Characterization of mmWave Channel Properties at 28 and 60 GHz in Factory Automation Deployments

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Abstract*—Future cellular systems are expected to revolutionize today's industrial ecosystem by satisfying the stringent requirements of ultra-high reliability and extremely low latency. Along these lines, the core technology to support the next-generation factory automation deployments is the use of millimeter-wave (mmWave) communication that operates at extremely high frequencies (i.e., from 10 to 100 GHz). However, characterizing the radio propagation behavior in realistic factory environments is challenging due to shorter mmWave wavelengths, which make channel properties be sensitive to the actual topology and size of the surrounding objects. For these reasons, this paper studies the important mmWave channel properties for two distinct types of factories, namely, light industry and heavy industry. These represent the extreme cases of factory classification based on the level of technology, the density and the size of the equipment, and the goods produced. Accordingly, we assess the candidate mmWave frequencies of 28 and 60 GHz for licensed- and unlicensed-band communication, respectively. After analyzing the signal propagation (e.g., in terms of path loss) and the line-of-sight (LoS) probability, our understanding is that in a factory automation environment the presence of metallic equipment and various objects produces many dissimilarities in the mmWave channel properties, thus making them difficult to describe with conventional empirical or stochastic models. Our findings suggest that the deployment of the practical mmWave systems in indoor industrial environments should not therefore rely on past propagation studies available in the literature blindly but might take into account more accurate and reliable evaluation of the environment that is possible with ray-based simulations.

***Index Terms*—Industrial IoT, factory automation, mmWave communication, 5G systems, ray-based modeling, radio channel properties.**

I. INTRODUCTION AND RATIONALE

It is envisioned that the emerging fifth-generation (5G) wireless networks are going to drive the forthcoming industrial revolution by offering high-reliability and low-latency connectivity which, so far, was only possible to achieve with wired connections [1]. In fact, the avalanche of wireless networked devices as well as new services enabled by the 5G technology pose unprecedented challenges in future industrial Internet of Things (IoT) applications, including data acquisition and monitoring, remote control, training, and maintenance. Depending on a specific factory application, the needed requirements to be satisfied may include seamless connectivity for a high number of devices in e.g., a factory hall (on the order of 10 – 1,000 items), ultra-high reliability of $1 - 10^{-9}$, and extremely low-latency of under 1 ms [2].

It is anticipated that by enabling physical execution in the digital domain of industrial processes, where automation, control, and monitoring are among the main components, the Industrial IoT will deliver the much needed boost to productivity and trigger economic growth. This thinking is supported by a large number of global initiatives that aim at defining various aspects of the Industrial IoT roadmap. For instance, the German effort named Industry 4.0 [3] has been one of the first attempts to tackle the requirements and solutions for industries to convert factories into smarter environments. Another example is represented by the Industrial Internet Consortium (IIC)[1], whose main goals are to create new industry use cases and applications for 5G systems as well as influence the global standardization process with respect to the industrial ecosystem.

However, the integration of 5G technologies into the industrial processes is still under active investigation where many challenges and issues remain open. Among them, catering for ultra-reliable low latency communications (URLLC) plays a pivotal role to achieve intelligent facility management of factory automation environments [4]. In these scenarios, the use of millimeter-wave (mmWave) radio technology at extremely high frequencies of up to 100 GHz is rapidly gaining momentum and becomes the core 5G technology to meet the aforementioned stringent requirements [5].

To date, research literature on 5G-grade IoT focused primarily on the use cases related to outdoor environments and ultra-dense deployments of machines (in the context of massive Machine-Type Communications – mMTC) [6], [7]. However, the vision of 5G mmWave cellular systems suggests not only further growth in the number of bandwidth-hungry devices but also a new paradigm where industries among other vertical sectors (automotive, eHealth, agriculture, etc.) will take advantage of URLLC (a.k.a. mission critical MTC – mcMTC) [8].

Along these lines, the target of this paper is to provide with a comprehensive analysis of mmWave channel propagation in factory automation environments in both licensed (i.e., 28 GHz) and unlicensed (i.e., 60 GHz) bands. Today, one may classify industries based on their technological "intensity" into four categories: *(i)* high technology, *(ii)* medium-high technology, *(iii)* medium-low technology, and *(iv)* low technology. We reiterate the fact that signal propagation at microwave frequencies (i.e., lower than 6 GHz) is not strongly affected by the distribution of objects in a given environment.

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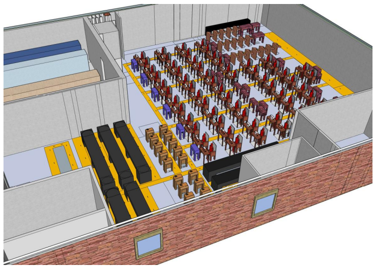
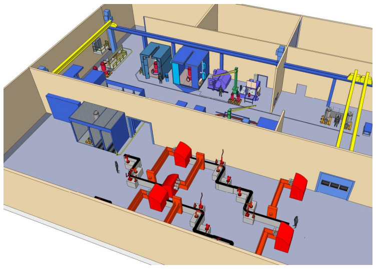
[1] Industrial Internet Consortium. Available at: http://www.iiconsortium.org



(a) Light industry.



(b) Heavy industry.

Fig. 1. Considered factory automation deployments.

However, as 5G systems will employ mmWave frequencies (i.e., from 10 GHz up to 100 GHz), such effects as blockage, diffraction, and scattering begin to play a fundamental role in accurate channel modeling and characterization.

Taking into account these important aspects, in this work we focus on the analysis of two extreme factory deployments, namely, *light industry* (low technology) and *heavy industry* (high technology). In particular, we intend to shed light on how the considered deployments may affect the mmWave signal propagation. First, we compare statistical and deterministic channel models by highlighting the limitations of the former as well as articulating the need for new "accurate" solutions able to support the stringent requirements imposed by the factories of the future. Finally, we offer useful insights into the relevant factors that may be identified as a source of blockage for the mmWave signal propagation and explain how the deployment of a mmWave system can be performed according to the factory environment in question.

The remaining sections of this paper are organized as follows. A literature review on mmWave propagation is summarized in Section II. An overview of implications that the use of mmWave has in both light and heavy industry as well as the proposed channel assessment methodology are given in Section III. In Section IV, we outline our ray-based modeling approach and introduce the considered 3D factory deployments. Simulation results are discussed in Section V, while conclusions are drawn in Section VI.

II. STATE-OF-THE-ART ON INDOOR MMWAVE CHANNELS

To date, 2.4 GHz and 5 GHz unlicensed bands have been the most commonly implied when considering wireless communications in typical indoor environments (e.g., office, restaurant, hotel, factory). However, rapid densification with indoor hotspots and utilization of "mobile" access points (e.g., smartphones, wearables, tablets), supported by novel multimedia services and applications, bring tremendous traffic loads and, consequently, network congestion [9]. To overcome these issues, wireless connectivity at extremely-high frequencies, such as in mmWave systems, becomes a viable candidate solution for delivering high-bandwidth and URLLC communications to indoor scenarios.

Much research literature focused on understanding the channel propagation properties in indoor environments at mmWave frequencies, primarily in 60 GHz bands. In particular, in [10] the authors studied the large-scale path loss of the indoor multipath propagation channel at 60 GHz. In doing so, they utilized a spread spectrum channel sounder with directional, semi-directional, and omnidirectional transmitter (Tx) and receiver (Rx) antennas placed at the heights of 1.5 m. Another study based on indoor propagation measurements has been conducted in [11], where continuous-route (CR) and direction-of-arrival (DoA) measurements were taken into account. The obtained results demonstrated that the direct wave and the first-order reflected waves from smooth surfaces are sufficient to guarantee the adequate levels of received power, whereas diffraction is the most dominant factor in causing the propagation losses.

Complementing the work focused on the 60 GHz band, the authors in [12] conducted indoor laboratory measurements at 28 GHz by using horn antennas that rotated in the azimuth plane. Then, a vector network analyzer (VNA) was utilized to measure the channel. Further, reflection and penetration loss measurements at 28 GHz in and around buildings have been performed in [13]. Here, the produced results indicate high penetration losses of 45.1 dB through an office building with three interior walls. Additionally, outdoor tinted glass produced the penetration losses of 40.1 dB as opposed to indoor non-tinted glass that resulted in only 3.9 dB of penetration loss.

Despite these important past studies, the understanding of mmWave channel properties in factory automation environments still remains very limited. Different from other indoor environments like offices, hotels, or restaurants, the factory layouts incorporate a wide range of metallic equipment, robots, and painted materials that strongly affect the radio signal propagation. For these reasons, this work exploits a ray-based modeling methodology to assess two distinct factory automation scenarios that carefully reconstruct hand-labor and technology-intense industrial deployments, respectively.

III. MODELING APPROACH AND FACTORY DEPLOYMENTS

There is a general consensus that communication at mmWave frequencies will play a pivotal role to meet the stringent requirements of below 1 ms latency and high data rate on the order of 10-100 Gbps in the emerging 5G systems. According to this vision, for the factories of the future it becomes clear that automation will complement human workers, not only in jobs connected with repetitive tasks (e.g., production, transportation, logistics, office/administrative support) but also in the service industry. Moreover, in order to enable these high-granularity tasks it is essential to understand how to deploy mmWave systems in the factory environments of different topology with the goal to provide ubiquitous URLLC connectivity.

As we aim to characterize the channel properties for the considered factory environments, a principal distinction has to be taken into account regarding the level of technology that may be exploited in a given factory automation scenario. For this reason, our below study concentrates on revealing possible dissimilarities in channel propagation that different factory environments may have when employing mmWave frequencies. In fact, various densities of machines, industrial equipment, as well as other objects and materials lead to very dissimilar channel propagation behavior. In addition, the presence of humans poses additional challenges with respect to blockage of the radio signal. Therefore, there is a need for "accurate" channel models to e.g., be utilized in subsequent system-level simulations.

Therefore, we focus our attention on two very different industrial deployments, namely, light industry and heavy industry [14], by taking into account their technology level. As illustrated in Fig. 1, we term *light industry* to be the factories that are typically consumer-oriented and whose products (e.g., clothes, shoes, furniture) are directed at end-users. Here, the facilities, such as tables, chairs, and shelves, may have a relatively small impact on the radio propagation. On the other hand, *heavy industry* includes factories that deploy larger and heavier equipment (e.g., automotive, aerospace, chemical). The latter feature facilities, including large machine tools, automated robots, and intricate shapes of the buildings, which aid in executing complex processes and thus complicate propagation.

In these two factory automation scenarios, the deployment of a mmWave radio system may be challenging due to shorter wavelengths [15]. To overcome such an issue, this paper investigates the relevant channel properties that are able to provide a better insight into how the actual industrial deployment affects the channel behavior in terms of: (i) Line-of-Sight (LoS) and Non-LoS (NLoS) path loss and (ii) LoS probability. For 5G systems, the understanding of these parameters represents a fundamental requirement to develop future mmWave mobile systems that are able to offer URLLC in factory automation environments. The path loss, which is essentially a reduction in power density (attenuation) of an electromagnetic wave as it propagates through space, is a major factor in our analysis, since it determines the system design choices with respect to the link budget. With the LoS probability, we are further able to quantify how often there is a chance that the mmWave Tx and Rx are in reciprocal visibility at a particular distance.

Going into details of the analytical expressions that may be used to characterize the above metrics of interest, the path loss formula [16] (scaled in dB) can generally be assumed to have a logarithmic dependence on the linear distance. It is expressed as:

$$PL(d)[dB] = PL_0 + 10 \cdot n \cdot \log_1 0 \left(\frac{d}{d_0}\right) + \chi_\sigma, \quad (1)$$

where PL_0 represents the path loss at the reference distance d_0 (often named the free-space path loss), d is the distance (in meters) between the Tx and the Rx, and χ_σ is a log-normal random variable with 0 dB mean and the standard deviation of σ.

Further, the LoS probability is not a *conventional* probability function (such as a PDF, CDF, or CCDF) but rather a mapping from the positive distance d onto the probability of being in LoS within [0, 1]. There is a rich variety of different analytical models to capture the LoS probability. For instance, the international telecommunication union, radiocommunication sector (ITU-R), has proposed the models in [17] for both *urban micro* (UMi) and *indoor hotspot* (InH) environments in the form:

$$P_{LoS}(d) = min\left(\frac{d_1}{d}, 1\right)\left(1 - \exp\left(\frac{-d}{\alpha}\right)\right) + \exp\left(\frac{-d}{\alpha}\right), \quad (2)$$

$$P_{LoS}(d) = \begin{cases} 1, & \text{if } d \le d_1, \\ \exp(-(d-d_1)/\alpha), & \text{if } d_1 < d < d_2, \\ P_0, & \text{if } d > d_2, \end{cases} \quad (3)$$

where d_1 is the distance up to which we always have the LoS Tx-Rx paths, α is a decay parameter, and d_2 is the distance in correspondence to which we have that $P_{LoS} = P_0$. However, such generic formulations do not offer the needed methodology for characterizing the LoS probability within the environment in question. Therefore, in this work we provide with our derived LoS probability that is produced via thorough mmWave simulations in a 3D ray-based modeling tool. In addition, another motivation for targeting the sought expressions of the achieved LoS probability is because we argue that the forthcoming 5G systems should not solely rely on statistical/stochastic channel models available in the literature, since these may not provide an "accurate" solution for a given scenario.

IV. DESIGN OF UTILIZED 3D RAY-BASED MODELER

To conduct the intended mmWave channel estimation and extract the relevant statistical data, the signal propagation has to be modeled by taking into account the necessary details related to the equipment, materials, and topology of the considered industrial environment. To achieve this goal, we employ a commercial tool Wireless InSite[2], which is capable of conducting the receiver channel estimation by using the shooting-and-bouncing ray (SBR) model. We note that this method is particularly suitable in the presence of complex objects (e.g., robot arms and factory trucks), as it is able to provide very fast and reasonably accurate assessment of the signal (field) strength. Further, after some pre-processing, the simulator accepts at the input the 3D models completed in CAD programs or with scanning techniques, such as the Laser Imaging Detection and Ranging (LIDAR). For our purposes, we consider two factory scenarios corresponding to (i) *textile*

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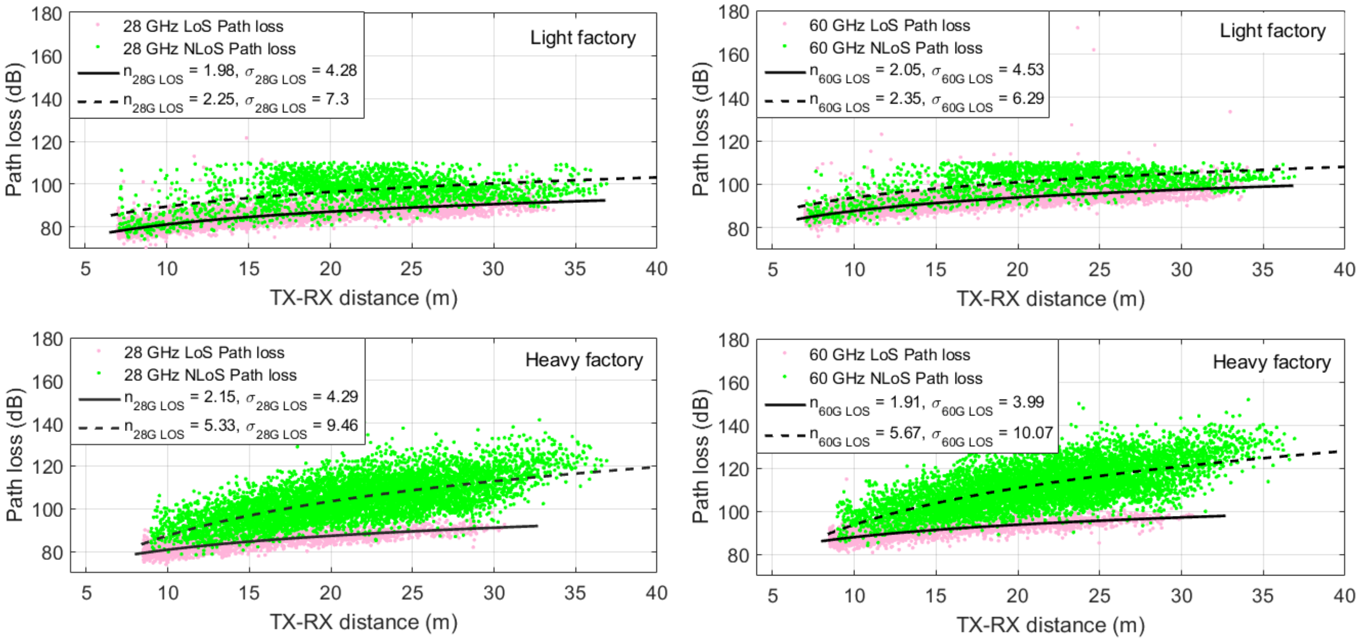
[2] Wireless InSite, available at: http://www.remcom.com/wireless-insite



(a) mmWave 28 GHz (licensed bands).

(b) mmWave 60 GHz (unlicensed bands).

Fig. 2. Produced path loss for light and heavy industry deployments.

(i.e., light) and (ii) *painting* (i.e., heavy) industry (refer to Fig. 1 for the considered deployments).

In particular, the two scenarios in question were recreated in Blender[3], where one isotropic antenna was deployed in the middle of the map (e.g., attached to the roof). The transmit power equals to 20 dBm and the antenna gain is 0 dB. The overall size of the map[4] is [50W x 9H x 50D] meters, while the simulations have been conducted at the operating frequencies of 28 GHz (licensed bands) and 60 GHz (unlicensed bands). Further, in order to achieve comprehensive accuracy of mmWave channel characterization, for each of the maps a grid of 8,000 receivers[5] was considered with the height of 1.5 meters. The materials used in our simulations together with their physical parameters (adopted from [18]) are summarized in Table I.

TABLE I
DIELECTRIC PERMITTIVITY OF MATERIALS USED IN SIMULATIONS

Material	**28 GHz**	**60 GHz**
Concrete	5.31 - j0.31	5.3 - j0.27
Brick	3.75 - j0.02	3.75 - j0.01
Plasterboard	2.94 - j0.08	2.94 - j0.063
Wood	1.22 - j0.12	1.99 - j0.1
Glass	6.27 - j0.01	6.27 - j0.019
Metal	0.98 - j6.48x10^6	1 - j2.9x10^6

Ultimately, the output metrics of our evaluation are: (i) *LoS/NLoS path loss (PL)*, (ii) *LoS probability*, (iii) *Rician K-factor*, (iv) *RMS delay* (see eq. (4.32) in [19]), and (vi) *RMS angular spread* (see eq. (4.40) in [19]). The PL was calculated as a difference between the transmit power and the total received power by taking into account the multipath propagation mechanisms, such as reflection, diffraction, and transmission. The K-factor indicates the contribution of the LoS vs. NLoS component by means of LoS to NLoS power ratio in log scale. The LoS probability has a purely geometrical nature and was calculated as the chance of having a direct LoS link between the Tx and the Rx at a certain distance. We note that since the LoS probability is an important factor in characterizing the radio channel properties in indoor environments, we compare our simulations with the standardized LoS probability models available in [20].

V. PERFORMANCE EVALUATION AND DISCUSSION

In this section, we report on our ray-based simulation results to understand how the two considered factory automation deployments (i.e., light and heavy industry) may result in different mmWave channel properties at 28 and 60 GHz frequencies. Our first results highlight the achieved path loss behavior for both LoS and NLoS propagation. As shown in Fig. 2, LoS and NLoS path loss scatter points produced for the light and heavy factory layouts have a completely different nature. In particular, for the heavy industry case we notice a high number of NLoS scatter points w.r.t. the other case. The explanation is in that the presence of machines and metallic objects is more typical for the heavy industry scenarios, thus producing more reflections during mmWave signal propagation.

Consequently, this translates into fewer LoS paths for the users that have slimmer chances to achieve strong radio signal of their possible transmissions. On the contrary, in light factory

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[3] Blender, available at: https://www.blender.org

[4] W = width, H = height, and D = depth.

[5] A large number of receivers yields higher accuracy of channel characterization.

TABLE II

PATH LOSS IN CONSIDERED FACTORY AUTOMATION DEPLOYMENTS

Freq.	Industry	Path loss formula
28 GHz	Light	$P_{LoS} = 57.1 + 10 \cdot 1.9 \cdot \log_{10}(d) + \chi_\sigma, \sigma = 4.2$
		$P_{NLoS} = 59.7 + 10 \cdot 2.2 \cdot \log_{10}(d) + \chi_\sigma, \sigma = 7.3$
	Heavy	$P_{LoS} = 54.9 + 10 \cdot 2.1 \cdot \log_{10}(d) + \chi_\sigma, \sigma = 4.2$
		$P_{NLoS} = 24.6 + 10 \cdot 5.3 \cdot \log_{10}(d) + \chi_\sigma, \sigma = 9.4$
60 GHz	Light	$P_{LoS} = 62.7 + 10 \cdot 2.0 \cdot \log_{10}(d) + \chi_\sigma, \sigma = 4.5$
		$P_{NLoS} = 64.0 + 10 \cdot 2.3 \cdot \log_{10}(d) + \chi_\sigma, \sigma = 6.2$
	Heavy	$P_{LoS} = 64.7 + 10 \cdot 1.9 \cdot \log_{10}(d) + \chi_\sigma, \sigma = 3.9$
		$P_{NLoS} = 26.8 + 10 \cdot 5.6 \cdot \log_{10}(d) + \chi_\sigma, \sigma = 10.0$

cases the NLoS path loss begins to be relevant when the distance between the Tx and the Rx is higher than 15 m. In this case, the results reveal that the usage of basic equipment (e.g., tables, chairs, shelves, and sewing machines) does not affect the signal propagation as much at shorter distances. Further, another interesting observation is that the path loss achieved in the two deployments is generally 10 dB lower (e.g., NLoS path loss at 40 meters) when considering 28 GHz (see Fig. 2(a)) as compared to 60 GHz (see Fig. 2(b)). For the sake of clarification and according to eq. (1), in Table II we provide the derived path loss analysis for both light and heavy industry scenarios at the considered mmWave frequencies.

Similar conclusions to those for the path loss can be formulated for the LoS probability, see Fig. 3. More specifically, the collected LoS scatter points demonstrated in Fig. 2 have been approximated with exponential model fits to explain the propagation effects in our 3D ray-based simulations for both light and heavy industry. The results are such that for the environments of interest it may be inaccurate to exploit the classical statistical models as per eq. (2) and (3). In fact, our reported formulation for the LoS probability can be described with the following analytical expressions:

$$P_{LoS}^{Light}(d) = \begin{cases} 1, & \text{if } d \leq 8m \\ 111 \cdot (\exp(-0.01829 \cdot d)) + \\ +(-0.0002933 \cdot (\exp(0.3443 \cdot d))), & \text{if } 7m < d < 35m, \\ 0, & \text{if } d > 35m, \end{cases} \tag{4}$$

$$P_{LoS}^{Heavy}(d) = \begin{cases} 1, & \text{if } d \leq 8m \\ 153.1 \cdot (\exp(-0.1141 \cdot d)) + \\ +(483.2 \cdot (\exp(-0.3254 \cdot d))), & \text{if } d > 8m \end{cases} \tag{5}$$

According to Fig. 3, we note that the LoS probability for heavy industry decays more rapidly in contrast to the light industry case as the Tx-Rx distance increases. While our heavy industry scenario is characterized by larger equipment and many more metallic objects, which become the main sources of blockage in the signal propagation, the light industry layout is mostly open space where the signal is free to propagate without too many obstacles on its path. We also note that in this case the main source of blockage is represented by human bodies, which however have the average height of 1.5 meters and do not impact the propagation losses drastically. Further, when comparing our achieved results with the standardized LoS probability models, see [20], we observe that none of them is able to offer a close match with the channel properties reported in our analysis. In fact, while the LoS probability for the heavy industry case may have a similar behavior w.r.t. one of the WINNER II B3 channel models, for the distances of under 15 m the probability in our case is 10% and 50% higher for heavy and light industry scenarios, respectively.

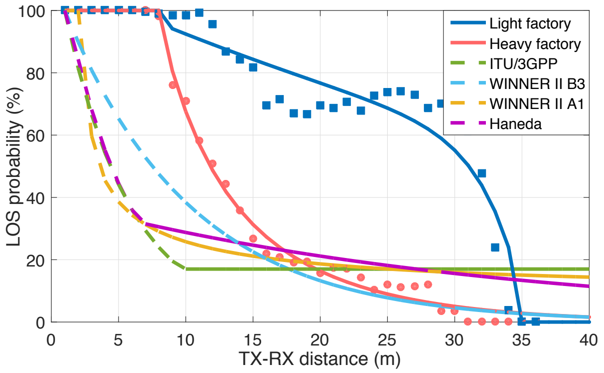

Fig. 3. LoS probability for light and heavy industry at 28 and 60 GHz.

TABLE III

COMPARISON OF CHANNEL PROPERTIES FOR LIGHT AND HEAVY INDUSTRY

Parameter	H28	L28	H60	L60
Rician K-factor	6.7	19.3	6.7	19.3
RMS Delay spread, ns:				
LoS:	38.5	13.7	38.3	13.4
NLoS:	49.4	29.1	49.4	29.3
RMS AoA spread, °:				
LoS:	58.7	21.6	58.9	21.0
NLoS:	53.3	42.7	51.6	41.6
RMS AoD spread, °:				
LoS:	43.1	14.4	42.1	13.9
NLoS:	65.3	35.6	62.6	35.5

Finally, in Table III we compare the more relevant channel properties for the two factory automation deployments considered (see Section IV). First, we observe that our obtained results are very different for light and heavy industry cases. Clearly, this is due to the geometrical distribution of the scatter objects that in the former case is much denser. In fact, this observation reflects in a way the findings that we have in terms of the Rician K-factor, delay, Angle of Arrival (AoA), and Angle of Departure (AoD). In particular, by analyzing the Rician K-factor we may notice that the contribution of the LoS component as compared to the NLoS one is more relevant for the light industry case. More generally, the values of other properties in our study make us conclude that the heavy industry deployment observes mmWave channel propagation that is more difficult to predict due to a higher spread of the considered properties. This important result is also confirmed when analyzing the angles at/from which the rays arrive and depart.

In summary, we argue that realistic factory environments strongly affect the channel properties at mmWave frequencies.

Further, stochastic models available in the literature may not reliably represent the industrial scenarios of interest due to their "inaccuracy" in channel characterization. Indeed, our conducted study indicated that there is a large number of factors in the real-world industrial environments that have a dramatic impact on the mmWave signal propagation. For these reasons, constructing a channel model that will be more reliable to help achieve the high data rates and lower delays in 5G is something that may need to be done case-by-case.

VI. CONCLUSIONS AND FUTURE WORK

Accounting for the strict requirements imposed by the forthcoming industrial services and applications enabled by the 5G technology, the need for more accurate and reliable channel models is articulated. These should be strictly related to the characteristics of the environment under consideration. To achieve better channel characterization in factory automation, industrial sites can be classified based on their level of technology, density (and type) of machines used, as well as goods in production. These important factors make the channel properties very dissimilar w.r.t. the mmWave signal propagation. The main focus of this paper has thus been set on the assessment of channel propagation at 28 and 60 GHz frequencies for two different industrial layouts that represent the opposite extremes according to their characteristics.

Our obtained results highlight that radio signal behavior differs substantially when accounting for various densities of machines, presence of human bodies, and topology of the industrial site. In particular, higher numbers of NLoS scatter points have been observed for the heavy industry deployments due to the presence of machines and metallic objects. This observation was also confirmed by analyzing the LoS probability, where for the heavy industry case the decay was more rapid in contrast to the light industry layout. In conclusion, we argue that heavy factories observe mmWave channel properties that are more difficult to predict due to more reflections caused by the higher density of metallic machines/robots. Therefore, we may summarize that in deploying future 5G mmWave systems more accurate radio channel characterization has to be performed without relying on past statistical and stochastic channel models employed for microwave transmissions.

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