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Virtual Automation Network Simulation (VANSIM): A tool for shared 5G campus networks in industrial working and co-working spaces

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Abstract: 5G networks are currently adapted more and more in industrial applications due to their high-speed data transfer, low latency, and increased capacity. To address growing demands and increase cost-effectiveness, the idea of shared 5G campus networks has emerged, akin to co-working spaces known from office environments. This is especially beneficial for small and medium enterprises in industrial parks looking to incorporate 5G technology into their automation needs. In order to ensure the network can meet the diverse application requirements of all companies involved, a simulation platform called Virtual Automation Network Simulation (VANSIM) is under development. VANSIM aims to allow companies to validate and test the feasibility and compatibility of shared 5G networks pre- and post-installation from the perspective of the automation applications. This paper focuses on validating this simulation platform for passive environmental influences by comparing its results to real-world measurements.

Keywords: Industrial wireless networks, Shared campus network, Private networks, Non-public networks, Co-working spaces, Network management, Network simulation, 5G network, Application requirements.

1 Introduction

In recent times, considerable attention has been directed toward 5G campus networks due to their remarkable attributes compared to preceding cellular network generations. These intrinsic capabilities have opened doors to various applications, such as industrial automation, remote healthcare, and autonomous vehicles. The surging demand for 5G connectivity, coupled with its substantial costs and environmental ramifications, has prompted the investigation regarding the concept of shared 5G campus networks. These networks enable multiple companies to share a single 5G infrastructure, particularly relevant for smaller enterprises in clusters like industrial parks (dt. "Gewerbegebiet").

Utilizing a shared network offers cost-saving benefits for individual companies, encompassing both initial installation and ongoing operational and maintenance expenses. However, the suitability of a 5G campus network within an industrial park relies on its capacity to meet the diverse application requirements of all companies concurrently. For example, one company may rely on a network of RFID tags and readers to manage logistics, another needs to monitor equipment remotely using IoT devices, such as temperature sensors. The first requires low-latency communication to ensure real-time updates, while the latter needs to transmit large volumes of data. These unique

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communication needs must be accommodated within the shared 5G campus network infrastructure. Therefore, it is essential to assess the feasibility of implementing such a shared network before installation and thoroughly test its performance afterward. This research aims to facilitate this evaluation process by introducing a simulation platform called Virtual Automation Network Simulation (VANSIM).

In the following sections, we introduce a general model for shared 5G campus networks. This model sets the foundation for our document's primary focus, which involves the modeling and analysis of passive environmental factors affecting shared 5G communication within industrial and co-working spaces. We then offer an overview of our investigations into channel models and present an in-depth analysis of our findings.

1.1 Related work

In the previous work [YCU23], the authors introduced VANSIM and investigated its validity against passive environmental conditions. Their findings suggested that modifications to current channel models, particularly in terms of fading calculations, were necessary. Building upon this foundation, our work follows a similar structure and aims to further validate and improve VANSIM.

While previous research, such as [Or19] and [AC19], has motivated the deployment of non-public 5G networks, and web articles like [Gr18] have highlighted the benefits of shared network usage, and papers like [Dü19] have delved into signal propagation within indoor industrial environments, our primary goal sets us apart. Our ultimate objective is to develop a platform that not only evaluates propagation conditions but also focuses on the broader perspective of applications. In essence, we are providing a holistic assessment from the applications' perspective, considering their diverse needs and the specific conditions in which they operate.

1.2 Area of consideration

The findings outlined in this paper are derived from the research project "5G Industrial Working and Co-Working Space (5GIWCoW)". The project consortium comprises companies located within the Technology Park Ostfalen (TPO) close to Magdeburg, as illustrated in Figure 1. The specific project partners are enumerated in [5G23]. Presently, preparations are underway to deploy a dedicated, non-public 5G network intended for shared utilization. Within this context, the project partners are strategically planning the implementation of 5G communication for a pilot system, encompassing the following illustrative applications such as programming of welding robots and enabling remote control of robotic systems.

TPO has served as the geographical domain under consideration for the validation of the VANSIM in the previous work of the authors [YCU23]. In the present work, new measurements have been conducted at Wissenschaftshafen in Magdeburg. These measurement results have been used for further validations and modifications of the physical layer representation in VANSIM.

Figure 1: Position of the project participants and the shared 5G base station (gNB) [Go22].

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2 Methodology

2.1 General

The approach begins with the development of a model for the shared use of a non-public 5G network inspired by a model of the wireless industrial automation system outlined in [IE22]. This model is then implemented using an open-source network simulator. Subsequently, it has been examined how environmental factors such as intervisibility, mobile or static objects, and natural environmental conditions impact the shared 5G network’s performance in an industrial park. This would help us to validate the physical layer of the channel model in VANSIM and progress toward our goal, which is a reliable platform that can consult the industrial park members on the effectiveness and feasibility of the shared network before and after installation.

2.2 Model for 5G communication in industrial working and co-working spaces

Drawing from a general model of the wireless industrial automation system outlined in [IE22], we have developed a tailored model designed for the deployment of shared non-public 5G networks within industrial parks. In contrast to the original model, which accounts for the coexistence of various wireless systems within a unified radio environment, the model, depicted in Figure 2, is designed for a single 5G network shared among different companies, with distinct applications and distinct radio environments. In this model, we view the various applications in the industrial park as a wireless industrial automation system. This system encompasses one or more distributed automation systems, multiple radio environments, and a singular 5G communication infrastructure. Each distributed automation system serves as a representation of a specific application, with the potential for multiple applications to be associated with a single company.

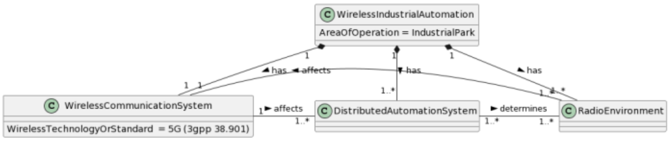

Figure 2: The class model of the wireless industrial automation system based on [IE22].

Given the possibility of having varied environmental conditions within each distributed automation system, the need arises for one or more models of these radio environments. For instance, if one automation system involves temperature and humidity sensors in both indoor and outdoor environments when modeling the transmission medium, it's essential to represent both environments accurately, as they vary significantly. The specifications of the distributed automation system, for example, the positioning of wireless devices, primarily determine the behavior and attributes of the radio environment. Conversely, changes in the radio environment have an impact on the 5G communication system, indirectly influencing the distributed automation system.

The class models of the 5G communication system, distributed automation system, and radio environment and their interfaces are demonstrated in Figure 3. According to this model, the radio environment influences can be classified into two categories: active and passive influences. Active influences arise from disruptions caused by external wireless devices or equipment emitting electromagnetic waves within the relevant frequency range. In contrast, passive influences are a consequence of the physical environment, which includes factors like stationary and moving obstructions, reflective surfaces, and transmission distances. These passive influences result in path loss and fading effects. For this paper, our primary focus will be on exploring the passive influences.

The impact of the radio environment on the application can be assessed by examining network-related performance parameters, including the Signal to Interference plus Noise Ratio (SINR). These parameters are provided by the communication system's functions and can be quantified using specialized equipment, such as the Mobile Network Scanner (TSMA) from Rohde & Schwarz. TSMA measures signal strength independent of any device being active on the network. Furthermore, we can gauge the impact of the radio environment by considering application-related performance parameters, such as transmission time or update time. These parameter values are established in connection with logical links that interconnect locally distributed automation functions.

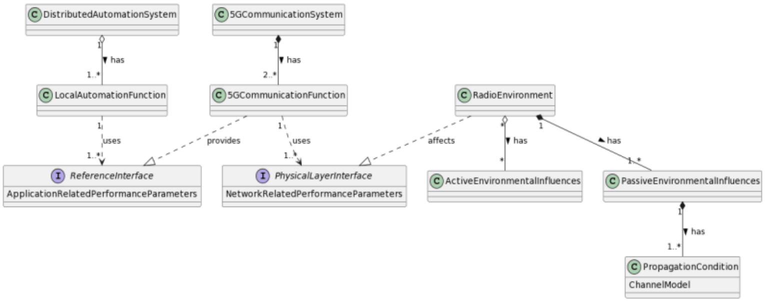

Figure 3: The class models of the WCS, DAS, and RE in accordance with [IE22].

2.3 Simulation platform for 5G communication in industrial working and co-working spaces

VANSIM is designed to be adaptable for various use cases, whether in an industrial park with multiple companies or a single company with diverse applications. The foundation is built upon the open-source 5G new radio network simulator, Simu5G, which empowers users to create new modules, algorithms, and protocols [Si23]. This framework is inherently well-suited for implementing the shared 5G communication system model and is built on top of OMNeT++.

The network simulators provide a virtual representation of the network infrastructure, protocols, and components involved in a 5G network deployment that replicates the behavior of a real 5G network. It enables users to evaluate the impact of different configurations or algorithms and test various scenarios without the need for real-world deployment. There exists plenty of 5G network simulators that could have been used to implement VANSIM such as Ns-3 [Ns23], NetSim [Bo23], and OPNET [Op23]. Among these, we have chosen OMNeT++ because of its application perspective which makes it well-suited for implementing the distributed automation system model, presented in Section 2.2.

Our objective is to evaluate the suitability of existing Simu5G channel models for the specific conditions in industrial working and co-working spaces in TPO. This section provides an overview of Simu5G and its channel models.

Simu5G supports both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) modes, supporting heterogeneous gNBs (macro, micro, pico, etc.). The simulator employs a customizable channel model at the physical layer, although it lacks the granularity of modeling resource elements, thus not including reference signals. Consequently, the received power calculations in Simu5G are independent of the specific resource element used for signal transmission.

The 5G device and gNB are implemented as compound modules, allowing connections to other modules for network composition. Both include the New Radio stack and all its sublayers. Additionally, Simu5G supports Carrier Aggregation (CA) and various numerologies.

Communication through Simu5G occurs via an OMNeT++ message exchange when a MAC Protocol Data Unit (PDU) is transmitted from sender to receiver. Upon receiving the message, the receiver employs various channel models to determine the received power. These channel models are capable of computing path loss, slow fading, and fast fading. The specific path loss calculation utilized is contingent upon the chosen scenario. Available scenarios in Simu5G's NR channel model are Urban Macrocell, Urban Microcell, Rural Macrocell, and Indoor [Side23].

The path loss models consider two critical parameters for each scenario: distance and Line-of-Sight (LOS) or Non-Line-of-Sight (NLOS) conditions. These are modeled according to 3gpp documentation [3G22]. The log-normal distribution model calculates slow fading, with a specified standard deviation for both LOS and NLOS scenarios. Fast fading in Simu5G primarily depends on the doppler shift induced by a moving 5G device. In the absence of a doppler shift, and with a stationary 5G device, the fading remains constant.

3 Evaluation of models for passive environmental influences

3.1 Conductions of real-world measurements

The mobile network scanner measurements provide essential values for assessing VANSIM. These measurements indicate the Reference Signal Received Power (RSRP) of the second synchronization signal within the Physical Broadcast Channel (PBCH) block. This parameter, termed SS-RSRP, reflects the power level of the synchronization signals received by the 5G device from the base station; further details can be found in [Ko19].

Figure 4: Different measurement points at Wissenschaftshafen [Go23].

For the measurement campaign conducted at Wissenschaftshafen, the TSMA was specifically set up to measure 5G band n78. This band, with compatibility spanning from 10 to 100 MHz and a carrier frequency range of 3.3 to 3.8 GHz, aligns with the parameters of Wissenschaftshafen‘s network. Following these configurations, the base station was positioned on one of ifak's balconies with a height of 17.76 m, and the TSMA antenna was placed in various LOS and NLOS locations to measure SS-RSRP. The distinct measurement points, depicted in Figure 4, will be utilized in the subsequent sections to validate the incorporation of passive environmental influences in VANSIM.

3.2 Channel modeling in VANSIM

In this section, the modification and configuration of the channel model implemented in Simu5G are presented. These enhancements are guided by a comparative analysis between the simulation results and empirical measurement results obtained within the Wissenschaftshafen area, aiming to closely replicate real-world conditions. As concluded in [YCU23], for the stationary devices, the simulation results were found to be time invariant. This has shown the limitation in the existing Simu5G, which does not account for the dynamic influence of the physical environment on the signal strength, i.e. it needs to be time variant. The channel model has been modified further in this work to incorporate these environmental influences.

Table 1 is a list of the main parameters in Simu5G that are set according to the 5G network’s configuration at Wissenschaftshafen.

Parameter name	**Value/unit**
gNB transmit power (P_{tx})	23 dBm
Bandwidth	100 MHz
Subcarrier spacing	30 KHz
TDD ratio (DL:UL)	4:1
Carrier frequency (f_{c})	3.75 GHz

Tab. 1: Main parameters of the channel model.

The Received Signal Reference Power (RSRP) is determined by equation (1). The sender’s transmit power is determined by P_{tx} and is adjustable. The computation of distance-related path loss is predicated using the eta power law (a_{pl}) as, for example, described in [UWR20] shown in equation (2). The main reason is that the a_{pl} model can easily be adapted to a specific environment by adapting eta (η) as opposed to using e.g. free space loss. Subsequently, the slow fading phenomenon (a_{sf}) is characterized by a log-normal distribution [Qu23] as shown in equation (3). Noise Figure (F) and implementation loss (I) are also defined in this calculation. These refinements collectively contribute to a more realistic representation of the wireless communication channel within the Simu5G framework.

$$\text{RSRP} \;=\; P_{\text{tx}} - a_{\text{pl}} - a_{\text{sf}} - F - I \tag{1}$$

$$a_{\text{pl}} = \eta \cdot 10\log_{10}\left({}^{d}\!/_{\text{m}}\right) + 20 \cdot \log_{10}\left({}^{f_{\text{c}}}\!/_{\text{GHz}}\right) + 32.44 \tag{2}$$

$$a_{\text{sf}} = 10 \cdot \log_{10}\left(e^{\mathcal{N}(\mu,\sigma)}\right);\;\; \forall\sigma = \sqrt{\log(1+\sigma_{\text{l}}{}^{2})}, \mu = 0 \tag{3}$$

3.3 Results and Discussion

In this section, first, the parameter η for each measurement point is estimated. This estimation is performed by excluding the a_{sf} calculation. Subsequently, we proceed to estimate the variance of the log-normal distribution (σ_{l}) for each data point, accomplished by omitting the a_{pl} calculation. The detailed findings derived from these analyses are presented in Table 2 for reference and examination.

Inter-visibility	**Measure-ment point**	**η (F+I included)**	**η (F+I = 30 dB)**	**η (F+I = 50 dB)**	**σ_{l}**
NLOS	Point 1	5.25	3.79	2.83	0.6
	Point 2	4.89	3.44	2.48	1.1
	Point 3	4.86	3.41	2.44	0.6
	Point 4	5.22	3.78	2.82	0.3
	Point 5	4.7	3.25	2.29	0.2
	Point 6	5.3	3.84	2.87	0.2
	Point 7	5.65	3.79	2.54	1.3
	Point 8	6.54	4.77	3.59	0.3
LOS	Point A	5.45	3.11	1.54	0.1
	Point B	4.62	3.05	1.99	0.3
	Point C	5.76	4.03	2.88	0.6
	Point D	5.65	3.81	2.57	0.7

Tab. 2: Estimated parameters for measurement points.

To prove the robustness and consistency of the calculations, we calculated η in three modes as shown in Table 2. In the first mode, we factored in the *F* and *I* within the computation of the a_{pl}. Subsequently, in the second and third modes, we explored scenarios where *F*+*I* was estimated at 30 and 50 dB, respectively. The results have shown a consistent distribution across all three modes. This confirms the reliability and uniformity of the RSRP calculations within the VANSIM. Besides, the value of η in LOS scenarios is supposed to be around 2 which results in the free path loss. With this fact, it can be concluded that the approach with *F*+*I* = 50 dB is more reasonable than the other two.

In Figure 5, the distribution of one NLOS and one example LOS point is illustrated. The blue distribution shows the real-world RSRP behavior, while the orange distribution visualizes the predicted RSRP behavior. It can be seen that if we use the estimated parameters extracted from the same point, the calculated RSRP distribution looks close to the measured one.

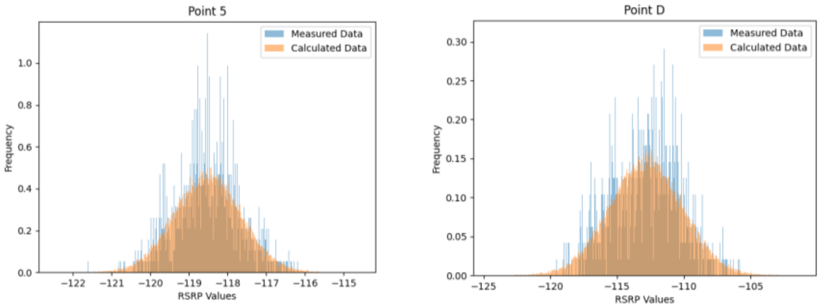

Figure 5: Points 5 and D simulation results vs TSMA measurements using corresponding estimated parameters.

On the other hand, if we take the average of estimated parameters derived from two NLOS points to predict the RSRP at a third NLOS point, the distributions are different. Figure 6 depicts the calculated RSRP values of points 1 and 5, using the estimated parameters obtained from measurements conducted at points 2 and 4. An intriguing observation emerges from the comparison: the prediction accuracy for point 1 appears to be better than that for point 5. This could be due to the passive environmental influences, such as signal reflections originating from structures located on the opposite side of the harbor, which exclusively affect point 5. However, the inaccuracy is – from a wireless system's perspective – reasonably small.

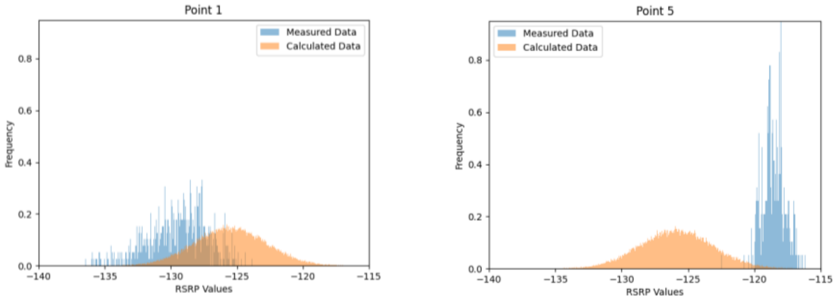

Figure 6: Points 1 and 5 simulation results vs TSMA measurements using the average of the estimated parameters for points 2 and 4.

From these results, it can be concluded that the conventional categorization of LOS and NLOS could be extended to achieve a representation of real-world conditions that are accurate enough to ensure a simulative validation adhering to industrial applications' requirements. To enhance the predictive precision, additional categories are to be introduced that account for diverse passive environmental influences including reflection, scattering, and diffraction. Another category could be the obstructed LOS. Point 3 is an example of such a propagation condition. This nuanced categorization promises a more comprehensive and realistic modeling of wireless signal propagation in complex environments.

4 Conclusions

In order to predict the behavior of the network it is important to have a stochastic estimation of the passive environmental influences. This aspect has been implemented and investigated in the present paper. Specifically, slow fading has been implemented to mimic temporal variations through a lognormal distribution. This serves as a step towards achieving a more realistic representation of wireless channel characteristics.

To validate these modifications, the channel model was assessed using the measurements obtained from the 5G network deployed at Wissenschaftshafen considering LOS and NLOS locations. The consistency of the RSRP calculations has been validated and further steps have been identified.

Our future work will focus on specifying more categories and critical locations in our measurement campaigns to enhance the adaptability of our simulation. Moreover, we will validate VANSIM for application-related performance parameters using the Funk-Transfer-Tester (FTT) results. FTT, a device developed by ifak, assesses communication solutions for industrial automation applications by emulating the communication behavior of the application and measuring application-related performance parameters. An essential component of FTT is the Multiface, which integrates real devices with various communication interfaces into the test system and generates test data traffic [If23]. FTT tests in accordance with [Vd19] and [5G19]. See [Gr08] for more details. Finally, we aim to test the shared network concept through the use cases that consider several properties with different physical environments to validate VANSIM for shared network scenarios.

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