

Implementation and Calibration of the 3GPP Industrial Channel Model for ns-3

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Abstract—The Fifth Generation (5G) of mobile communications has brought a change of paradigm in the way cellular technologies are conceived. 5G has been designed to provide services not only to people, but also to industries and verticals. One of the verticals that will benefit most from the 5G is the Industry 4.0. Channel modeling for this vertical is receiving significant attention, mainly due to the increased complexity that comes with multipath fading scenarios. In order to overcome this problem, the Third Generation Partnership Project (3GPP) defined a new stochastic channel model as part of Release-16, called Indoor Factory (InF). This paper describes the implementation process of this channel model as an extension tool for one of the most well-known open-source software simulators, ns-3. Calibration results have been obtained and compared with other 3GPP references. This work permits to use ns-3 as a reliable tool for evaluating new industrial scenarios and use cases.

Index Terms—ns-3, 3GPP, calibration, indoor factory, channel modeling

I. INTRODUCTION

Channel modeling for the Fourth Industrial Revolution (Industry 4.0) vertical is gaining significant attention during last few years. The industry is requiring the connection of large amounts of devices in a factory environment, thus requiring real-time communications and creating huge amounts of data. This is achieved thanks to the massive parameterization and monitoring that occurs in these complex scenarios. In this sense, 5G connectivity, together with other technologies such as edge/cloud computing or big data will be key enablers for this vertical.

5G will have a huge impact in the global market, being manufacturing one of the most affected areas [1]. New Radio (NR) will be a key technology for industrial connectivity in different application scenarios, i.e., Ultra-Reliable and Low Latency Communications (URLLC), Enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC). In fact, since 2020 the deployments are taking place worldwide, but only for eMBB scenarios, oriented to human-centric use cases. Thus, the incorporation of a wireless network to connect humans, machines, and data will soon be a reality [2]. With Rel-16 [3] and Rel-17, which include URLLC and mMTC services, these will make the Industrial Internet of Things (IIoT) scenarios a fact.

Since real deployments for these scenarios are not optimum yet, network simulators come as a key component for the

evaluation of industrial scenarios without the need of real deployments and the costs that they entail, both in time and resources. This is observed in [4], which proposed the use of System-level Simulation (SLS) results for network optimization. The accuracy of the results obtained with the simulations are strongly dependent on the models used, which characterize the performance of the signals propagation according to the target scenario. This effect could change drastically between a factory and other indoor scenarios, as the factory may have clutter and metal objects all spread out, modifying the electromagnetic behaviour.

One of the most popular open-source simulation tools is ns-3. This software provides SLS results and currently has a large community supporting its development.

In the last recent years, different versions have been released in ns-3, each one including new channel models as specified by 3GPP, e.g. Urban Macro-cell (UMa), Urban Micro-cell (UMi), Rural Macro-cell (RMa), Vehicle-to-Vehicle (V2V), Indoor Hotspot (InH); which are defined in [5]. 5G-LENA [6], which is a NR network simulator designed as a module to ns-3, has incorporated fundamental features regarding Rel-15. Other publication [7] has addressed a channel model implementation for Vehicle-to-everything (V2X) in ns-3. Even so, none of these contributions has considered the implementation of the so-called InF channel model, defined by 3GPP for Rel-16 in [3]. In fact, the current version of the ns-3 simulator does not include this channel model, and that is the main motivation of this work. The aim is to extend the ns-3 code with the InF channel model implementation and provide calibration SLS results for its validation. To do so, the results will be compared against other 3GPP reference [8]. This will be done by comparing the Key Performance Indicators (KPIs) associated with the channel model, i.e. Coupling Loss (CL), Geometry with noise, Geometry without noise, and Delay Spread (DS).

The remainder of the paper is as follows. In Section 2, a study of the industrial channel model standardized by the 3GPP in TR 38.901 [3] is carried out. Section 3 describes the implementation of the channel model within the ns-3 simulator. Section 4 provides calibration SLS results and compares with the aforementioned references. Finally, Section 5 gathers the conclusions extracted from the work.

II. INDUSTRIAL CHANNEL MODEL RELEASED BY 3GPP

The channel model proposed by 3GPP for IMT-Advanced [9] is a valid model for a range of specific scenarios, i.e. UMa, UMi, RMa, and InH. The only indoor scenario of this list is InH. It represents a office environment consisting of open cubicle areas, walled offices, open areas and corridors. Since InH does not represent nor include any industrial scenario, the 3GPP TSG RAN #81 group started study and definition of a channel model for industrial scenarios for IMT-2020 [10]. As a result, typical characteristics of industrial scenarios and their propagation parameters were defined in [3].

A. Industrial scenarios

There is a wide variety of industrial scenarios, ranging from large warehouses or industrial halls to complex production lines with a large amount of machinery. According to [2], the main characteristics of the InF environment are a larger physical size, higher ceiling, more metallic objects producing the specular reflection, objects in the environment with irregular sizes and link blockage is mainly caused by machines and not by walls. In that sense, the 3GPP divided the InF scenario into 4 sub-scenarios, which are defined by the state of clutter (sparse or dense) and the Base Station (BS) height (low or high):

- 1) Indoor Factory-Sparse Low (InF-SL)
- 2) Indoor Factory-Dense Low (InF-DL)
- 3) Indoor Factory-Sparse High (InF-SH)
- 4) Indoor Factory-Dense High (InF-DH)

This classification is based on two criteria, i.e., the BS antenna height and the clutter density. Regarding the first criterion, the height of a BS antenna can be set from 5 to 25 metres, which offers great coverage options. Moreover, the height of the User Terminal (UT) and clutter can vary from 1 to 10 metres. Two configuration can hence be defined, which are “clutter-embedded” and “clutter-elevated”, where clutter-embedded indicates that BS height is below clutter, and clutter-elevated when is above the average clutter height. The second criterion considers the clutter density (r) defined by the ratio of area occupied by clutter. Clutter density is classified into two types: sparse clutter ($r \leq 40\%$) and dense clutter ($r > 40\%$).

B. Propagation model

1) *Channel Condition Models*: Loss models require knowing whether two nodes are in Line of Sight (LoS) or in Non Line of Sight (NLoS). In order to ascertain whether the state of a channel is LoS or NLoS at a given distance, the LoS probability model is implemented using the stochastic model defined in [2], [3], expressed as:

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

where, $k_{subsc}e$ is a constant determined for each sub-scenario, and defined as:

$$k_{subsc}e = \begin{cases} -\frac{d_{clutter}}{\ln(1-r)} & \text{for InF-SL, InF-DL} \\ -\frac{d_{clutter}}{\ln(1-r)} \frac{h_{BS} - h_{UT}}{h_c - h_{UT}} & \text{for InF-SH, InF-DH.} \end{cases} \quad (2)$$

2) *Path Loss Model*: The attenuation of electromagnetic waves propagating through space is complex in industrial scenarios. Multiple propagation mechanisms are involved, such as free space losses, refraction, diffraction, reflection and absorption. Several new models of Path Loss (PL) for LoS and NLoS conditions are proposed by 3GPP [3]. The PL represents a high percentage of the total loss in a system and therefore has a clear influence on both coverage and transmission rates. The established model by 3GPP to calculate the PL is the Alpha Beta Gamma (ABG) model. Equation 3 represents the expression to calculate PL for each scenario, where d_{3D} is the 3D distance between the transmitter (Tx) and receiver (Rx) in meters, f_c denotes the center frequency normalized in GHz, the A , B and X are variables which depend on the state of the channel and the break point distance d_{BP} , as detailed in [3].

$$PL = X + A \log_{10}(d_{3D}) + B \log_{10}(f_c) \quad [\text{dB}]. \quad (3)$$

III. NS-3 IMPLEMENTATION

This section introduces the implementation of a new channel model for ns-3 based on the guidelines of 3GPP [3]. The last ns-3 version 3.35 includes channel models for environments, i.e. UMa, UMi, InH (open and mixed office) [11]. However, it does not include the new industrial scenarios. As part of this work, the main components such as propagation and spectrum modules have been modified accordingly to reflect the sub-scenarios of InF. New separate classes for each industrial sub-scenarios are implemented, the interfaces are provided without compromising the support of existing models and ensuring an easy integration in the main base code. In addition, some 5G-LENA components have been used in this channel modeling. Considering that 5G-LENA [6] is a pluggable module to ns-3 for 5G and has already performed implementations of this nature [12].

The aim of this paper is to achieve a flexible and re-usable architecture, enabling the possibility to adapt new scenario conditions according to the demands. In the following sections, the extensions for the modules are described and schematically detailed in the diagram in Fig. 1.

A. Propagation module

Within the propagation module, several components are modified following the 3GPP specification. This paper introduces the new models for LoS/NLoS probability and PL described in the previous section in the ns-3 simulator, and also includes the standard deviation of Shadow Fading (SF) for each sub-scenario, which is described in Table 7.4.1-1 of [3]. In short, Fig. 1 shows a development overview of all

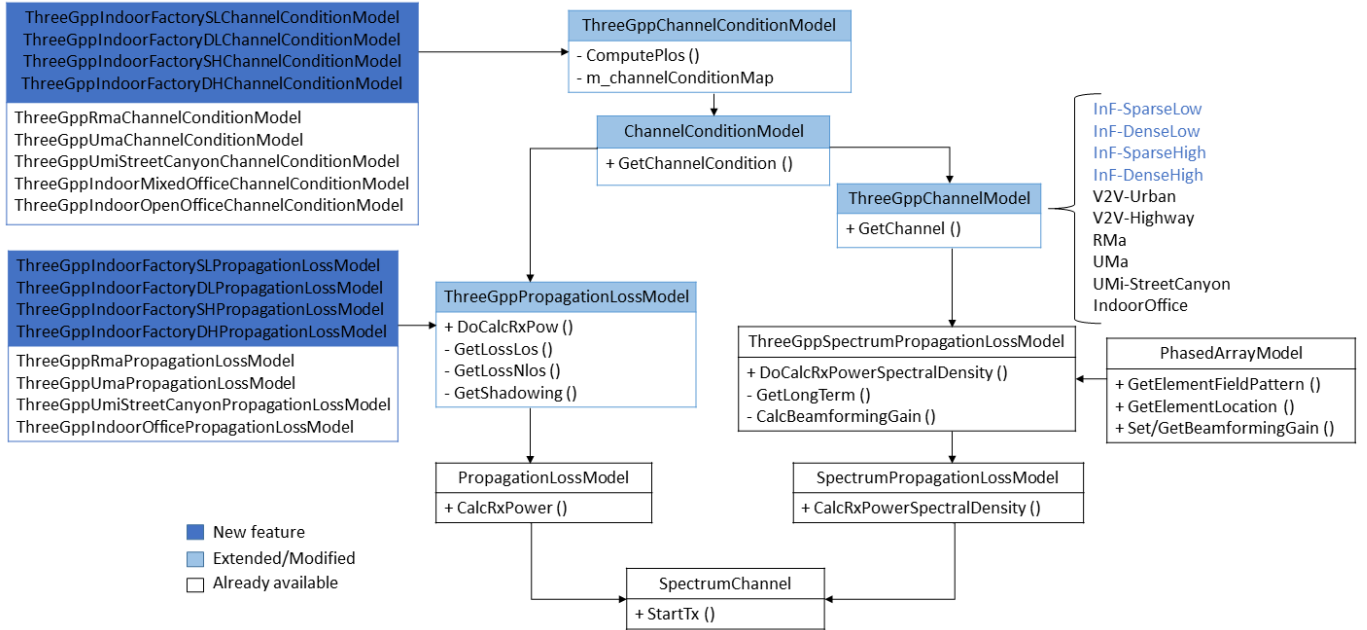


Fig. 1. Code structure for the proposed next release of ns-3.

propagation classes. In order to allow simulation of signal propagation for industrial environments, some modifications are detailed below.

1) *Channel condition models*: In this test environment, the new probability models are included within the **ChannelConditionModel** interface. Then, four different sub-classes have been developed, each with name **ThreeGppIndoorFactoryXXChannelConditionModel**, where XX is replaced according to the sub-scenario to be simulated (i.e. SL, DL, SH or DH). These sub-classes determine the channel state for the InF-SL, InF-DL, InF-SH and InF-DH scenarios, respectively. Similarly to other scenarios that were already implemented in the previous ns-3 versions, these new sub-classes have the **ThreeGppChannelConditionModel** as base class. This provides the possibility to periodically update the status of each channel.

Unlike channel models made for other environments, industrial scenarios establish new parameters to define the state of the channel, namely r and the clutter height (h_c). Thus, within these sub-classes, the ns-3 simulator is now able to develop new global variables that were not created in earlier version with other scenarios.

2) *Path loss and shadowing models*: Using the Equation (3) for calculating the signal propagation, the ns-3 base code has the class **ThreeGppPropagationLossModel**, which extends the **PropagationLossModel** interface and implements the general logic used to handle the computation of the mean PL and the SF component. It is in turn divided into four sub-classes that are represented as **ThreeGppIndoorFactoryXXPropagationLossModel**, where XX will be replaced according to the sub-scenario to be simulated (i.e. SL, DL, SH or DH). Each of the four sub-classes considers a log-normal shadowing, and 3D distance according to the Table 7.4.1-1 in [3]. In order to calculate the PL according to the state LoS and NLoS, some

steps are required:

- 1) Using the functions `GetLossLos` and `GetLossNlos`, it will assist in calculating the PL according to the channel state. These operations will depend on the parameters namely 2D distance, 3D distance, the height for both UT and BS.
- 2) Then, the PL is computed with the state of scenario returning the power received with the main method of `DoCalcRxPower` or `CalcRxPower`.
- 3) Additionally, the `GetShadowing` function gives the value regarding the applying SF model. This function pairs other functions, `GetShadowingStd` and `GetShadowingCorrelationDistance` that are used by `GetShadowing` to retrieve the standard deviation of the SF component and the correlation distance.

B. Spectrum module

The ns-3 simulator implements the 3GPP channel modeling framework as defined in [3]. The features for stochastic Spatial Channel Model (SCM) are included in the class **ThreeGppChannelModel**, whereas a first step the channel matrix $\mathbf{H}(t, \tau)$ is computed according to the random distributions of large scale parameters. The small scale parameters are not implemented, since small variations in the InF channel are the same as in other indoor test environments, as well as the radiation model of antennas.

Using the Cholesky decomposition, the cross correlation matrix is constructed following the 3GPP specifications in Table 7.5-6 [3], where involves parameters of SF, Ricean factor (K), DS, Azimuth Angle Spread of Departure (ASD), Azimuth Angle Spread of Arrival (ASA), Zenith Angle Spread of Departure (ZSD), and Zenith Angle Spread of Arrival (ZSA). This matrix is computed according to the channel

condition (LoS or NLoS). It should be noted that the value of K is neglected under NLoS conditions.

The ns-3 module then considers for simulations the propagation models, the four sub-scenarios already described, the channel conditions, and finally, the fast fading model that allows characterizing the Multi-path Component (MPC) with a stochastic model.

TABLE I
INDOOR FACTORY - SIMULATION ASSUMPTIONS

Parameter	Values
Scenario	InF-SL, InF-DL, InF-SH, InF-DH
Room size (WxL)	InF-SL: 120 x 60 m InF-DL: 300 x 150 m InF-SH: 300 x 150 m InF-DH: 120 x 60 m
ISD	For small hall 20 m For big hall 50 m
Room height	10 m
BS antenna height	InF-SL and InF-DL: 1.5 m InF-SH and InF-DH: 8 m
UT Height	1.5 m
Min. BS - UT distance (2D)	1 m
UT distribution (horizontal)	Uniform
UT attachment	Based on PL
Carrier frequency	3.5 GHz and 28 GHz
Bandwidth	100 MHz
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

Within spectrum module, the class `ThreeGppChannelModel` generates large-scale parameters, involving the same parameters for the calculation of the channel matrix, including the K factor. These values are configured in the `GetThreeGppTable` function according with the channel conditions, following Table 7.5-6 Part-3 in [3]. It is important to emphasize that these parameters do not depend on the type of sub-scenario.

On the other hand, the DS is a measure of the MPC profile of a mobile communications channel. It is generally defined as the difference between the time of arrival of the earliest component (e.g. the LoS wave if there exists) and the time of arrival of the latest MPC [13]. For the DS modeling, different options are described in [2]. However, given the complexity of the channel and reflective elements, for InF the DS model is based on the ratio of volume to total area, and it is defined by 3GPP as shown in Equation 4 and 5. The expression of DS follows a normal distribution, which standard deviation is 0.18 and the mean depends on both LoS (Equation 4) and NLoS (Equation 5) condition and stage volume.

$$\mu_{lgDS} = \log_{10}(26(V/S) + 14) - 9.35, \quad (4)$$

$$\mu_{lgDS} = \log_{10}(30(V/S) + 32) - 9.44, \quad (5)$$

where V is the volume and S is total surface of each sub-scenario. As the room size of each sub-scenario is different,

three variables (floor, walls and ceiling) have been implemented in the `ThreeGppChannelModel` class to obtain V/S . In this way, V/S changes according to the parameters of scenarios defined in Table I. Furthermore, the Angular Spread (AS) parameters are based on the circular standard deviation in the directional statistics. In this paper, these parameters have been determined following the expression defined by 3GPP in the Annex A.1 of [3].

Finally, The function `GetNewChannel` encloses the global variable `m_numCluster`, which is determined by the cluster number equals according with the Table 7.5-2 and 7.5-4 in [3].

IV. CALIBRATION ASSUMPTIONS AND RESULTS

This section compares the performance of the implemented industrial model InF with the 3GPP reference [8] for calibration and validation. Using an example (`three-gpp-industrial-channel-example`) that was designed according to the parameters of Table I, obtaining results for the suggested KPIs. The aim is clearly to validate the channel model through different metrics.

The distance between BS antennas and their height, carrier frequency, transmitted power, noise figure, number of BS and UT, can be configured for any of the propagation sub-scenarios, i.e. InF-SL, InF-DL, InF-SH or InF-DH. On the other hand, the sub-classes described in Section III are the ones used to compute the channel state, propagation loss, Signal to Interference & Noise Ratio (SINR) and DS.

For instance, to obtain InF-SL results, it is necessary to create an instance of the `ThreeGppIndoorFactorySLChannelConditionModel` and `ThreeGppIndoorFactorySLPropagationLossModel` sub-classes. Consequently, both sub-classes must be modified according to the required sub-scenario.

Even though both 3.5 and 28 GHz frequency bands have been simulated as established in Table I, this paper focus for simplicity on those results obtained at 28 GHz only. The rest of the results are available at the following repository [14].

For the network deployment, the system layout and hall locations detailed in Table I were considered. A total of 180 UTs uniformly distributed and 18 BSs based on Inter-Site Distance (ISD) of the respective sub-scenarios have been deployed. All users in the mapped area are attached to the BS server, considering the best Reference Signal Received Power (RSRP). For each sub-scenario, the ns-3 isotropic antenna model has been used with an antenna element (vertically polarized) [3], for both Tx and Rx. The following metrics are analyzed using the Cumulative Distribution Function (CDF).

A. Coupling loss

In this case, both antenna gains at the receiver and transmitter are 0 dB for the RSRP computation. Moreover, the total transmit power per Transmission and Reception Point (TRxP) is 30 dB. Fig. 2 shows the coupling loss for each of the InF sub-scenarios. It can be appreciated that the range of values is slightly different. The high scenarios (InF-SH and InF-DH) have narrower ranges, and the sparse ones (InF-SL

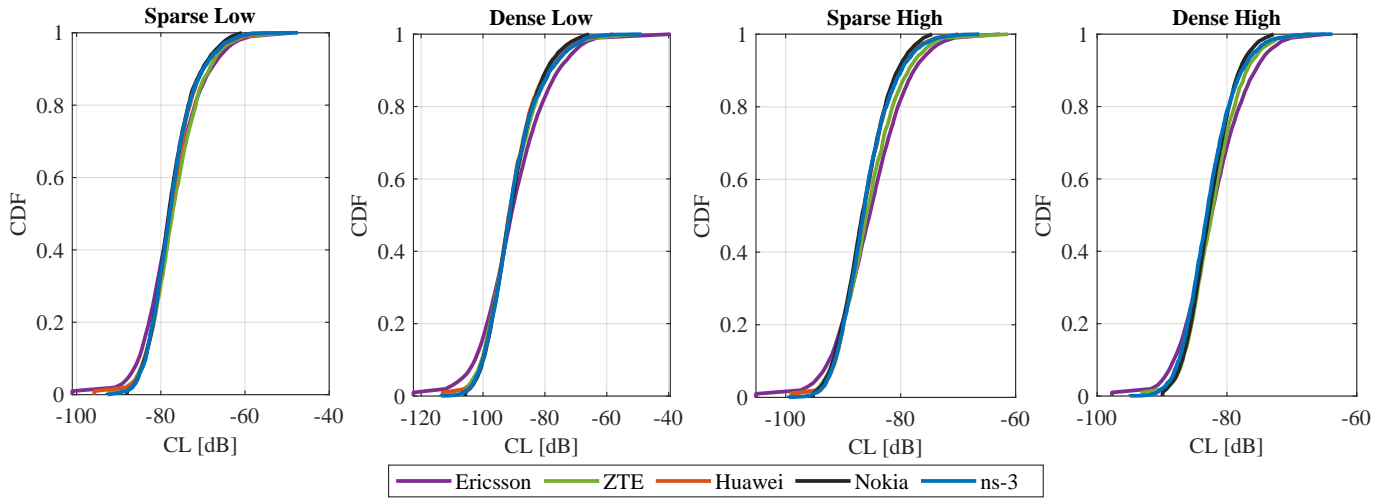


Fig. 2. Coupling loss for four sub-scenarios at 28 GHz.

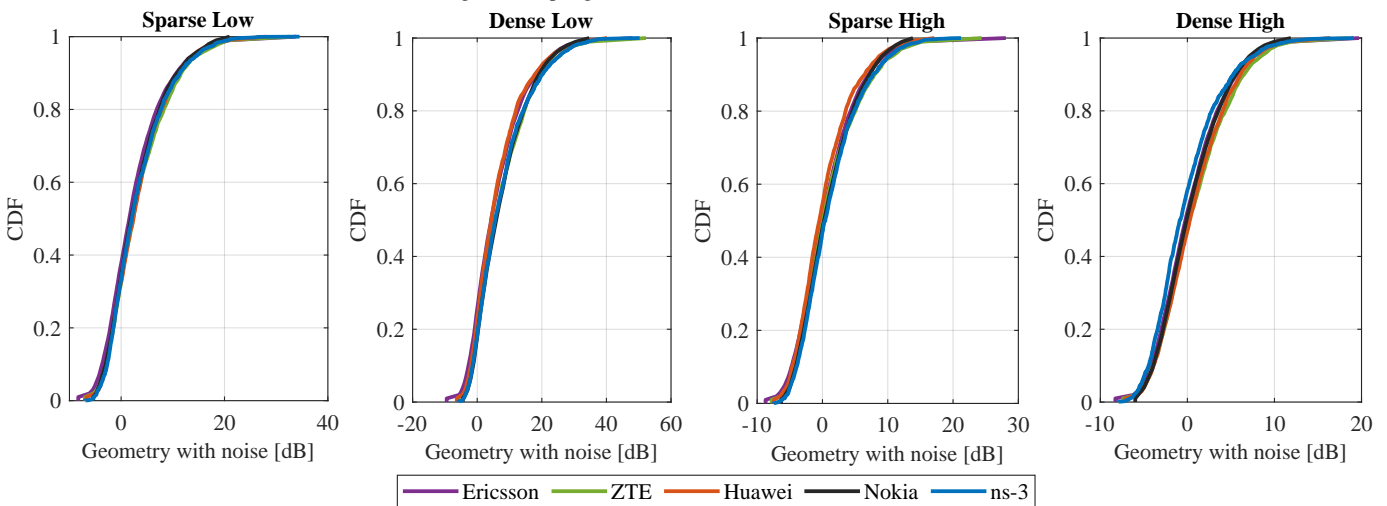


Fig. 3. Geometry with noise for four sub-scenarios at 28 GHz.

and InF-DL) have higher top values. Overall, the trend is very similar to the results obtained in [8], which leads to the conclusion that the channel model is validated.

B. Geometry with noise

The geometry with noise or SINR is reflected in Fig. 3. The highest levels of interference signals are reached in low scenarios (InF-SL and InF-DL). Almost all sub-scenarios fit perfectly, except for InF-DH, where the curve shifts to the left when the CDF values are intermediate. This means that there are some users with the worst SINR, while the majority receive a better SINR.

C. Geometry without noise

Fig. 4 shows the geometry without noise of ns-3 against companies, The InF-SL, InF-DL and InF-SH trends are almost similar to the behaviour of the aforementioned companies and suggest that majority of users receive better geometry without noise.

At the same time, InF-DH curve is slightly positioned to the left, this shows that lower values of geometry without noise are achieved. This suggests that in this sub-scenario, more users receive worse signals according to this KPI. Comparing these metrics with the aforementioned companies, their and ns-3 plots are almost aligned in the four sub-scenarios. This proves that this channel is validated with this KPI.

D. Delay spread

Fig. 5 shows a highly accurate results comparing to the other references. For this particular KPI, the results in red are different than the rest of references in some areas. However, the results of this work fit perfectly within the calibration curves. This result means that the delay spread of the ns-3 InF is the same as that obtained by other entities evaluating the same models. In [15] suggests modifying some parameters that may improve DS. Nevertheless, this work shows results with the initial configuration proposed by 3GPP [3], since the metrics obtained fulfill the expectations.

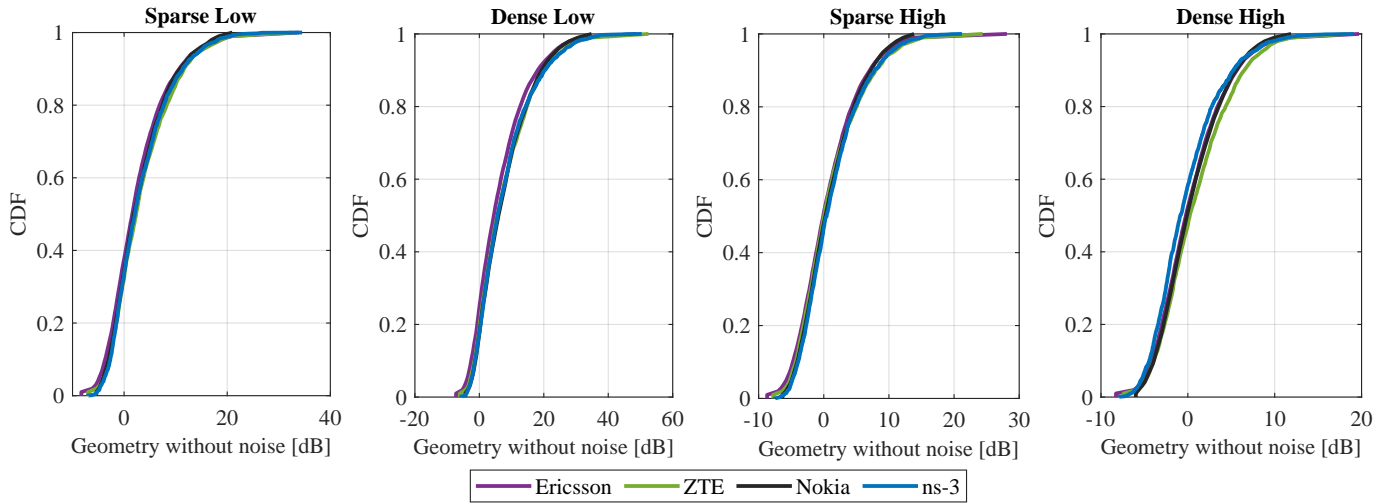


Fig. 4. Geometry without noise for four sub-scenarios at 28 GHz.

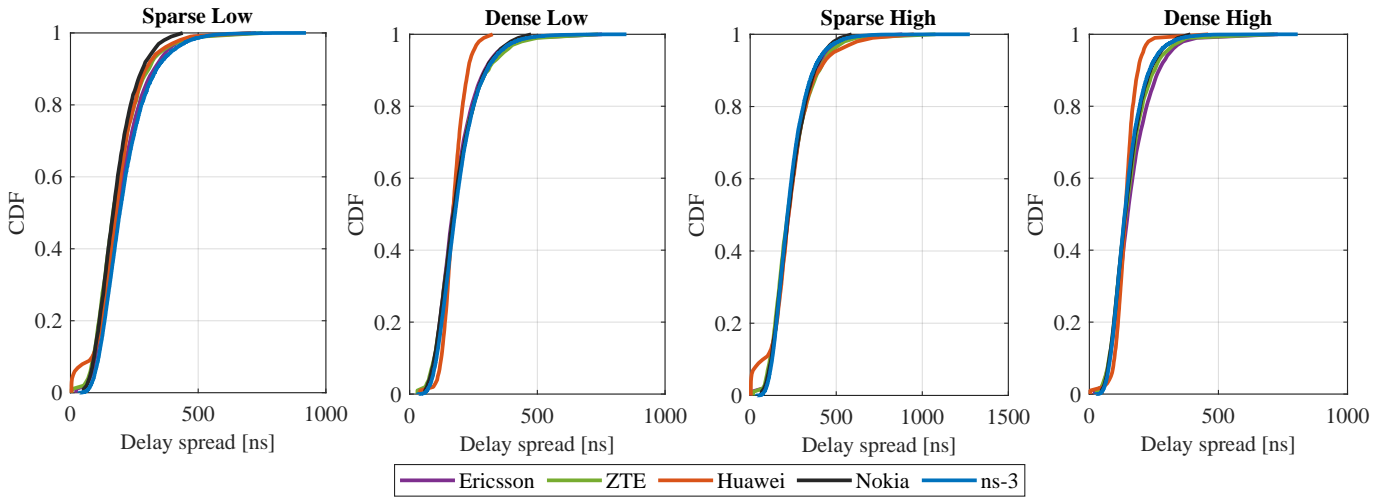


Fig. 5. Delay spread for four sub-scenarios at 28 GHz.

V. CONCLUSION

This paper described in detail the implementation process of the InF channel model, defined in 3GPP Release-16, as an extension tool for the ns-3 open-source simulator. As main contribution to the research community, this work permits to easily update the ns-3 simulator with the code provided in [14]. To validate such implementation, a calibration process has been also performed, considering the specific parameters proposed by 3GPP in [3]. The results obtained have been compared against those in [8]. Such results show a similar trend for all the metrics considered, i.e., CL, Geometry with noise, Geometry without noise and DS. After such calibration, we can conclude that this work will permit future initiatives to use ns-3 as a reliable tool to evaluate industrial scenarios, by using the InF channel model herein implemented.

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