6G-LoRaGRAN: A Testbed for Researching LoRaWAN and 5G Integration

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***Abstract*—The rapid growth of the Internet of Things (IoT) has increased demand for Low Power Wide Area Networks (LPWANs) that support massive Machine-Type Communications (mMTC) in Fifth Generation (5G) ecosystems. However, integrating LPWAN technologies like Long Range Wide Area Network (LoRaWAN) with 5G infrastructure presents challenges. This paper introduces 6G-LoRaGRAN, a novel testbed framework designed to facilitate research on LoRaWAN and 5G integration. Developed at the University of Granada, this testbed connects a real LoRaWAN network to 5G cores across multiple pilot sites as part of the European 6G-SANDBOX project. The testbed supports remote experimentation through an Experiment Manager, enabling researchers to explore diverse configurations, including customizable network slices, traffic patterns, and real-time resource management. With over 100 deployed LoRaWAN devices and automated connectivity monitoring, the platform serves as a powerful tool for experimentation within a real-world LoRaWAN-5G testbed. Two experiments are presented. The first compares empirical results to theoretical collision probabilities, demonstrating the testbed's ability to support research on LoRaWAN performance and scalability. The second uses two LoRaWAN slices to demonstrate inter-slice isolation.**

***Index Terms*—LoRaWAN, 5G, testbed, IoT, network slicing.**

I. Introduction

The Internet of Things (IoT) represents a transformative technological paradigm, enabling billions of devices to connect and communicate over the Internet. This interconnectivity allows for real-time data collection, monitoring, and automation across a wide range of sectors, including smart cities, healthcare, agriculture, industrial, etc. The growing popularity of IoT has driven a significant increase in the deployment of Low Power Wide Area Networks (LPWANs), thanks to their advantages in performance and cost. These networks offer low power consumption, extensive coverage, cost-effective deployment, and scalability, which makes them suitable for supporting one of the three core services of Fifth Generation (5G)—massive Machine Type Communication (mMTC). However, LPWANs typically suffer from lower data rates and reliability, making them unsuitable for high data rate applications. Research into integrating these networks is gaining attention in both industry and academia to develop a flexible, reliable, scalable, and cost-effective infrastructure that can support a wide range of IoT applications [1].

Long Range Wide Area Network (LoRaWAN) is one of the most popular LPWAN technologies, and integration with cellular networks has been investigated to support mMTC applications in large-scale deployments [2]. Its benefits extend beyond low power consumption and long-range capabilities. LoRaWAN is highly scalable, capable of supporting thousands of devices within a single network, and operates on the Industrial Scientific and Medical (ISM) unlicensed band, thereby reducing deployments costs.

This paper presents the 6G-LoRaGRAN testbed framework, a real LoRaWAN network integrated with 5G, deployed at the School of Technology and Telecommunications Engineering and the Research Center for Information and Communication Technologies at the University of Granada, Spain. Connecting to 5G Cores (5GCs) from various pilot sites -Berlin and Malaga, as well as UGR's own 5GC- within the European 6G-SANDBOX project, 6G-LoRaGRAN acts as a non-3GPP network. This integration provides a real validation example for Mobile Network Operators (MNOs) to reuse their existing infrastructures with minimal investment and seamlessly incorporate LoRaWAN services into their operation and maintenance platforms. It should be highlighted that LoRaWAN and other cellular-based technologies such as Narrowband-IoT (NB-IoT), while serving different use cases and offering distinct advantages, can be complementary technologies, working in tandem to address diverse IoT needs. The main objective of 6G-LoRaGRAN is to offer researchers a real LoRaWAN deployment integrated with 5G networks to support their research, enabling remote experimentation through an Experiment Manager (EM) and eliminating the costs associated with building and maintaining the communication infrastructure.

The rest of the paper is structured as follows. Section II provides a brief overview regarding standalone LoRaWAN deployments by means of both real deployments and simulations, as well as a set of examples of testbeds that includes the integration of LoRaWAN and a 5G backbone. Section III gives a comprehensive technical description of the 6G-LoRaGRAN

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infrastructure along with an explanation of its functionalities. Section IV presents a step-by-step guide for users that want to use this infrastructure platform. Section V presents two sample experiments conducted with the testbed. Finally, Section VI draws the main conclusions from this work.

II. Related Work

In recent years, several studies have proposed real LoRaWAN deployments across a variety of scenarios, such as smart cities, smart agriculture, smart campuses, and indoor environments. Examples include smart city frameworks [3], smart campuses [4], and indoor applications [5]. Additionally, numerous works have focused on simulated LoRaWAN networks to evaluate resource allocation strategies, MAC layer enhancements, and other theoretical solutions without the need for a physical LoRaWAN testbed, as seen in [6] and [7].

LPWAN-5G integration has gained considerable attention as LPWANs can provide connectivity for the majority of IoT devices in 5G mMTC scenarios, meeting requirements for low cost, low power consumption, and wide coverage—capabilities that cannot be fully supported by cellular technologies alone [8]. Several studies have proposed guidelines for integrating unlicensed-band and licensed-band LPWAN technologies with 5GC infrastructure. For example, [9] introduces a LoRaWAN and 4G integration for Industrial IoT, where the LoRaWAN gateway emulates UE/gNB signaling. In [10], the authors explore integrating LoRaWAN with a 5G test network at the University of Oulu, Finland. Among the four proposed methods, they implement the first, utilizing the 3GPP access network for the LoRaWAN gateway to incorporate LoRaWAN packets into cellular traffic. Similarly, [8] proposes integrating a private LoRaWAN into a non-standalone 5G network. In this setup, the LoRaWAN gateway communicates with the gNB as a 5G UE via a 5G modem, allowing LoRaWAN end-devices to interact with LoRaWAN servers—deployed within the 5G core network at the edge—via the gateway, gNB, and EPC. This hybrid network supports both 5G UEs and LoRaWAN end-devices concurrently. Finally, [11] proposes two integration approaches for LoRaWAN and 5G to enhance the mobility and roaming capabilities of LoRaWAN by leveraging 5G security services. The authors validate a non-standalone Long Range (LoRa)-5G connectivity approach using a real-world integrated LoRaWAN and 5G testbed with a single IoT device.

This testbed, to our knowledge, is the first hybrid system integrating LoRaWAN into a 5G architecture with remote accessibility for researchers. It features a private LoRa network with numerous devices and gateways, leveraging network slicing across LoRaWAN and 5G to support differentiated traffic patterns, isolate radio resources via channel frequency reservation, and provide remote access for experimentation.

III. Design and Implementation of the 6G-LoRaGRAN Platform

As commented, the 6G-LoRaGRAN project aims to provide researchers with a LoRaWAN testbed seamlessly integrated with 5G networks, offering a robust platform to support and advance their research activities.

For that purpose, the testbed infrastructure comprises the University of Granada's private LoRaWAN network, which includes a LoRaWAN Radio Access Network (RAN), a LoRaWAN cluster —encompassing all LoRaWAN backend interfaces and integrating an Experiment Manager— and a connectivity module that links the testbed with various 6G-SANDBOX pilot sites through their 5GCs. Fig. 1 illustrates the architecture of the 6G-LoRaGRAN testbed and its components. In the figure, only two computers in the cluster are shown, labeled master and slave nodes.

Key configurable elements for an experiment include selecting a time schedule, choosing the 6G-SANDBOX pilot site for integration, defining LoRaGRAN slices —groups of isolated channels dedicated to a specific tenant— and customizing traffic patterns for each end-device. Additionally, the platform provides APIs for monitoring configuration and performance metrics, as well as for real-time adjustments to resource allocation and traffic patterns.

The following subsections describe the various components of the 6G-LoRaGRAN platform, which together enable the functionality previously discussed.

A. 6G-LoRaGRAN RAN

Over 100 LoRaWAN end-devices have been deployed, including 24 Pycom Fi-Py, 20 TTGO LoRa32, and 60 Heltec LoRa32 units. Both the Pycom and Heltec devices are capable of operating in class A and C modes, while the TTGO devices function exclusively in class A mode. All devices connect via Wi-Fi to the Experiment Manager to receive their transmission parameters (e.g., channel, Spreading Factor (SF)) and traffic patterns to accordingly generate LoRaWAN traffic. Their firmware includes watchdog timers to automatically recover after non-expected failures and can be updated via over the air (Firmware Update Over The Air (FUOTA)). Additionally, the 6G-LoRaGRAN infrastructure encompasses several gateways: one outdoor carrier-grade CISCO IXM gateway (model IXM-LPWA-800-16-K9) and 10 indoor gateways, comprising 5 PyGate units and 5 WiMOD Lite Gateway units. Their Wi-Fi connectivity is checked every minute and recovered if no connection is found, to avoid instability problems and to avoid missing LoRaWAN frames. By enabling or disabling gateways, users can test under various radio conditions, overcoming the limitation imposed by a lack of node mobility. Fig. 2 shows the LoRaWAN deployment for the 6G-LoRaGRAN project.

B. 5G Connectivity Module

The 6G-LoRaGRAN RAN and the cluster are both configured to establish a connection with some of the 5GCs of the 6G-SANDBOX pilot sites. One Intel NUC computer (labeled as "NWU emulator" in Fig. 1) is the responsible of the connectivity towards the different pilot sites. For that, two options have been devised: using a Non-3GPP Interworking

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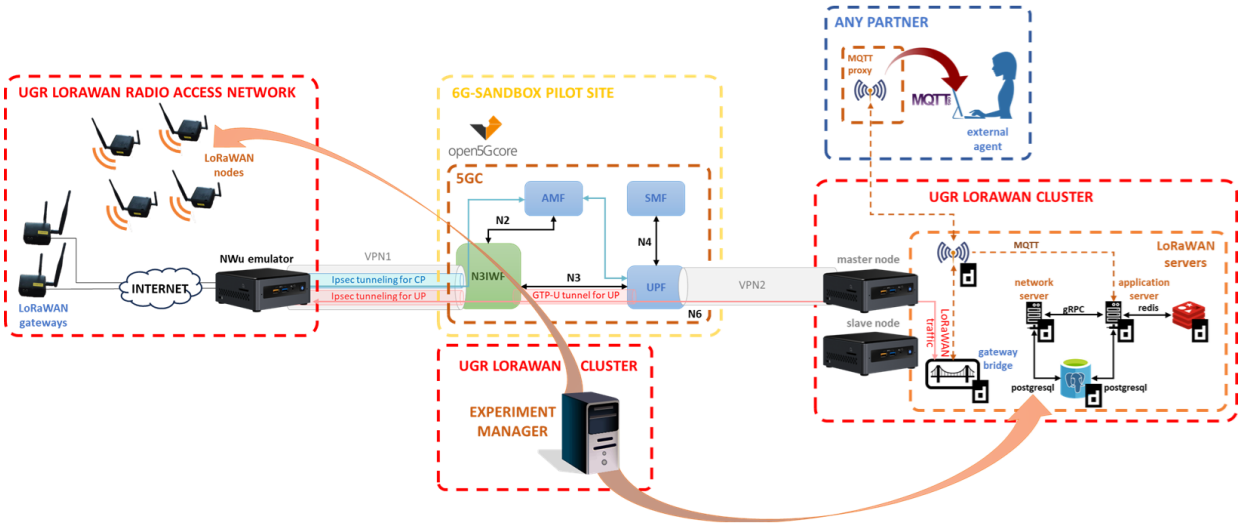


Fig. 1. Connectivity between UGR's LoRaWAN cluster and 6G-SANDBOX pilot sites.

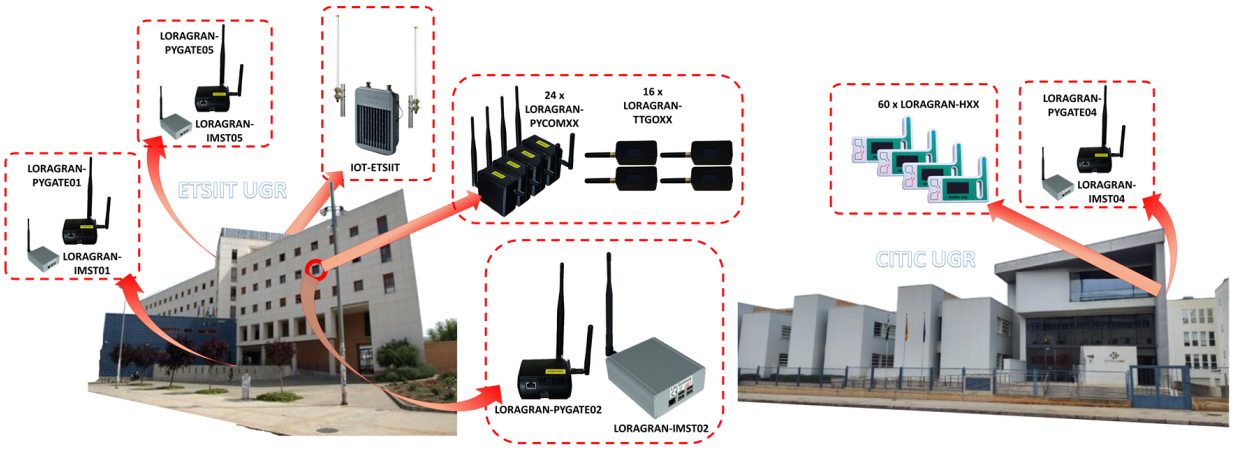


Fig. 2. Deployment of the 6G-LoRaGRAN Radio Access Network.

Function (N3IWF) client (also known as NWu emulator due to the name of the interface between the User Equipment (UE) and the N3IWF) or using UE/gNodeB (gNB) emulators. With the first option, the LoRaWAN RAN is seen as a non-3GPP network. With the second option, the LoRaWAN RAN is seen as a UE/gNB from the 5GC perspective. The selection of one or another option depends on the support from the specific core network. As N3IWF client we have employed the NWu emulator at [12]. We have modified this program, which only worked with Free5GC [13], to support Open5GCore [14] and the Amarisoft core [15]. As gNB/UE emulators, we have employed UERANSIM [16], although other options were available (e.g. srsRAN [17]). Our tests show that UERANSIM performs better due to the simplified emulation of the radio interface and demonstrates high stability, with uninterrupted connections lasting over a month.

Both options employ an mMTC slice (Slice/Service Type SST=3), and the Service Differentiator (SD) allows us to distinguish between traffic from different LoRaWAN slices. Fig. 3 shows a log obtained from an N3IWF client's connection to the UGR Amarisoft core network (see Section 7.2.1 from 3GPP TS 33.501 v15.2.0 [18]).

The connectivity towards the pilot sites is automatized by the Experiment Manager, which checks that VPNs and 5G connections are working properly every 5 minutes. If there is any connectivity issue, the VPNs and 5G connections are recovered automatically. In the case that the connectivity cannot be automatically recovered, a Telegram message is sent to inform about this situation, so one member of the 6G-LoRaGRAN project will perform further checks and actions.

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```
STATE 1:
-------
[ 2024-10-17 20:42:26.971810 ] sending IKE_SA_INIT
[ 2024-10-17 20:42:26.999969 ] received IKE_SA_INIT
[ 2024-10-17 20:42:27.001943 ] DIFFIE-HELLMAN KEY 23bb3d3817488520a6e0d36ebdb92529108ca03dacb69987932f6228e5aa54
[ 2024-10-17 20:42:27.002245 ] IKEv2 DECRYPTION TABLE INFO: "AES-CBC-128 [RFC3602]", "HMAC_SHA1_96 [RFC2404]"

STATE 2:
-------
[ 2024-10-17 20:42:27.002486 ] sending IKE_AUTH (1)
[ 2024-10-17 20:42:27.029517 ] received IKE_AUTH (1)
[ 2024-10-17 20:42:27.029609 ] EAP - EAP_5G_START - AN_ESTABLISHMENT_CAUSE_MO_DATA, 5G_INITIAL_REGISTRATION, n3i

STATE 3:
-------
[ 2024-10-17 20:42:27.029801 ] sending IKE_SA_AUTH (2)
[ 2024-10-17 20:42:27.057407 ] received IKE_AUTH (2)
[ 2024-10-17 20:42:27.057515 ] NAS Received: AUTHENTICATION_REQUEST (RAND 0b19898d7051c2bd9315a6bdb7267112, AUTN

STATE 4:
-------
[ 2024-10-17 20:42:27.058243 ] sending IKE_SA_AUTH (3)
[ 2024-10-17 20:42:27.085290 ] received IKE_AUTH (3)
[ 2024-10-17 20:42:27.085346 ] NAS Received: SECURITY_MODE_COMMAND (Integrity Algorithm chosen: 2, Encryption Al

STATE 5:
-------
[ 2024-10-17 20:42:27.086067 ] sending IKE_SA_AUTH (4)
[ 2024-10-17 20:42:27.115244 ] received IKE_AUTH (4)

STATE 6:
-------
[ 2024-10-17 20:42:27.115943 ] sending IKE_SA_AUTH (5)
[ 2024-10-17 20:42:27.143391 ] received IKE_AUTH (5)
[ 2024-10-17 20:42:27.143494 ] IPSEC PROPOSAL 2 (IPV4 ADDRESS ['192.168.10.2'], TUNNEL IP FOR TCP 192.168.10.2,
[ 2024-10-17 20:42:27.144036 ] ESP SA INFO: "IPv4","172.16.0.1","172.16.0.2","AES-CBC [RFC3602]","HMAC-SHA-1-96

Signaling SA CHILD created. Establishing TCP session towards NAS...

STATE 7:
-------
[ 2024-10-17 20:42:27.339025 ] NAS Received: REGISTRATION_ACCEPT
[ 2024-10-17 20:42:27.339347 ] Preparing REGISTRATION COMPLETE to send...
[ 2024-10-17 20:42:27.339694 ] Preparing UL NAS TRANSPORT message with PDU SESSION ESTABLISHMENT REQUEST to send
[ 2024-10-17 20:42:27.367920 ] NAS Received: MESSAGE TYPE 84
[ 2024-10-17 20:42:27.397346 ] sending CREATE_CHILD_SA response IPSEC (STATE N3IWF SENT A CREATE CHILD SA: 5G QO
[ 2024-10-17 20:42:27.426919 ] NAS Received: DL_NAS_TRANSPORT -> Received: PDU_SESSION_ESTABLISHMENT_ACCEPT (USE
[ 2024-10-17 20:47:26.145905 ] Received CREATE_CHILD_SA request IPSEC
[ 2024-10-17 20:47:26.147324 ] sending CREATE_CHILD_SA response IPSEC
```

Fig. 3. Log from N3IWF client connected to UGR core network.

DNAT rules and routing tables are automatically configured in order to redirect the LoRaWAN traffic to the selected pilot site.

C. 6G-LoRaGRAN Cluster

The cluster, comprising three Intel NUCs and Ethernet switches, hosts the ChirpStack platform [19], which provides the necessary backend interfaces and servers for the LoRaWAN network, including network and application servers, gateway bridges (MQTT Forwarder and Gateway Bridge), a web interface, and a gRPC API. In addition, an EM is integrated, featuring a web interface and automation scripts to perform experiments. The EM also includes a database containing detailed information on end-devices, gateways, experiments, network slices, traffic patterns, and more, accessible via a REST API.

All components run on a Kubernetes cluster, deployed using MicroK8s, to streamline operations such as the deployment of the ChirpStack platform, the creation and modification of security credentials, and the automated configuration of the LoRaWAN network—including the definition of tenants, applications, gateways, nodes, and network slices. Kubernetes further facilitates the scaling and management of containerized applications, ensuring high availability, data persistence, and automatic recovery.

1) Experiment Manager: The Experiment Manager is designed as a web server, available at [20], featuring multiple web pages and PHP/JavaScript scripts that implement its core functionality. The primary logic behind these pages involves querying and updating information in a PostgreSQL database [21] utilized by the EM. In addition, it automates remote access to the equipment described in earlier sections through the *phpseclib* library [22]. The *PHPMailer* library [23] is also integrated to automate email notifications during the user registration process.

As mentioned above, the database forms a core component of the EM. Next we provide an explanation of the tables and their key fields. The *loragran* database contains two key tables: *devices_status* and *gateways_status*, which maintain the status of devices and gateways, respectively. These tables store their unique identifiers (*dev_eui* for devices and *gatewayid* for gateways, serving as primary keys), along with information such as name, model, location, firmware version, and whether a firmware update is required (to be performed via Over-the-Air (OTA) updates). Additionally, they store the last seen timestamp (as devices and gateways periodically report their status) and the last reset timestamp (whether due to watchdog timers or standard reboots). For gateways, the IP address is also recorded for debugging and update purposes. These tables operate independently of users and experiments, serving only to monitor the status of the LoRaWAN equipment used in this project.

Upon registration, the user's main details are stored in the *users* table, including the email address (the primary key of the table), username, email verification status (*verified* field), administrator approval status (*verifiedbyadmin* field), maximum experimentation time allowed (in hours or 0 for unlimited time), and indicators for whether the user is an administrator (*admin* field) or a beta tester (activating features that are not fully tested). Additional user information is also stored, such as organization, avatar URL, registration time, first and last name, country, city, phone number, and physical address.

During user setup, a default slice (slice 0, encompassing all available channels) and a default traffic pattern (pattern 0, with a uniform frame arrival time between 300 and 600 seconds and a constant frame size of 10 bytes) are created. These are stored in the *slices* and *trafficpatterns* tables, respectively. Users can create custom slices and traffic patterns that are saved in these tables for use in their experiments.

When a user creates a new experiment, identified by the tenant and the ID of the experiment, its key parameters are recorded in the *experiments* table. These parameters include the tenant (allowing users within the same tenant to share experiments), experiment start and stop times, the 6G-SANDBOX pilot site for integration, and other metadata such as the experiment's title and description. The *devices* and *gateways* tables are then populated with pairs of devices and gateways linked to the experiment, allowing users to customize the behavior of these components for that particular experiment. For devices, users can configure slices, traffic patterns, channels (ranging from 1 to 8, depending on the definition of the slice, or 0 to cycle through all available channels in

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the slice), and SFs. Users can enable or disable gateways to test under various radio conditions. These configurations can initially be set through the Experiment Manager's user interface and subsequently modified in real-time using the REST API.

The core logic of the Experiment Manager operates via a *scheduler*, which periodically checks and executes the necessary actions. When a new experiment begins, the *scheduler* automates tasks such as selecting the appropriate pilot site, assigning devices and gateways to the correct tenant in the ChirpStack platform, transmitting slice and traffic pattern information to the devices, and more. To streamline implementation, the scheduler is written in PHP and executed every minute via a *crontab* job.

2) MQTT API: The ChirpStack platform provides functionality for publishing LoRaWAN frames [24] received by both the network (encrypted) and application (decrypted) servers via a Message Queuing Telemetry Transport (MQTT) broker [25]. These frames contain metadata, including radio link conditions and transmission parameters. However, this published information is accessible to any user who possesses the MQTT credentials (username/password or certificates, if applicable).

To prevent users from accessing information related to other users' experiments through MQTT, we have employed the *mosquitto_ctrl* tool [26]. This tool allows for the creation of groups and rules assigned to specific users, each with their own MQTT usernames and passwords, ensuring they can only receive information from designated topics. We have restricted access to only the topic associated with the application of each user's tenant in ChirpStack. The assignment of MQTT credentials to a particular topic (corresponding to an application ID assigned to a specific 6G-LoRaGRAN user) is automated during the registration process.

Users can utilize any MQTT client to subscribe to these frames. To do so, they must download the MQTT broker certificate available on the 6G-LoRaGRAN website and configure their MQTT client with the username and password created during their registration. The published frames allow users to monitor transmission parameters (such as channel and spreading factor) and assess radio link conditions (including RSSI and SNR). This information can be valuable for developing resource allocation algorithms, considering network slicing, or for other research purposes, by implementing e.g., a Python program using the *paho-mqtt* library [27].

3) REST API: The 6G-LoRaGRAN platform provides a REST API that enables users to query the status and configuration of the Experiment Manager and modify its parameters. This API is built using the FastAPI framework [28] and runs on a Python server within the Kubernetes cluster. Most HTTP methods interact with the *loragran* database, leveraging the *psycopg2* library [29] for database operations. The API supports real-time retrieval and modification of data related to users, pilot sites, devices, gateways, experiments, traffic patterns, and LoRaWAN slices, offering users dynamic control over their experimental setups.

IV. Platform Usage

This section provides a comprehensive set of instructions for anyone wishing to remotely access the 6G-LoRaGRAN infrastructure via the EM web interface, including how to log in, configure end-device settings, create experiments, etcetera. A video demonstrating how to use this platform is available on YouTube [30].

To access the EM webpage, the user should open a browser and navigate to [20]. If the user has not registered previously, they should select 'Create an Account' and complete the registration process, which requires providing a username, email address, tenant name (to be shared among team researchers), organization, and password. The administrator will receive an email notification regarding the registration request, approve it, and subsequently, the user will be able to log in.

The home page features a left-hand menu that contains a set of categorized pages. The most important ones include:

- **Experiments**: On this page, users can create their own experiments. Additionally, users can view anonymized experiments from other users, providing insight into the platform's current activity and indicating if it is occupied at a given time. When users click at "Add new experiment" they can specify the start and end times, select the pilot site for integration, and provide a title and description for the experiment. To ensure a fair use of the platform, each user is permitted to create experiments with a maximum duration of 48 hours or contact the administrator to ask for additional resources.
- **Slices**. In this testbed, network slices are defined as sets of dedicated channels that cannot be shared between slices. The assignment of slices to end devices, along with the initial channel and spreading factor (SF), is managed through the web UI of the Experiment Manager (EM). We utilize the concept of a channel mask, which is a binary representation where each bit corresponds to one of the eight channels operating at 125 kHz within the 868 MHz band used for LoRaWAN. For instance, a channel mask of 15 (represented as 00001111 in binary) indicates that the slice includes channels 1, 2, 3, and 4. It is important to note that the user determines whether slices share channels. To ensure isolation, slices must not have any common bits set to 1.
- **Traffic patterns**: During an experiment, traffic generation can be customized by defining specific traffic patterns for end devices. These devices will generate frames according to a selected frame arrival distribution, with support for both uniform and normal distributions. Each frame will adhere to a specified size, which can also follow either a uniform or normal distribution.
- **Devices**: Users can configure end devices by selecting the appropriate slice and traffic pattern for either individual devices or groups of devices. Additionally, users can specify the spreading factor (SF) that each device will utilize for transmission. Similarly, users can choose a channel from 1 to 8 for the end devices or select

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'periodic' (by choosing 0), which enables the device to hop between the channels defined in the selected slice. These configurations for end devices are specific to each experiment, necessitating users to repeat this process for every new experiment.

- **Gateways**: All the LoRaWAN gateways belonging to the testbed are enabled during the experiment. Through the EM platform, the users can select which gateways are enabled or disabled for a given experiment. This increases the possibilities of experimentation by being able to vary radio conditions based on whether closer or more distant gateways are enabled.
- **Status**: Within the Experiment Manager (EM) menu, the 'Status' section provides users with the ability to monitor the operational status of end devices and gateways. Additionally, users can verify that the LoRaWAN cluster is successfully connected to the various 5G Core (5GC) pilot sites.
- **Chirpstack**: Our testbed uses Chirpstack as the LoRaWAN backend, which includes the functionalities of the network and application servers, among others. User can open the Chirpstack platform web page by clicking on the "Chirpstack" button. If it is the user's first time, the logging must be done using the username and password selected in the registration.
- **MQTT API**: This page includes the Certification Authority (CA) certificate for the MQTT broker, as well as instructions to subscribe -using the *mosquitto_sub* tool- to the LoRaWAN frames generated during the experiment (see Section III-C2). In addition, it also shows the last ten MQTT messages.
- **REST API**: This page includes a User Interface (UI) for the REST API explained in Section III-C3. It allows users to request the status, check, verify or modify the settings of the experiment (such as the assignment of the channels and slices) in real time.

V. Sample Experiments

A. Sample Experiment 1

As the first sample experiment, we configured all LoRaWAN devices to operate across 1, 3 and 8 channels (channel masks 1, 7 and 255, respectively) of the 868 MHz band. The traffic patterns of the end devices used 50-byte frames with inter-frame intervals of 20, 30, 40, 50, 100, 200, 300, and 600 seconds. We compared the results from this experiment campaign to the collision probability predicted by the Pure Aloha model with a finite number of sources.

Fig. 4 presents the results obtained. Some differences were expected, as our testbed incorporates factors not accounted for in the Pure Aloha model, such as the capture effect in LoRaWAN [31], the possibility of avoiding collisions between devices located in different buildings due to radio conditions, and connectivity issues with the EM that could reduce the effective number of transmitted frames, among others. A similar trend is clearly observed, showing that the number of devices in our testbed generates sufficient traffic to produce a high collision probability —up to 80% with 1 channel and more than 60% with 8 channels. This implies that even higher collision rates could occur with fewer channels. These results highlight the testbed's capacity to support diverse, realistic scenarios, making it a valuable tool for research in LoRaWAN technology.

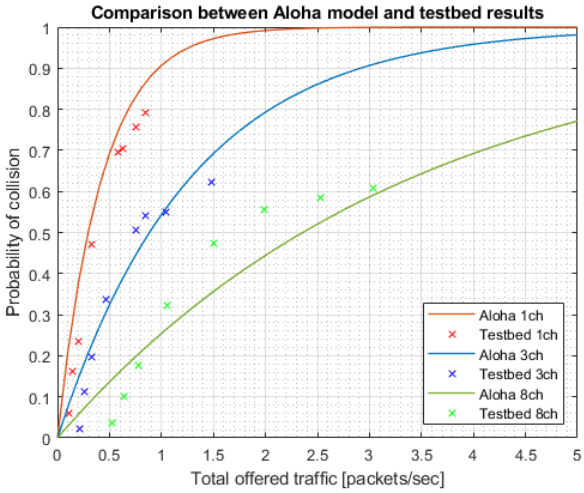


Fig. 4. Comparison of Aloha model and testbed results (8 channels).

B. Sample Experiment 2

The second experiment evaluates isolation between two LoRaWAN slices, each using two channels defined by the binary masks 00001100 (decimal 12) and 00000011 (decimal 3). Each slice comprises 30 nodes. Nodes in the first slice transmit one frame every 50 seconds on average, while nodes in the second slice transmit one frame every 20, 30, 40, 50, 100, 300, and 600 seconds on average during each run.

Fig. 5 illustrates the collision probabilities observed for each slice. Notably, the collision probability of Slice 1 (blue crosses) remains stable between 70% and 80%, with only minor variations attributable to the inherent randomness of individual runs. This stability persists despite the collision probability of Slice 2 (green crosses) varying considerably between 0% and 80% due to changing traffic patterns. This observation confirms the effective isolation between slices. For completeness, Fig. 5 also includes the global collision probability calculated across both slices.

VI. Conclusions and Future Work

This paper introduces the 6G-LoRaGRAN testbed, a cutting-edge platform designed to integrate LoRaWAN with 5G networks, developed as part of the European 6G-SANDBOX project. The testbed offers a real-world environment for IoT research, allowing remote access and experimentation with over 100 LoRaWAN devices. It supports flexible configurations such as network slicing, customizable traffic patterns, and real-time resource management using

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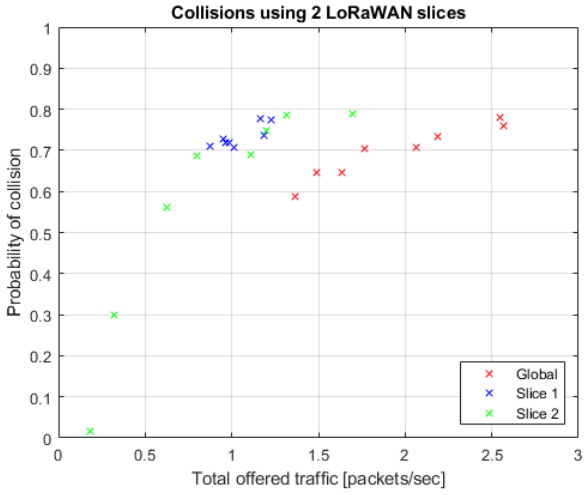


Fig. 5. Collisions in each slice of the experiment.

REST and MQTT APIs enabling dynamic adjustments during experiments. Two sample experiments were conducted. The first demonstrated the platform's ability to analyze LoRaWAN behavior under high-load conditions, with results closely aligning with theoretical collision models. The second employed two LoRaWAN slices to demonstrate inter-slice isolation.

Future work will include the development of advanced real-time radio resource management algorithms and the expansion of our LoRaWAN network slicing concept.

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