Open Source 5G-NSA Network for Industry 4.0 Applications

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***Abstract*—Industry 4.0 seeks the digitization and interconnection of all production processes. Due to the huge number of sensors, robots, machines and other devices that need to be interconnected, the Fifth Generation (5G) becomes an enabling technology. In order to address this challenge, this paper presents the implementation procedure of a 5th Generation 5G Non-NSA private network based on Open Air Interface (OAI) and presents the advantages and limitations of OAI that will be useful for academia and the industrial sector. A real use case has been evaluated to demonstrate the capabilities of the network, where an Automated Guided Vehicle (AGV) is remotely controlled and monitored using an open source 5G-NSA private network. This paper presents the key steps of the network implementation and analyzes the results measurement campaign. Indeed, a network created with OAI allows evaluating the benefits of many smart manufacturing solutions but with certain limitations in terms of bit rate, latency and number of active users in the private network.**

***Index Terms*—Industry 4.0, Open Air Interface, Non-StandAlone 5G, Latency, Automated Guided Vehicle, Remote Driving.**

I. Introduction

The industry is constantly evolving and is now on its way to a new stage known as the fourth industrial revolution or Industry 4.0. This revolution is a paradigm shift that consists of the digitization and interconnection of all production processes with the aim of increasing market supply and increasing operational efficiency [1].

Nowadays, the communications of industrial process devices are based Ethernet or fiber. However, new technologies are being introduced, such as Time Sensitive Network (TSN) and Open Platform Communications Unified Architecture (OPC UA), which enable important requirements for automation systems to be met. [2] However, due to the dynamism of Industry 4.0, a shift from wire-based solutions to high-speed and reliable wireless solutions is required to make the deployment of industry components more flexible [3]. A strong candidate to provide the wireless solution for Industry 4.0 is the 5G mobile. New Radio (NR) is the new radio access interface that has been developed to support the new requirements of 5G. Within those requirements are the three types of communications defined by the International Telecommunications Union (ITU) for 5G: Ultra-Reliable and Low Latency Communications (URLLC), Enhanced Mobile Broadband (eMBB) and massive Machine Type Communications (mMTC) [4]. On the other hand, it is important to note that two solutions have been proposed as strategies for the deployment of 5G networks. The first one, known as Non-Standalone (NSA), is a transition to 5G where the radio interface is 5G but the control functions relies entirely on the Evolved Packet Core (EPC) of Fourth Generation (4G) Long Term Evolution (LTE) network. The second solution, known as Stand-Alone (SA), is a complete stand-alone 5G network that integrates both NR and a new Fifth Generation Core (5GC).

An interesting 5G network deployment option for the industrial and research sector is the use of private 5G networks operating in unlicensed bands. To this end, one alternative is to implement a 5G network using OAI [5]. OAI is an open source initiative that provides a Third Generation Partnership Project (3GPP)-compliant reference implementations of key elements of 5G Radio Access Network (RAN) and 5GC that run on general purpose computing platforms together with Software-Defined Radio (SDR) cards for the radio functions. [6] It allows users to set up a compliant 5G network and inter-operate with commercial entities [7].

This paper presents how to deploy a OAI-based 5G network in a factory environment and highlights its main advantages and limitations. On the other hand, the performance of the Fifth Generation Non-Standalone (5G-NSA) network has been evaluated in a real scenario, where an AGV is remotely monitored through the 5G-NSA network. The AGV remote driving system is based on an operating system based on Ubuntu LTS with open source licence called Robot Operating System (ROS). The remote control of an AGV within the industry allows optimizing the logistics in the plant, performing tasks such as collection and distribution of all types of materials. It also helps to reduce accidents in the workplace, as it can be used to inspect high-risk areas for the operator. Finally, for this testbed, an analysis of some KPI, such as Signal to Interference plus Noise Ratio (SINR), latency and throughput, is presented.

The remainder of the paper is as follows: in Section II explains the 5G-NSA system setup using OAI. In Section III the features of the AGV system setup base on ROS is presented. In Section IV presents the discussion of the results, in which an evaluation of coverage, throughput and latency is made. The conclusions and future lines are found in section V.

II. 5G–NSA System Setup

This section presents the deployment of an open source 5G-NSA network based on OAI. The deployed configuration is shown in Fig. 1, which consists of one server for the EPC and two Universal Software Radio Peripheral (USRP) that are configured as g-Node B (gNB) and Evolved Node B (eNB). In this setup the EPC is used to launch 5G services and the traffic is split for both the 4G and the 5G networks.

Fig. 1. Components used for the deployment of a OAI 5G-NSA network.

A. Technical Features

The EPC implementation is done by dockers on Ubuntu 18.04 installed on a server. The server contains the network elements corresponding to the Mobility Management Entity (MME), Home Subscriber Service (HSS), Serving Gateway (S-GW) and Packet Data Network Gateway (P-GW). To implement the HSS, Cassandra version 2.1 was used (available in [8]). The same server is used for the implementation of the RAN, for which the OAI repository has been cloned. Additionally, two onmidirectional monopole antennas and two USRPs have been used as radiating elements. It is important to mention that the network operates in the NR 78 band, in 3.6 GHz. The technical features of the software and hardware used are detailed in Table I.

B. USRP Setup

Before deploying the setup it is necessary to decide which USRP model it is going to be used as radiance element. Ettus Research provides a wide fan of possibilities, depending on the use and performance desired. While serie “b” is cheaper and simple to use, serie “N” provides better performance since it can make bigger use of the specter. Serie “b” loads the configuration in its Field Programmable Gate Array (FPGA) each time an execution is made. On the contrary, serie “N” includes a Linux based operating system that permanently modify some of the features of the USRP in order to adapt it to the desired deployment. An USRP makes use of his integrated FPGA in order to perform all the radio functions via software. Those functions were classically implemented using hardware, like filters, transceivers or amplifiers. An FPGA is organized in different sections each of which have a number of pins that can be used to perform a particular function. In order to assign a function to a FPGA pin, the USRP Hardware Driver Ultra High Definition (UHD) is used. These drivers are adapted to each USRP in order to simulate the radio features necessary in order to allocate a 4G or 5G node.

TABLE I
Technical features of the software and hardware used to deploy the OAI-based 5G-NSA network.

OAI Hardware	
Component	**Features**
Server	Superserver 1029P-WTRT(Supermicro)
CPU	Intel Xeon Silver 421632 cores @2.10 GHz
Hard Disk	960 GB SSD
Ethernet Ports	2x10 Gigabit Ethernet + 2x1 Gigabit Ethernet
USB Ports	USB 3.0
Radio device	
Component	**Features**
eNB	USRP b210
gNB	USRP N321
Antenna	Omnidirectional Monopole
OAI Software	
Component	**Features**
Operative System	Ubuntu 18.04
Kernel Linux	Low Latency
OAI Branch	Develop

During the deploy process of the 5G-NSA network within an industry environment, two models of radiance elements were used in order to make different tests. The first solution includes 2 USRP b210, a model that is designed for 4G networks but can also work in 5G networks.

Despite the network was stable, its features were limited by the hardware of the USRP, due to the low sampling rate used, that only allowed bandwithds up to 40 MHz. In addition, other features as using higher power or the possibility of implementing Multiple-Input Multiple-Output (MIMO), are not allowed using these devices.

Therefore, a second deployment was performed, in which an additional bandwidth of 20 MHz was allocated to 5G, and the gNB b210 was replaced by a higher-performance USRP, and the latest USRP released by Ettus Reseach was used, the USRP is N321. It can sample in a rate up to 200 MHz and perform MIMO 2x2. Nevertheless, OAI solution was not compatible with these USRP since the code worked with an UHD that did not control USRP N321 FPGA properly. Consequently, OAI code crashed, since the Linux machine was not able to the control General Purpose Input/Output (GPIO) pins of the USRPs motherboard. GPIO pins are used by OAI to exchange information with the USRP, if those pins of the motherboard are not operative, communication is not effective.

To make OAI code install this UHD, some changes in the build were done. The script is called *“build_oai”* and is used by OAI to install all the dependencies necessary in order to run their solution. In this script there is a function that installs the the UHD is called *“install_usrp_uhd_driver”*. This function installs the UHD from the OAI repository and they have the version 3.14 by default, which is not operative with the USRP. To make the script install the 3.15 version the UHD needs to be installed from source, which downloads it from the provider Ettus Research. In order to make this change, function *"install_usrp_uhd_driver_from_source"* is used. This function is located in the *"build_helper"* script in the path: *"cmake_targets/tools/build_helper"*. In the function, *"git checkout tags/v3.14"* needs to be replaced with *"git checkout tags/v3.15.0.0"*. Using these modifications, once build is done with the command *"build_ oai -I -w USRP −−eNB −−gNB"* it will install UHD 3.15.

Once UHD is installed properly in the Linux machine, there are two ways of updating the UHD of the USRP. The first one needs physical access to the device, and is done by simply load by Secure Digital (SD) card the UHD version, which was previously downloaded and moved to the card. The second makes use of Mender in order to simplify the process. The mender file contains all the processes needed to update the UHD and needs to be sent using File Transfer Protocol (FTP) to the USRP. Once this file is in the USRP, Mender tool will remove previous versions and install the desired one. If the version is not exactly the same as the one installed in the Linux machine a similar error will pop: *"RuntimeError: FPGA component 'noc_shell' is revision* 5 *and UHD supports revision w*4*. Please either upgrade UHD (recommended) or downgrade the FPGA image"*. This means that some components of the UHD are not compatible within versions.

Both the adaptations made to the OAI source code to make it compatible with the USRP N321 and the eNB and gNB configuration files that will be explained below are available for be downloaded from GitHub repository at [9].

C. OAI Setup

The parameters set for the correct operation of the gNB and eNB according to the EPC and USRP used in this deployment are detailed in Table II. The same ones found inside the configuration files for LTE soft modem and NR soft modem. The Internet Protocol (IP) addresses assigned to the network interfaces are configured in the range of our private network.

D. OAI Execution

The process to follow for the execution of eNB and gNB is as follows:

1) Connect the first USRP to the server and run on the console:
   $sudo./lte-softmodem-O<CONFIGURATION\ FILE\PATH>
2) Connect the second USRP and run on the console:
   $sudo./nr-softmodem-O<CONFIGURATION\ FILE\PATH>

III. AGV Remote Driving System Setup

Centralized control of an AGV in an industrial environment was developed with ROS Kinetic Kame, and interconnected through a 5G-NSA network.

The interconnection of different entities is illustrated in the box on the left-hand side of Fig. 2. The technical features of the software and hardware used for the deployment of an AGV in an OAI network are detailed in Table III.

TABLE II
CONFIGURATION PARAMETERS FOR THE GNB AND ENB WITHIN THE OAI REPOSITORY.

Common parameters		
Description	**Acronym**	**Value**
Mobile Country Code	MCC	208
Mobile Network Code	MNC	93
Tracking Area Code	TAC	1
Number of antennas	nb_antennas_tx nb_antennas_rx	1 1
Resource blocks	MN_RB_DL	100
Gain	tx_gain rx_gain	90 115
X2 interface	enable_x2	yes
IP address of the MME	mme_ip_address	"IP_ADDRESS _MME"
X2 interface	enable_x2	yes
LTE soft modem		
Description	**Acronym**	**Value**
Band frequencies	dowlink_band uplink_frecuency_offset	$2680000000L$ -120000000
Networks interfaces	ENB_IPV4 _ADDRESS_FOR_S1 _MME ENB_IPV4 _ADDRESS_FOR_S1U _S1U ENB_IPV4 _ADDRESS_FOR _X2C	"IP_ADDRESS _S1" "IP_ADDRESS _S1" "IP_ADDRESS _S1"
NR soft modem		
Description	**Acronym**	**Value**
Band frequencies	absolute_FrequencySSB dl_frequencyBand dl_absolutyFrequency PointA ul_frequencyBand	641272 78 640000 78
X2 interface	target_enb_x2_ip_address	"IP_ADDRESS _S1"
Networks interfaces	GNB_IPV4 _ADDRESS_FOR_S1 _MME GNB_IPV4 _ADDRESS_FOR_S1U _ADDRESS_S1U GNB_IPV4 _ADDRESS_FOR _X2C	"GNB_IP _ADDRESS _S1" "GNB_IP _ADDRESS _S1" "GNB_IP _ADDRESS _S1"

The architecture used to control the AGV through a 5G-NSA network is shown in the physical scenario depicted in Fig. 2. The area of interest in the factory has 5 rooms and a corridor. The architecture follows a scheme client-server with the client (Control Station) located in Room 1 and the server (Controlled Vehicle) located in Room 3. It is important to mention that the tests was performed only in the rooms $1-3$ (right-hand of Fig.2), which together have an area of 80 m^2, which corresponds to 10 m long and 8 m wide. Room 1, with an area of 6.25 m^2, was assigned to the Control Station. The other rooms represent the space in which the AGV will move

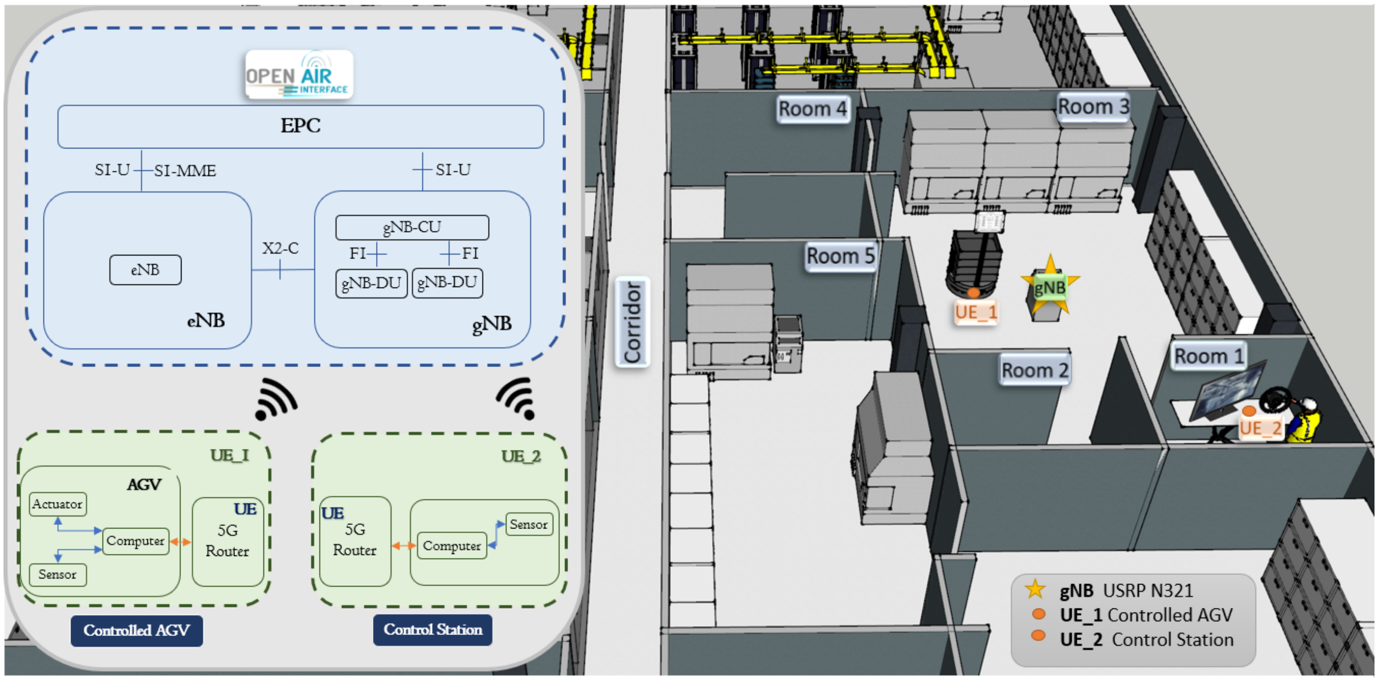

Fig. 2. Schematic of the AGV deployment and 5G-NSA network of the real scenario evaluated.

with a speed of 1.5 m/s.

Room 1 represents the control station where the factory operator controls the movement of the AGV by means of a steering wheel and visualises the environment through a camera installed on the AGV.

The information about the current positioning, speed and image is sent from the different sensors to the computer inside the AGV. Then, via the router that has a Subscriber Identity Module (SIM) configured with the parameters of our network, the data is sent to the router in the control station. In order for the data to pass through the network, the User Equipment (UE) in this case the UE_1 corresponding to the AGV must connect to the gNB which in our case is the USRP N321 and authenticate itself to the EPC. After successful authentication, the data is routed to UE_2. In the opposite case, the positioning and speed data are obtained from the sensor of the control station (steering wheel) and sent from UE_2 to the actuators of UE_1.

The AGV is designed to work only indoors, can transport small materials that together do not exceed 50 kg and has an autonomy of 10 hour. In order to control it within an industrial environment, it is necessary to transmit a good image quality to the controller. In this scenario, a main stream resolution and frame rate of 30 fps (1280 × 720) with a data transmission rate of 7 Mbps was set. It should be noted that this deployment does not contemplate a solution based on planned routes in which the AGV has autonomy, given that it is controlled by a factory operator.

TABLE III
TECHNICAL FEATURES OF THE SOFTWARE AND HARDWARE USED FOR AGV CONTROL.

Hardware	
Component	**Features**
PC	Intel® Core™ i7-10750H CPUs @2.60 GHz (12 CPUs)
CPU	Intel Xeon Silver 421632 cores 2.10 GHz
Camera	USB 3.04 Intel RealSense Depth Camera D4351"
AGV	Summit robot
Router	$H112-370$ "Huawei 5G"
Software	
Component	**Features**
System Operative	Ubuntu 16.04
Kernel Linux	Low Latency
ROS Distribution	Kinetic Kame

IV. Discussion of Results

In order to analyze the coverage of the deployed network, data were obtained at different points in the rooms $1-4$. For the room 5, an extrapolation was made with external points as there was no access to it. On the other hand, the radio equipment was located in the center of room 3, in order to obtain the best possible coverage

A. Coverage evaluation

In order to evaluate the performance of the open source network deployed in an industrial environment, an analysis of the network coverage, Reference Signal Receive Power (RSRP), Reference Signal Received Quality (RSRQ) and SINR measurements has been performed. The SINR obtained is shown in Fig. 3, where it can be seen that it reaches values greater than 30 dB and minimum values close to -5 dB. The low SINR levels correspond to room 4 and are caused by attenuations due to the walls and other obstacles. The first conclusion is that the indoor propagation at 3.6 GHz is limited and the range is not as good as it could be desirable.

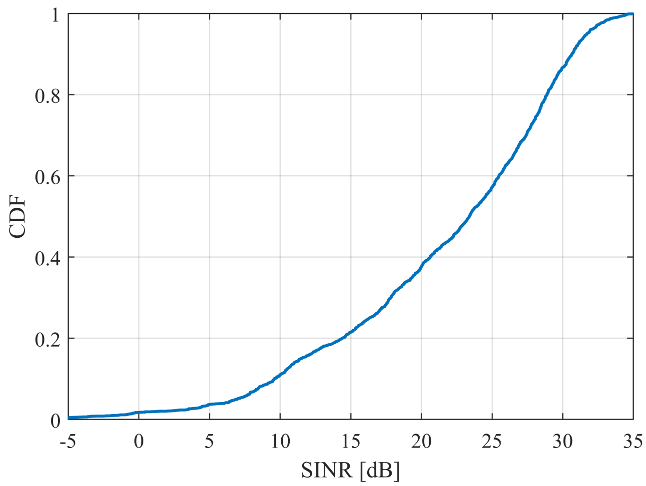

Fig. 3. SINR Measurements.

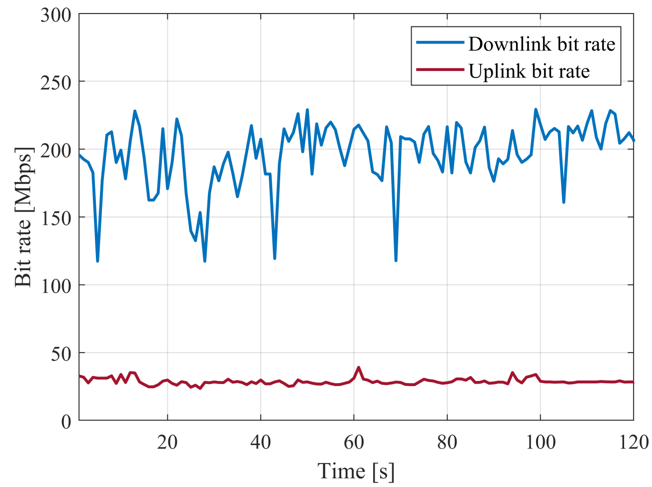

Fig. 5. Bit rate Measurements

In the coverage map represented in Fig. 4 the highest signal power is found in the center of room 3, around the gNB and has values near > -70 dBm. The signal strength decreases quickly while separating from the gNB and the coverage is only good (meaning a value greater than -90 dBm only in Room 3 where the gNB was deployed.

Performing an analysis by rooms, Room 3 has a SINR of $20-30$ dB equivalent to excellent signal level. Rooms $1-2$, on the other hand, have a SINR of $10-20$ dB which also guarantees a good performance but the received signal power presents an important degradation. Room 4 experiences Signal to Noise Ratio (SNR) levels less than 5 dB. This room does not represent an important factor for our final analysis since the AGV will not be controlled in it. It is important to remark that the SINR obtained is very high, due to the fact that the network works in a free band, and it does not coexist with other networks. This ismainly to the fact that the deployment was carried out on the 1st floor of a 5-story industrial building and the walls of the building almost totally diminish the power of the external signals. On the other hand, the deployment is indoors, which helps to isolate it from possible interference from outside, given the huge penetration losses of the walls at the frequency of operation.

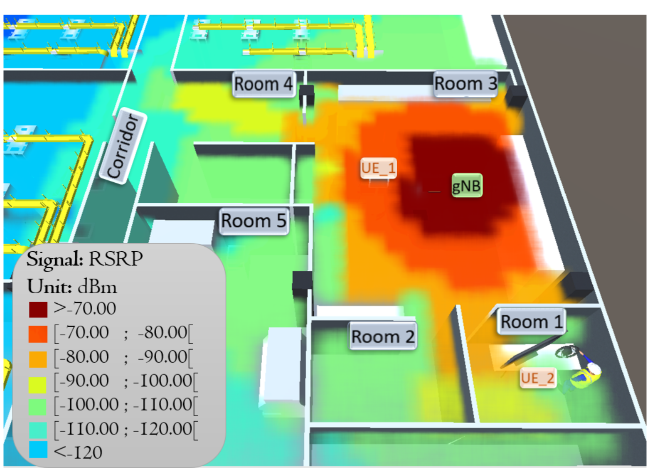

Fig. 4. Coverage Map

B. Throughput and latency evaluation

Although only a maximum bit rate of 228 Mbps in downlink and 46 Mbps in uplink can be achieved as shown in Fig. 5, it is sufficient for the control of the AGV, because between the control data and the transmitted video a higher bit rate of 10 Mbps is required to achieve a correct operation.

Before discussing the results obtained on latency in the OAI-based 5G-NSA network, it is necessary to mention that the deployed solution theoretically allows to connect 16 users by default and up to 256 users if compiled using a dedicated flag [10]. However, there were only 5 5G devices available to perform the testbed. They managed to successfully authenticate and connect to it, but only two of them can receive resources at the same time. This is a important limitation of the OAI-based deployment.

The latency experienced in the network in different scenarios is shown in Fig. 6. In a first scenario where only one user is connected, the minimum end-to-end latency experienced is 19 ms. In other words, the time it takes to transmit the data packet from the control station to the AGV through the 5G-NSA network is 19 ms. As the user requests more resources from the network, the latency increases to values over 45 ms. In a second scenario where two users (UE_1, UE_2) are requesting resources from the network at the same time, the minimum latency raises a little but the median increases from 26 to 28 ms. It is worth mentioning that, in order to evaluate the difficulty of maneuverability, of the AGV with different latency values, in addition to the 5G-NSA network described before, an additional OAI-based LTE network was deployed. The deployment of the LTE network is not discussed in this paper.

To evaluate the difficulty of maneuverability of the AGV as a function of latency, a survey was performed in with 30

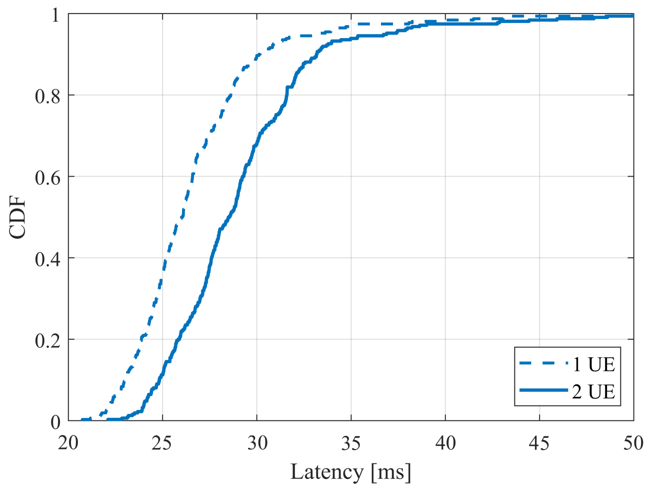

Fig. 6. Latency experience

people participated. They rated their experience on a Mean Opinion Scale (MOS) of five degrees of difficulty. These were: low, low-medium, medium, high and very high. The results obtained are shown in the Table IV. It is observed that there is a directly proportional relationship between the increase in latency experienced in the network and the difficulty of maneuverability of the AGV. Therefore, based on the results of the tests carried out, it is recommended that the control of the AGV be executed over a network whose latency does not exceed 30 ms.

TABLE IV
DIFFICULTY OF AGV MANEUVERABILITY AS A FUNCTION OF LATENCY.

Latency (ms)	**MOS**	**Difficulty of Maneuverability**
20	5	Low
25	5	Low
30	5	Low
40	4	Low-Medium
50	3	Medium
60	3	Medium
70	3	Medium
100	2	High
400	2	High
600	2	High
800	1	Very High
1000	1	Very High

V. CONCLUSIONS

This paper has shown an open source 5G-NSA network deployment applied successfully to an Industry 4.0 use case. With values of SINR, in median, greater than 20 dB, good signal quality and maneuverability was possible in the remote driving of an AGV. Therefore, although the performance of OAI is worse than that offered by commercial solutions currently, it meets the coverage, stability and latency levels required for the correct operation of the AGV communication and control system in real time.

The stage of adapting USRP N321 to the OAI source code has included bug fixing, register debugging and changes to the OAI scripts, which are available in a GitHub repository as indicated in the subsection II-C. In addition, the use of N321 as a radiating element meant that higher bandwidths were supported, which led to higher performance in the tests carried out.

The 5G-NSA network based on OAI has enabled successful and stable interaction between the AGV, the different machines and operators. As a result, the time required to perform tasks such as moving small tools from one place to another has been reduced. Another advantage of using open source networks is that it allows achieving a higher level of debugging, since there is full access to all the source code.

Future research lines include the optimization of the deployed 5G-NSA network, using the USRP N321 with different MIMO configurations and a 5G Core Network. It is also required to investigate other possible open source solutions for 5G networks other than the one provided by OAI, such as Open Ran (O-RAN) Alliance and to migrate the centralized control of the AGV to a decentralized control, in which navigation will be autonomous, using a real-time map of the industrial environment.

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