissions only, using mid-band frequencies for MWSN and AMR use cases, and high-band mm-wave bands for AR use case. In this section, the study is expanded to both UL and DL results, as well as both frequency bands for all use cases and with a user speed of 0 km/h.

Simulations of the four combinations of UL-mid-band, UL-high-band, DL-mid-band and DL-high-band were run, and results are shown in Figure 12. It can be observed that for MWSN use case, all options are similar in terms of latency, being slightly reduced in high-band. For AMR use case, the performance in UL is better when using mid-band, due to the higher distance between the UE and the gNB (big-hall). In terms of DL, both bands have a similar performance. For AR use case, the latency in UL is less than in DL, and the difference between mid-band and high-band is similar, although in high-band the performance is better. It is likely that for higher throughput demands the performance gap between bands increase, as more bandwidth is available.

V. CONCLUSION AND FUTURE WORK

This work has evaluated the performance of 5G in the four InF sub-scenarios identified by the 3GPP, and strategically selected industrial use cases with the most stringent requirements from 5G-ACIA. The manuscript focused on three KPIs as the main group for our study: latency, reliability and throughput. We considered the impact of several system aspects on these KPIs: mobility, connection density, link direction (uplink or downlink), and frequency band (mid- or high-frequency).

The performance differences of the 5G system between the InF sub-scenarios have been firstly analyzed. The InF-DL sub-scenario, with dense clutter and low height of antennas compared to the clutter height, presented the worst performance, while the InF-SH sub-scenario, with sparse clutter and high antennas, outperforms the rest of the sub-scenarios. Thus, the sub-scenario employed along the manuscript was the InF-DL for considering the worst case. The differences between the sub-scenarios have been observed to be larger for longer distances between UE and gNB, due to the larger differences in terms of the increased pathloss and the reduced LoS probability as the distance increases.

Three use cases have been evaluated, namely, massive wireless sensor networks (MWSN), autonomous mobile robots (AMR) and augmented reality (AR). The main conclusion is that 5G fulfills almost all requirements set by 3GPP, for the assumptions and parameters considered in the three use cases. Some specific configurations do not fulfill such stringent requirements, depending on the type of link, frequency band or speed used, demonstrating that there are still challenges to overcome, especially in terms of reliability. Table 5 provides a summary of the values obtained for all use cases. Requirements not fulfilled are set in red.

As for the mobility analysis, the performance is stable up to 20-30 km/h. At this point, latency starts to increase while reliability and throughput decrease. Although the change is not significant for latency and throughput, the reliability decrease may have a detrimental effect on the fulfillment of the requirements. In fact, the availability at 50 km/h is the KPI not fulfilled in some cases according to our results. Concerning the connection density analysis, results show that the a priori very strict requirement of 1M UEs for the MWSN use case can be fulfilled. In fact, more UEs could be supported reducing the performance for the other KPIs while keeping them within the acceptable boundaries.

This work is a first step for evaluating real industrial use cases, considering the differential aspects of these specific scenarios thanks to the InF channel model. Future lines of this work are: (a) to wider this study with more use cases from the 5G-ACIA industrial proposals used in this work; (b) to explore other new use cases such as remote driving for Automatic Guided Vehicles (AGVs), digital twins or cloud-edge collaboration, as they will increase their importance in the next years in the industry; and (c) to study new Releases of 5G for the considered scenarios and use cases.

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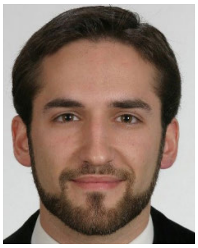

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