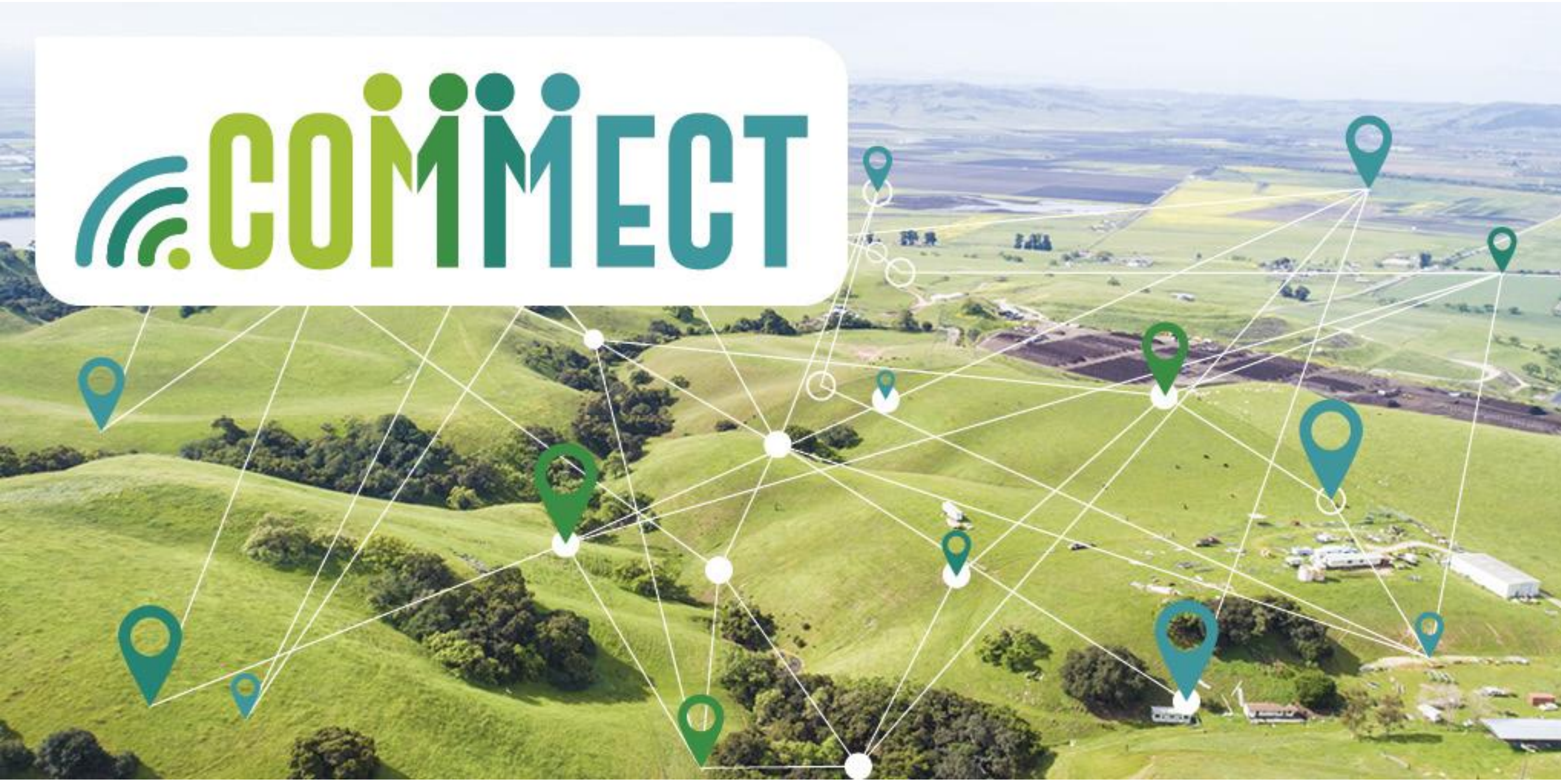
Bridging the digital divide and addressing the need of Rural Communities with Cost-effective and Environmental-Friendly Connectivity Solutions



Deliverable 5.1
Technical performance of COMMECT solutions – Version 1

November 2023

PUBLIC

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COMMECT

Bridging the digital divide and addressing the need of Rural Communities with Cost-effective and Environmental-Friendly Connectivity Solutions

Grant agreement No. 101060881

Technical performance of COMMECT solutions Version 1

WP5 - Validation of COMMECT Solutions

Deliverable ID	**D5.1**
Deliverable Name	**Technical performance of COMMECT solutions**
Lead Partner	VITECH
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COMMECT Project Abstract

Over the last years, the importance and need for broadband and high-speed connectivity has constantly increased. The Covid-19 pandemic has even accelerated this process towards a more connected society. But this holds mainly true for urban communities. In Europe a 13% lack access persists, and mainly concerns the most rural and remote areas. Those are the most challenging to address since they are the least commercially attractive. COMMECT aims at **bridging the digital divide**, by providing quality, reliable, and secure access for all in rural and remote areas. The **goal of extending broadband connectivity in rural and remote areas** will be achieved by *integrating Non-Terrestrial Networks with terrestrial cellular XG networks, and low-cost Internet of Things (IoT). Artificial Intelligence, Edge and Network Automation will reduce energy consumption both at connectivity and computing level.*

Participatory approach with end-users and ICT experts working together on development challenges will be the key **for the digitalization of the sector**. To ensure the rich exchange of best-practice and technical knowledge among the actors of the agro-forest value chain, COMMECT will set up **five Living Labs across and outside Europe**, *where end-users "pain" and (connectivity) "gains" will be largely discussed, from different perspectives.*

COMMECT aims at contributing to a balanced territorial development of the EU's rural areas and their communities by making smart agriculture and forest services accessible to all. COMMECT will facilitate that, by developing a **decision-making support tool** able to advise on the best connectivity solution, according to technical, socio-economic, and environmental considerations. This tool, incorporating collaborative business models, will be a *key enabler for jobs, business, and investment in rural areas, as well as for improving the quality of life in areas such as healthcare, education, e-government, among others.*

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Executive Summary

The COMMECT project aims at bridging the digital divide and addressing the need of rural communities with cost-effective and environmental-friendly connectivity solutions. With that in mind, COMMECT focuses on proposing technologies that are already available in the market and capable of fulfilling the needs of stakeholders and end users.

To propose the most suitable solution per use case, this deliverable presents the COMMECT approach allowing to better organize and evaluate the different connectivity and computing technologies. This structure will be used across different Work Packages of COMMECT. Connectivity solutions such as XG, 5G private networks, Internet of Things (IoT), Non-Terrestrial Networks (satellite and Unmanned Aerial Vehicles) will be compared not only depending on the segment of the network where they can operate (Last-mile and backhauling) but also for different types of user services. Besides connectivity, we will evaluate the Edge computing capabilities that will be needed in rural areas to analyze and post-process in real-time the data collected from different IoT devices, or for offloading data from/to the cloud.

This deliverable mainly focuses on describing the planned COMMECT Performance Assessment Tests (PATs) that will help analyze and compare (under laboratory conditions) the performance of the connectivity solutions proposed by COMMECT, listed above and previously discussed in WP2. The organization of COMMECT PATs follows the COMMECT approach described in this deliverable, and it promotes the collaboration between partners and helps to compare these technologies under different conditions and for different use cases, especially those identified in the different Living Labs.

In conclusion, this document describes the output of Task 5.1 - Technical performance of COMMECT solutions. This is the first version of the document (version 1), where the technical performance assessment test plans are described. More content and information will be provided in the second version, due in April 2025, where the results of the tests will be presented and analyzed.

This document is used as input for the deliverable D5.4 (version 2 of Task 5.1), and it will also serve as feedback for WP2 and a basis for the Living Labs (LLs) deployment in WP4 and Task 5.2 – Technical Validation in the Living Labs.

Table of Contents

List of Figures

List of Tables

Glossary of Terms

ACPI	Advanced Configuration and Power Interface
ADR	Adaptive Data Rate
AI	Artificial Intelligence
AR	Augmented Reality
B5G	Beyond 5G
COMMECT PAT	COMMECT Performance Assessment Test
CR	Coding Rate
CSS	Chirp Spread Spectrum
DECT	Digital Enhanced Cordless Telecommunications
DL	Downlink
DST	Decision-making Support Tool
DVB	Digital Video Broadcasting
DVB-RCS2	DVB Second Generation Return Channel over Satellite
DVB-S2	DVB Satellite Second Generation
E2E	End-to-End
ECU	Electronic Control Unit
GEO	Geostationary Earth Orbit
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPU	Graphics Processing Unit
GSM	Global System for Mobile communication
GW	Gateway
ICP	Intelligent Connectivity Platform (ICP)
ICT	Information and Communication Technology
IoT	Internet of Things
ISL	Inter-Satellite Link

ITU	International Telecommunication Union
KPI	Key Performance Indicator
LEO	Low Earth Orbit
LL	Living Lab
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
LAS	LoRaWAN Application Server
LNS	LoRaWAN Network Server
LTE-M	Long-Term Evolution for Machines
LPWAN	Low Power Wide Area Network
MAGW	Multi-Access GateWay
MC	Mobility Campaign
MIMO	Multiple Input Multiple Output
ML	Machine Learning
MPTCP	Multi Path TCP
MSS	Mobile-Satellite Service
NB-IoT	Narrowband IoT
NTN	Non-Terrestrial Networks
NoW	Network on Wheels
NUC	Next Unit of Computing
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAPL	Running Average Power Limit
Rpi	Raspberry Pi
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality

RTT	Round-Trip-Time
SATCOM	Satellite Communication
SBD	Short Burst Data
SDR	Software-Defined Radio
SF	Spreading Factor
SIMO	Single Input Multiple Output
SINR	Signal to Interference & Noise Ratio
SISO	Single Input Single Output
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TOPS	Tera-Operations Per Second
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
UL	Uplink
UPF	User Plane Function
UT	User Terminal
VR	Virtual Reality
WP	Work Package
WPA	Wi-Fi Protected Access
4G	Fourth Generation mobile networks
5G	Fifth Generation mobile networks

1. Introduction

One of the main objectives of COMMECT is to extend connectivity in rural areas, where traditional infrastructure is often limited. The idea is not to propose revolutionary technologies that are not yet available, but to analyze which are the best connectivity solutions that can fit better the user needs in rural areas, in terms of provided services, cost and carbon footprint. According to COMMECT Methodology and Work Plan, the partners will evaluate in a controlled environment (lab facilities) the most adapted solutions before their deployment in the Living Labs.

In this chapter, we present the classification of COMMECT solutions, the scope of the deliverable, the main link to other Work Packages (WPs) and Tasks, and the document structure that has been chosen to introduce the COMMECT Performance Assessment Tests (PATs) considered in *Task 5.1 - Technical performance of COMMECT solutions.*

One of the main objectives of COMMECT is to extend connectivity in rural areas and to support digital applications. Figure 1 illustrates the connectivity solutions proposed in WP2 (*XG, Edge and Last-Mile Energy Efficient Solutions for coverage extension*), for the use cases identified in WP1 (see deliverable D1.1 [1]) for the five COMMECT Living Labs described in deliverable D4.1[2]. COMMECT focuses on (i) Connectivity Access in Rural/Remote Areas (Terrestrial vs. Non-Terrestrial Networks) and (ii) Computing Technologies in rural areas.

Connectivity solutions are explored by many partners who will compare the performances of different Terrestrial networks (XG, IoT-based and Wi-Fi) and Non-Terrestrial Networks (NTN – satellite and Unmanned Aerial Vehicles [UAVs]) on two portions of the network: the Last-mile network next to the end-user and the backhauling network (intermediate links between the core networks or Backbone and the small subnetworks).

In addition, COMMECT aims at evaluating the advantages of using Edge computing, versus cloud computing, especially for those use cases and applications where a large amount of data generated by IoT devices should be processed and analyzed in real-time. Some of the targeted applications are video processing using Machine Learning (ML) algorithms and the use of local breakouts on 5G networks. The objective is to compare Edge to Cloud computing in terms of energy consumption, latency, bandwidth consumption, etc.

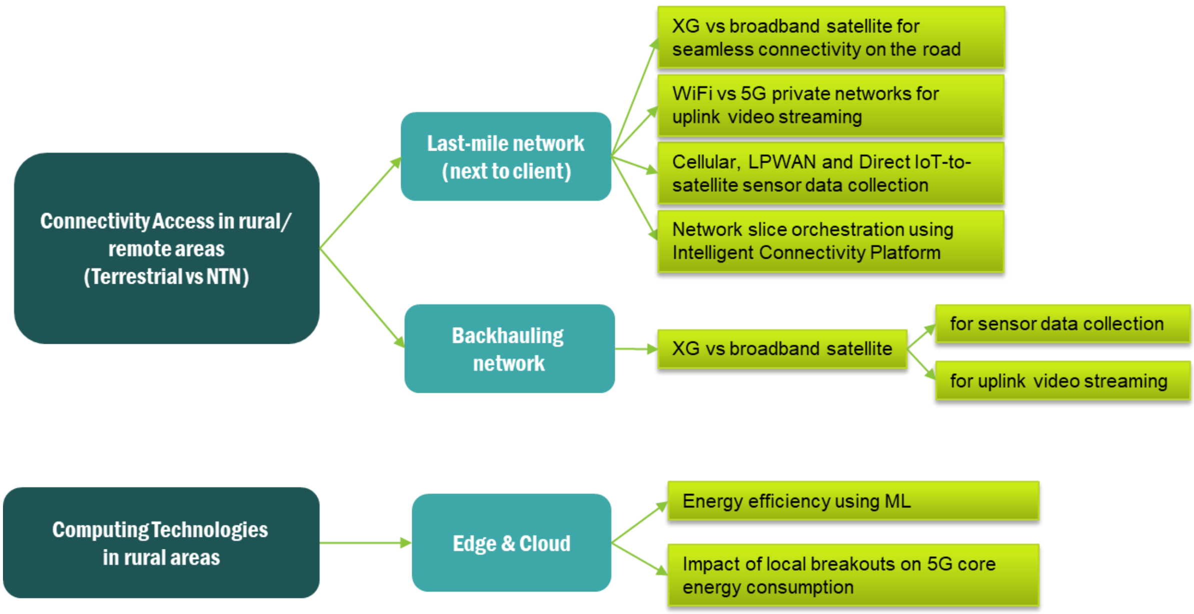


Figure 1. Organization of COMMECT solutions to extend connectivity in rural areas

This deliverable addresses the first part of the work carried out in *Task 5.1*, which focuses on testing and evaluating the performance of different technologies, solutions or equipment in laboratory conditions (i.e., in a controlled environment), and sometimes using emulated/simulated components to simplify some of the test conditions that are not available on the laboratory (or to show the eventual real effect of alternative conditions).

COMMECT partners have several motivations to perform these tests in a controlled environment. Such motivations, described below, reflect the close link of this task to the other WPs of the project.

One of the main motivations of this task is to evaluate the performance of solutions and technologies that have been proposed in WP2 (*Task 2.2 - Local 5G Private Networks, Task 2.3 - IoT and Edge Computing and Task 2.4 - AI and Network Automation*) and that need to be analysed/evaluated under laboratory conditions. This will be done using equipment and facilities discussed in *Task 2.1 - 5G Connectivity Platforms* (described in deliverable D2.1 [3]). For example, solutions or equipment belonging to 5G private networks, IoT networks or Edge devices that allow to provide the requested services to users located in rural and isolated areas.

This is also a task where COMMECT partners can perform risk mitigation of the future network deployment in the Living Labs (*WP4 - COMMECT Living Labs*). In other words, partners have the opportunity to test components/technologies/ equipment under a controlled environment, using simulation/emulation tools, before selecting those that will be integrated into the Living Labs. The work carried in this task also helps evaluating the performance of technologies that cannot be deployed in the current Living Labs (due to specific constraints or lack of equipment) but that are important for the scope of the COMMECT project. This can include comparisons between 5G and satellite networks, special features of IoT devices, etc.

Create synergies between partners and take advantage of common work (or complementary work that will benefit COMMECT) are also big assets of this task. For example, comparing the performance of different types of networks and devices under different conditions. This helps improve partnership between partners that do not necessarily work in the same LL. The idea behind these comparisons is to show that there is not a single solution to address the different needs of different rural communities, in different remote areas of different EU and non-EU countries, in different sectors of agri-food ecosystem, transport, forestry or environmental surveillance.

Finally, this task will include the technical validation of the Decision-making Support Tool (DST) under laboratory conditions, i.e., before deploying it for the Living Labs (LLs). But such validation will not be addressed in this deliverable given the early stage of the conception and development of DST's first deliverable (D3.3 [4]).

1.1 Document objective and link to other Work package

The work carried in Task T5.1, summarized in the current deliverable (version 1), has been organized based on the segment of the network we target (Last-mile and backhauling), on the type of available connectivity solution (terrestrial, satellite, etc.), on common performance tests and also on technology comparisons. The performance tests have been organized as COMMECT PATs, and the following information is provided for each COMMECT PAT:

- The objectives and a description of the performance tests with references to the different tasks from WP2. Links to the future LLs (and use cases) are sometimes provided to justify the scope of the COMMECT PATs, but this deliverable/task tries to be agnostic to the LL and the work is structured following mainly COMMECT connectivity solutions and common COMMECT PATs.

- The plans for tests and/or a description of the test campaigns.
- A description of the equipment and tools that will be used, some of them already described in the COMMECT connectivity platforms, in deliverable D2.1[3].
- The metrics that will be used to evaluate and analyze the performance of the solutions. These metrics are linked to the requirements described in *Task 1.2 - COMMECT Requirements and KPIs* and deliverable D1.2 [5] from WP1, e.g., throughput, latency, energy consumption, etc.

The second deliverable (version 2) of this task (deliverable D5.4), to be completed by April 2025, will focus on showing and analyzing the tests' results, as well as describing the DST technical validation. Some COMMECT PATs not yet identified at this stage might also be included.

For the sake of clarification, this deliverable is based on in-lab testing (testbeds, hardware, simulation, emulations, etc.). It does not include operational/functional tests for devices/solutions to be deployed in the LLs, i.e., validate/check if a device does what it is supposed to do. Neither the test plans for LLs/WP4, given that this is addressed in *Task 5.2 - Technical Validation in the Living Labs* (deliverable D5.2).

1.2 Structure of the document

This document is structured following the work organization presented in the Introduction (Figure 1). The document is organized in two main chapters: the first one dedicated to "Connectivity Access in Rural/Remote Areas (Terrestrial vs. Non-Terrestrial Networks)" and the second focused on "Computing Technologies in rural areas". The first chapter is split into two subchapters that represent the two network segments that COMMECT is addressing: the backhauling network and the Last-mile network.

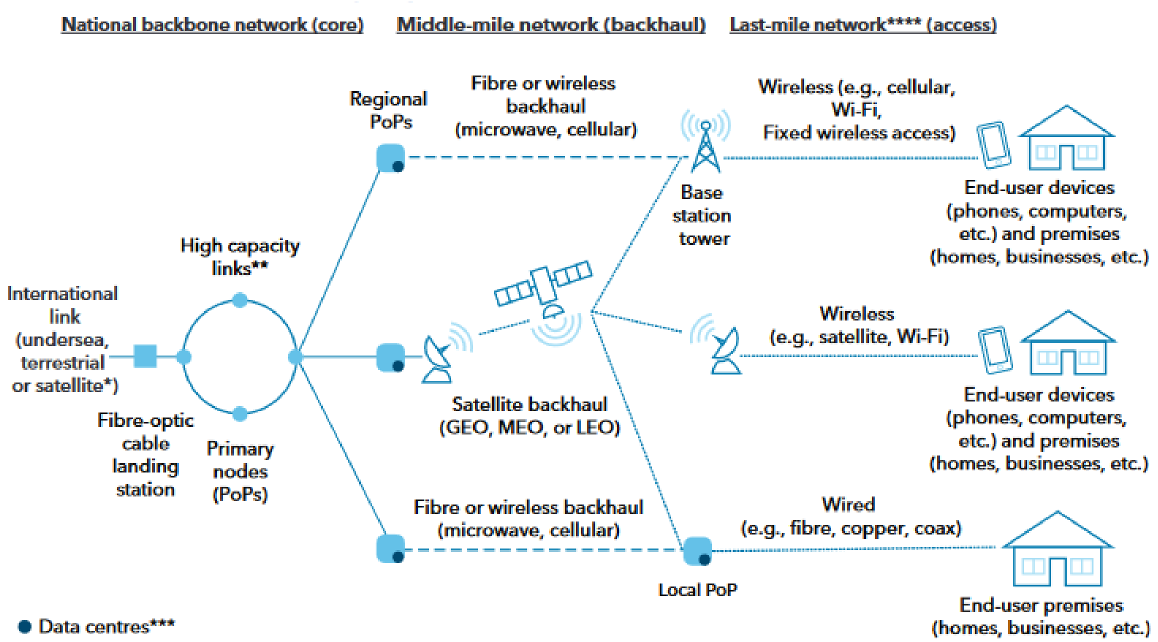
Note that although the COMMECT PATs have been classified as illustrated in Figure 1, some new tests might be added to version 2 of the deliverable (named deliverable D5.4), mainly because of the ongoing work in WP2 (the first version of the deliverable D2.2 [6] is submitted at the same time as this deliverable) can evolve and new performance tests might be needed. And besides, some tests that are expected to be done in Task 5.2 (in the Living Labs) might be considered not feasible in the following months (e.g., due to the lack of equipment, conditions, time, or resources) and thus finally not included in T5.2 but in T5.1. We have included two COMMECT PATs in this deliverable that are not confirmed yet at this stage of the project, and their feasibility will depend on the available resource, the WP2 ongoing work or the plans for T5.2. They are marked as "not confirmed".

2. Connectivity Access in Rural and Remote areas: Terrestrial versus NTN

Despite all the capabilities that XG has already provided, industry and society require more, and particular attention should be paid to rural areas. More and/or better technologies are necessary for low-cost and affordable network solutions, ultra-dense networks, networking convergence with cloud and IT, and backhauling to remote areas [7]. In particular, the integration of terrestrial networks (XG, Wi-Fi, IoT, etc.), with NTN, e.g., satellites and UAV, must be seamless to enable consistent and robust service delivery.

To understand the impact of using Terrestrial networks or NTN, this section focuses on comparing them both in the Last-mile network (i.e., the access network) and the backhauling network. This will allow us to propose the best solutions (or combining both) for different users' needs.

There are multiple ways to describe the different segments of a telecommunication network, see Figure 2 for an example published by International Telecommunication Union (ITU) in "The Last-Mile Internet Connectivity Solutions Guide: Sustainable connectivity options for unconnected sites" [8]. For the sake of clarification, in this document we describe the Last-mile as the network connecting the internet/access provider infrastructures (e.g., cellular base stations, antennas, routers, etc.) to the end devices; the core as the network where the majority of computing resources are situated and that routes data among various sub-networks; and the backhauling as the network connecting the access network to the core network. One type of connectivity solution might be used in different segments of the network, e.g., a satellite network can be used as Last-mile network but also as backhauling network when transporting data from the 5G core to a 5G base station.



Source: Authors, adapted from various sources

Notes: Not exhaustive, for illustrative purposes and some segments are interchangeable further, particularly in the last-mile;
*In few country cases, satellite continues to be the main, or only, source of international connectivity;
** These are predominantly fibre-optic links (terrestrial and undersea) but in few country cases, national backbone networks utilize wireless microwave and satellite;
*** Data centres can be placed in various parts of the network, depending on the need to aggregate data (such as in core networks, or place data as close to end users as possible (such as in middle mile and last-mile networks);
**** The technologies listed for the last mile are not exhaustive.

Figure 2. Overview of telecommunication network components (core, backhaul and Last-mile) from ITU.

2.1 Last-mile network

In a telecommunications context, the Last-mile network is referred as the final leg of the network that delivers connectivity, i.e., between a broadband internet service provider's infrastructure (a 5G base station, a LoRa GW, a Wi-Fi router or a satellite) and a customer's home or workplace. It is the final piece of the puzzle for achieving seamless connectivity, and traditional terrestrial infrastructure struggles to keep up with the demands of connectivity, particularly in remote areas. The challenge lies in reaching those areas where it is sometimes not economically feasible to lay fiber-optic cables or build new cellular base stations. Satellite network can be very helpful when bridging the Last-mile gap with their ability to transmits signal overs long distances and cover isolated areas, being complementary to XG and terrestrial infrastructures.

A list of COMMECT PATs of the Last-mile network (or access network) and how they are linked to WP2 tasks and Living Labs are shown in Table 1 to simplify the comprehension of their overall organization.

Note that the different tests performed are complementary. They will give very useful information regarding the performance of the aimed networks (satellite, Wi-Fi, XG, 5G private networks, IoT, satellite-to-IoT and UAVs) in rural areas under different conditions (with/without mobility, coverage ranges, etc.). A cross-cutting topic like orchestration and artificial intelligence will also be introduced at the end of this section, as a part of COMMECT PATs.

Main COMMECT PATs	Related WP2 tasks	Partners involved	Living Labs benefiting from this test	Confirmed test
XG vs broadband satellite for seamless connectivity on the road	T2.2 (Local 5G Private Networks) T2.4 (Network Orchestration)	AAU VITECH	Denmark LL Norway LL Luxembourg LL	Yes
Wi-Fi vs 5G private networks for uplink video streaming	T2.2 (Local 5G Private Networks) T2.3 (IoT and Edge)	TNO		Yes
Cellular vs Direct IoT-to-satellite sensor data collection	T2.3 (IoT and Edge) T2.4 (Network Orchestration)	AAU VITECH LIST	All LLs	Yes
Network slice orchestration using Intelligent Connectivity Platform	T2.4 (Network Orchestration)	TNOR HWIE	All LLs	Yes

Table 1: List of COMMECT PATs considered in the Last mile network section.

2.1.1 XG vs broadband satellite for seamless connectivity on the road

The seamless connectivity solution addresses the need for constant end-to-end connectivity while the end user is on the move. Despite what is claimed by cellular operators, trucks and other vehicles, using 2G/3G/4G/5G connectivity, do not have stable connectivity along routes especially in rural area and secondary roads, and sometimes they lose connectivity. 5G coverage is still lacking in many remote areas. Regarding 2G/3G/4G, rural areas are sometimes not well served by all operators, and the service might not be good enough (in terms of data rates and latency) for different applications. We propose multi-connectivity strategies combining two different networks or technologies in order to have a backup option in case cellular coverage is poor or nonexistent.

This COMMECT PAT tries to fulfil the needs that Danish stakeholders of livestock transport have expressed during COMMECT interviews/workshops. This solution is thus related to Denmark Living Lab, where it is necessary to send reports (vehicle location and sensor data information) from each mobile transport unit on the road to the operation center within and beyond EU member states. Additionally, as a future application, the truck will need to recalculate the route depending on traffic conditions, weather forecasts and risk infection areas and consider the location of recharging stations (for future electric truck). This will help minimize the trip time and thus improve animal wellness and driver's quality of life and reduce energy consumption. This data needs to be downloaded frequently, which is a big challenge due to mobility conditions in isolated areas. The networks and strategies that will be combined to evaluate a multi-connectivity solution are described below.

The first multi-connectivity solution is based on the combination of two cellular links with two different variants: same operator or multi-operator (Figure 3). In the first variant, both links belong to the same 5G operator, and the goal is to evaluate the improvements of using two receiving devices with antenna diversity. In the second case, each link belongs to a different operator; thus, the truck would be able to connect to two different eNBs/gNBs from different operators.

In the second multi-connectivity solution, we take advantage of a broadband satellite network when the cellular network is not available or signal quality is not enough to provide the required service (Figure 4). The satellite access will be used as a backup, and both a constellation of Low Earth Orbit (LEO) satellites or a Geostationary Earth Orbit (GEO) satellite will be considered.

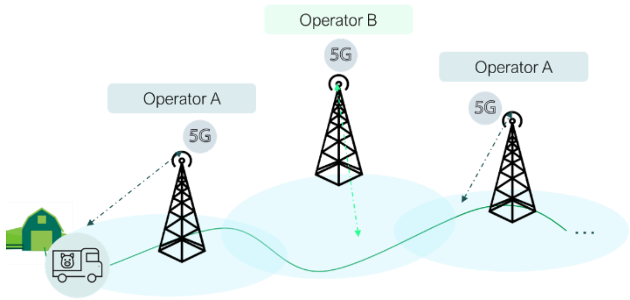


Figure 3. Multi-connectivity with two cellular networks (multi-operator case).

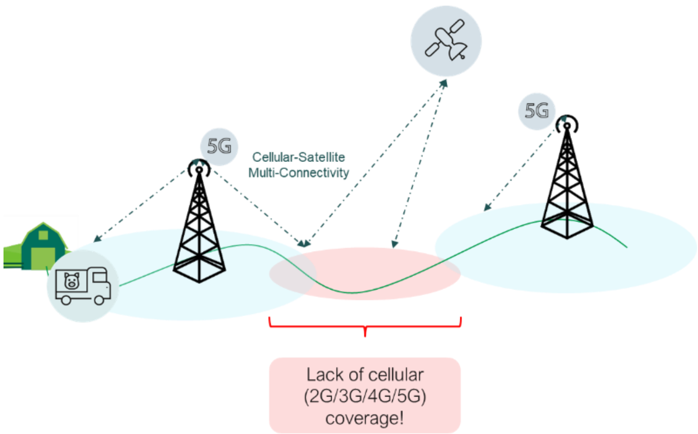


Figure 4. Multi-connectivity with cellular network and satellite network.

Strategies: Dynamic routing and packet duplication

The need for seamless connectivity cannot override other needs/requirements. The objective is to propose different solutions allowing to transmit/receive data frequently by means of a combination of wireless technologies but not at all costs; a trade-off must be found between the following conditions:

- Reduce energy consumption: From an ecological perspective, using two wireless technologies increases carbon footprint if they are not used correctly. Only one technology should be used most of the time, and only when needed they can be both enabled.
- Optimize bandwidth use: Like the previous one, an overuse of bandwidth is not fair in terms of carbon footprint, energy and data price.
- Service reliability: This is a challenging condition for many use cases and especially for livestock transport, where missing the localization information during a 10–12-minute time window might have a huge impact (see deliverable D1.2 [5]).
- Maximize Quality of Experience (QoE): Once the previous requirements are met, the quality of experience of end users must also be considered, in particular for services such as video streaming, video calls and other interactive applications. This is correlated to the available Uplink/Downlink (UL/DL) throughput and eventually the Round-Trip-Time (RTT).

To find the best trade-off under mobility conditions, three traffic engineering strategies will be tested: packet duplications, dynamic routing and Multi Path TCP (MPTCP).

Packet duplication across two links is the main strategy that will be tested since it is very useful when one wants to achieve the lowest possible latency and maximum reliability at the expense of bandwidth. This strategy is indeed able to minimize packet losses if configured correctly but might increase energy/bandwidth consumption if both links are used simultaneously for long time.

Minimizing the used bandwidth is important from an ecological point of view, and here is where a dynamic routing (or traffic switching) strategy between two links can help us. In this case, a smart scheduler/router can switch the traffic flows from one link to the other depending on different policies or the status of the networks. This strategy should minimize energy/bandwidth but might cause packet drops if not used correctly when channel conditions vary too fast. Furthermore, in the context of TCP-based services such as file transfer or web browsing, the transition between links can trigger the TCP congestion control algorithm to decrease its congestion window in response to detected latency variations, particularly in links with different RTTs. This will impact bandwidth use efficiency and reduce the quality of experience if the system is not tuned correctly.

The last envisaged strategy, MPTCP [9], is an effort towards enabling the simultaneous use of several IP addresses/interfaces/networks by a modification of TCP that is transparent for the transmitted applications, while in fact spreading data across several subflows. Benefits of this include a more efficient resource utilization (depending on the chosen policy), higher throughput and smoother reaction to failures, but it is only available for TCP-based services. If the default policy of MPTCP is used, it will first send data on subflows with the lowest RTT until their congestion-window is full. Then, it will start transmitting on the subflows with the next higher RTT. But if the 'redundant' policy is enabled, the scheduler will try to transmit the traffic on all available subflows in a redundant way, very similar to our first strategy based on "packet duplication".

The first two strategies must be driven by different policies that will decide when to trigger the packet duplication or the link switch, while the default policy of MPTCP will be based on network information (RTT and congestion window). The objective is to maintain two active links but use only one of them while the primary link is good enough, and to duplicate packets or switch traffic from primary link to secondary link depending on different policies, such as the examples listed in Table 2.

Type of policy	Policy	Target metrics
Physical layer based	If signal metrics from primary are below X dB during at least Y ms.	Reference Signal Received Power (RSRP) in dB
		Reference Signal Received Quality (RSRQ) in dB
		Signal to Interference plus Noise Ratio (SINR) in dB
Network layer based	If network Key Performance Indicators (KPI) are close to (or below) a defined value during at least Y ms.	Latency (s)
		Throughput (bits/s)
		Packet Loss Rate

Table 2: Examples of policies that activate packet duplication or traffic switching.

Finally, the strategies defined above might also be driven by network orchestrator and Artificial Intelligence (AI) algorithms. This will be analyzed in future deliverable D2.3[10].

Equipment / Software

OpenSAND

The open-source satellite emulator OpenSAND [11] see Figure 5) will be exploited to emulate an end-to-end Satellite Communication (SATCOM) system with a fair representation. OpenSAND is funded by CNES (Centre National d'Etudes Spatiales) and officially maintained by VITECH. The emulator currently implements DVB-S2 [12]/RCS2 [13] standard and can emulate several satellite terminal/gateways and either a GEO satellite or two regenerative LEO satellites connected via an Inter-Satellite Link (ISL). The terminals and the gateways can be connected to external real equipment as well as to the Internet. Different varying channel conditions can also be emulated (attenuation, losses, jitter and RTT), which allows to represent satellite link conditions.

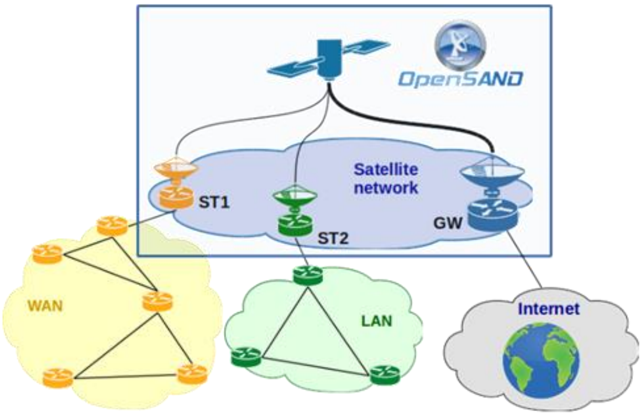


Figure 5. OpenSAND satellite emulator.

OSCAR truck

The truck OSCAR (see Figure 6), owned by CNES, is part of CESARS program (center of expertise and support for satellite telecommunications uses) [14]. It has been designed to evaluate the performance of real satellite antennas and SATCOM services from the market under mobility conditions and to demonstrate SATCOM on the Move. The truck includes the following equipment onboard:

- GPS.
- 360° camera for video recording the surroundings of the truck.
- Spectral analyzer or a Software-Defined Radio (SDR).
- Inertial reference systems.
- Different satellite antennas and modems (listed below in Table 3).
- Next Unit of Computing (NUC) and servers to generate traffic.
- A supervision and monitoring system allows the control of the equipment, launch of the test campaigns and collection of the desired metrics.

Figure 6. OSCAR truck in government satellite configuration.

Access/ Antenna name	Satellite	Throughput		Mobility
		Download	Upload	
Intelsat (Flexmove plan) / Kymeta U8	GEO (Intelsat)	5 Mbps	2 Mbps	Yes
Government access	GEO (Government Ka band satellite)	7 Mbps	3 Mbps	Yes
Starlink (Roam reagional plan)	GEO (Intelsat)	50 Mbps	5 Mbps	Only roaming (not mobile)
OneWeb / Kymeta U8	LEO (OneWeb)	Not Known		Expected for Q1 2024
Iridium Certus 700 (MSS)	LEO (Iridium)	700 Kbps	350 kbps	Yes
Inmarsat (MSS)	GEO (Inmarsat)	432 Kbps	256 Kbps	Yes

Table 3: Characteristics of satellite antennas available in OSCAR truck.

As part of the CESARS program, CNES has kindly agreed to lend the truck to VITECH/AAU to perform several seamless connectivity tests within the COMMECT project.

Starlink satellite user terminal

A round-shape commercial Starlink Gen-1 User Terminal (UT) from AAU 5G Smart Production Lab, already described in Deliverable D2.1[3].

Multi-Access GateWay (MAGW)

The Multi-Access GateWay (MAGW) (see Figure 7), designed by researchers at Aalborg University, enables seamless and technology-agnostic wireless control communication. A comprehensive description of the MAGW can be found in deliverable D2.1[3]. The MAGW incorporates the *mpconn* tunneling program [15]. As illustrated in Figure 8, this performs multi-connectivity by duplicating Layer 3 packets and transmitting them over IP using Layer 4 packets (User Datagram Protocol or UDP). It can do so through the same or different systems, making a versatile tool for evaluating multi-connectivity performance in different scenarios, even when the active links encompass different technologies, such as satellite and XG.

Figure 7, Multi-Access Gateway (MAGW).

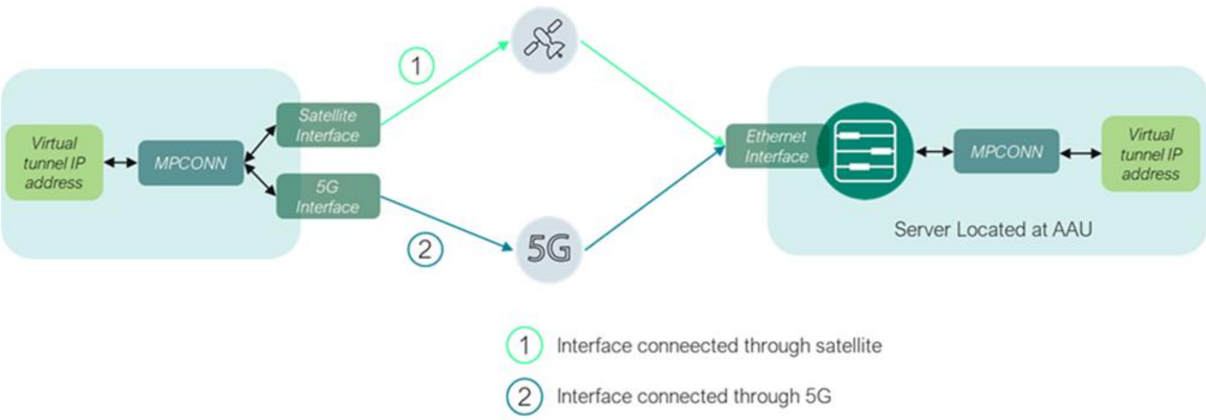


Figure 8. Basic scheme of multi-connectivity tool: mpconn tunneling program.

The tool offers various duplication strategies:

- Blind duplication: All incoming packets or data streams are duplicated through all active interfaces in this mode.
- Selective duplication: This strategy allows packets to be transmitted through the primary interface until a specific radio KPI falls below a predetermined threshold specified in the configuration file. Currently, the available KPIs for configuration exclusively depend on cellular parameters, namely: RSRP, RSRQ, and SINR.

Mobility test campaigns and metrics

Three test campaigns have been planned for this COMMECT PAT, and all of them will perform tests of single and multi-connectivity between one cellular operator and mobile broadband satellite access, under different conditions and with different equipment, though some equipment will be shared between the campaigns.

The **Mobility Campaign 1 (MC1) - "Cellular + Starlink"** will be performed in rural areas near South Aalborg (Denmark). The particularity of this campaign is that it will not only evaluate multi-connectivity performances between cellular and satellite but also multi-connectivity between different cellular operators. Regarding the satellite access, a Starlink antenna with a residential plan will be used.

The **Mobility Campaign 2 (MC2) - "Cellular + CNES truck"** will be performed in rural areas near Toulouse (France). Regarding the satellite access, we plan to use an Intelsat-based GEO antenna in 2023 and a OneWeb LEO antenna in 2024 (if mobility is enabled). One of the objectives of MC2 is to collect metrics allowing cellular 5G and satellite channels to be characterized, e.g., capturing packet captures (*.pcap) at the emission and the reception to calculate latency, throughput and packet losses during the tests. SNIR information from the satellite and cellular modems will also be very useful. All these metrics will be used to reproduce pseudo-real channel conditions in the last campaign by means of cellular/satellite emulators.

The **Mobility Campaign 3 (MC3) - "Cellular and satellite emulation"** will be performed in VITECH and AAU laboratories. The emulation will take advantage of the satellite and 5G channel/traffic conditions collected in rural areas during the MC2. The satellite channel conditions will be imported to OpenSAND that will emulate a satellite network. The 5G network will be emulated using a simple customized network emulator or replaying the traffic captures. The open-source network metrology testing tool OpenBACH [11] will be used to orchestrate the traffic generation, configure the testbed, collect the metrics and monitor the tests.

The main metrics that will be collected and used to evaluate the multi-connectivity performance will be based on the technical requirements defined in deliverable D1.2 (requirement *R3.1: UL Throughput,* requirement *R3.2: DL Throughput* and requirement *R3.3: Service Reliability*). We have summarized the main metrics that will be collected per MC in Table 4, and the tools that will be used to collect them when generating different types of traffic.

<table>
<tr><th>Mobility Campaign</th><th>Tools/service</th><th>Metrics</th></tr>
<tr><td rowspan="2">MC1 - "Cellular + Starlink</td><td>Ping</td><td>Latency measurements (s)</td></tr>
<tr><td>Iperf3 (UDP)</td><td>Throughput measurements (bps)</td></tr>
<tr><td rowspan="3">MC2 - "Cellular + CNES truck</td><td>Ping</td><td>Latency measurements (s)</td></tr>
<tr><td rowspan="2">Iperf3 (UDP/TCP)</td><td>Throughput measurements (bps)</td></tr>
<tr><td>File download time (s)</td></tr>
<tr><td rowspan="3">MC3 - "Cellular and satellite emulation"</td><td colspan="2">Same as in MC2 (ping and iperf)</td></tr>
<tr><td>Firefox web browsing</td><td>Page Load Time (s)</td></tr>
<tr><td>Video streaming</td><td>Video quality and video stalling/freezing</td></tr>
</table>

Table 4: Traffic generation tools and collected metrics per tool for each MC.

2.1.2 Wi-Fi vs 5G private networks for uplink video streaming

This COMMECT PAT aims at comparing Wi-Fi and 5G private network performances to ensure the transmission of high-quality real-time video surveillance services. Different items will be studied:

- Measure the maximum distance between the end-user and the access network that allows to send a video throughput of 10 Mbps (i.e., range/coverage).

- This is for different 5G carrier bandwidths and different UL vs DL frame configurations and using Wi-Fi 6.

This COMMECT PAT is related to two of the use cases of the Denmark LL, where computer-vision-based solutions are needed for automation of access to the farm of livestock transport units and for monitoring the livestock loading/unloading processes. The camera in the truck should transmit the video to the Wi-Fi modem or the gNB of the 5G Private network located at the farm, which might be far from the loading/unloading site.

Description of architecture and equipment

The main architecture (Figure 9) consists of several integral components. Firstly, there is the video camera with 5G communication capability. This component is designed to encompass a video camera communicating effectively over the 5G network. This integration can take shape in multiple ways, such as an integration of a video camera and a 5G modem, or pairing a video camera (e.g., GoPro) with a 5G-enabled smartphone.

An important part of the architecture concept is the fact of using the Local (Private) 5G Access Network and its features. This entails the creation and management of a localized 5G access network. This network can operate within the bounds of a licensed spectrum, particularly utilizing the 3.5 GHz band. Alternatively, it can function within an unlicensed 5 MHz guard band, specifically within the 1800 MHz Digital Enhanced Cordless Telecommunications (DECT-) band. However, it is crucial to ensure strict adherence to the relevant national regulations, with specific attention to the requirements of Denmark and Germany.

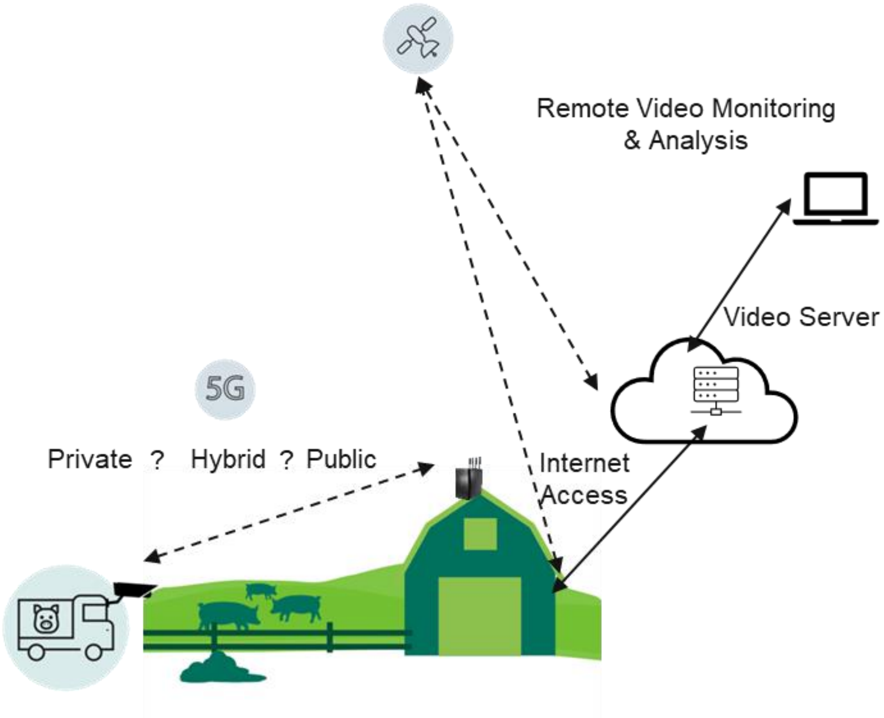


Figure 9. Communication architecture for UC 3.2 and UC 3.3 - Livestock video monitoring while loading/unloading.

Description of the performance evaluation tests

The performance evaluation tests focus on an in-depth exploration of the achievable uplink throughput concerning coverage within distinct 5G configurations. This multifaceted investigation encompasses several key considerations.

One significant aspect involves analyzing the relationship between uplink throughput and coverage under various conditions. The primary objective is to identify the maximum distance at which a consistent 10 Mbps UL video throughput can be sustained (requirement *R3.4:*

Uplink Throughput from deliverable D1.2). Several parameters come into play during this analysis.

The impact of local licenses is essential, with bandwidth options of 50 MHz or 100 MHz being evaluated. This evaluation extends to different frequency bands, as the local frequency licensing regulations dictate. A key focus is comparing 5G configurations that employ bandwidths up to 50 MHz, akin to certain Wi-Fi setups. This scope is driven by the intention to maintain a level of performance above or on-pair with Wi-Fi standards while also considering available bandwidths for local private 5G networks. Additionally, the video transmission device should support dual-mode Wi-Fi and 5G, and should ensure the tests are performed under similar network conditions.

The tests also delve into diverse Time Division Duplex (TDD) frame configurations, comparing UL and DL scenarios to understand throughput characteristics better. In addition, the analysis extends to encompassing Wi-Fi setups, examining their UL video coverage at frequencies such as 2.4 GHz, 5 GHz, and 6 GHz.

Authentication, roaming, and eSIM (embedded SIM) functionality form another critical focal point. This assessment involves architectural considerations, such as employing Wi-Fi Protected Access (WPA) Enterprise for Wi-Fi networks and analogous solutions for 5G setups. Concrete testing scenarios are essential to validate the efficacy of these protocols in both Wi-Fi and 5G contexts. The realm of operations and management is also under scrutiny, emphasizing the concept of 'zero management.' This concept aligns with the aspiration to create self-configuring and self-optimizing systems that minimize manual intervention by the farmer or network owner.

Lastly, the test encompasses a comprehensive study of energy consumption. A fundamental comparison is drawn between the energy usage of 5G and Wi-Fi systems. This analysis takes into account scenarios where the entire 5G infrastructure resides within a single physical unit versus cases where the 5G Core is hosted in the cloud.

Expected results on uplink performance

In wireless access systems such as e.g., 5G or Wi-Fi networks, the uplink throughput performance is more challenging due to the limited uplink transmission power and uplink RF and baseband processing at the wireless terminals in comparison to the transmit power and processing available at the wireless access point side. From the livestock transportation use case perspective, it is important to quantify the maximum allowed distance (i.e., the maximum allowed signal level attenuation) between the transportation truck and the nearby wireless (5G or Wi-Fi) access point such that there is an uplink video streaming with sufficient quality. According to deliverable D1.2, 10 Mbps throughput is the minimum acceptable quality threshold for the uplink video streaming quality.

Therefore, the intermediate 5G laboratory tests have focused on the uplink throughput measurements in the 3.5 GHz band with a controlled signal attenuation expressed in the downlink RSRP at the terminal for different configurations in terms of available bandwidth (e.g., 20, 30, 40, and 50 MHz) and two different TDD frame configurations labelled as “Conf. 2” having 7 and 2 downlink vs uplink time slots, respectively and “Conf.3” having 6 and 3 downlink vs uplink time slots, respectively.

The lab test set-up is depicted in Figure 10 consisting of a 5G Amari Callbox Classic [17] for providing the local 5G network, connected via a coaxial cable and a signal attenuator to a Faraday Box hosting a Quectel RM500 [18] as a wireless 5G terminal. This set-up enables very controlled signal attenuation conditions that were kept within the 5G RSRP range of -60 dBm (very good conditions) to -120 dBm (cell edge conditions). Due to the limitations of the number of antenna connectors at the used Faraday Box, we have only tested Single Input Single Output (SISO) antenna uplink transmissions. Therefore, the results depicted in Figure 11 should be interpreted only in relative context.

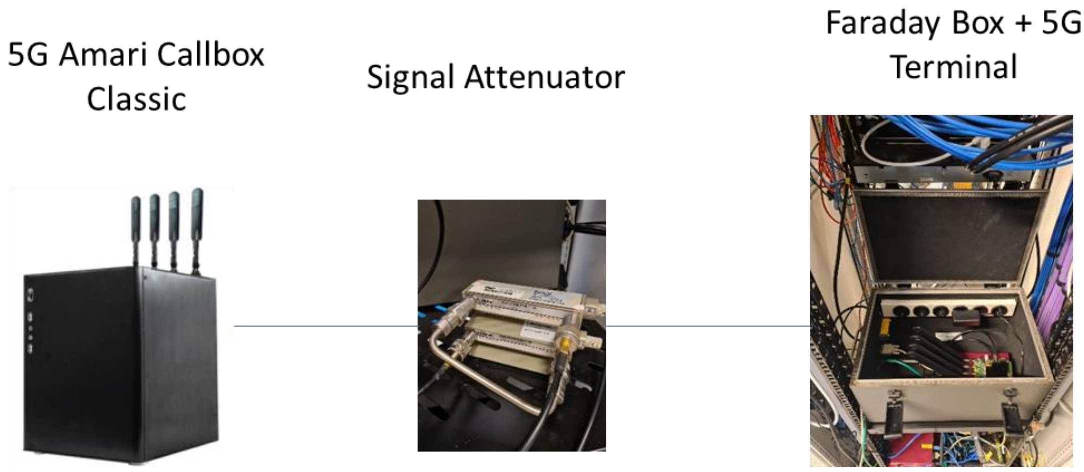


Figure 10. Uplink 5G throughput test set-up.

As the different curves indicate, if we increase the amount of bandwidth from 20 MHz to 50 MHz and allow for more uplink slots in the TDD frame configuration, we can increase the minimum allowed RSRP value to have 10 Mbps uplink throughput, or in other words increase the allowed distance between the truck and the nearby wireless access point. Regardless of the configurations the uplink throughput falls below 10 Mbps around RSRP = -98 dBm, and yet this observation needs to be revisited by allowing Single Input Multiple Output (SIMO) or Multiple Input Single Output (MIMO) uplink transmission.

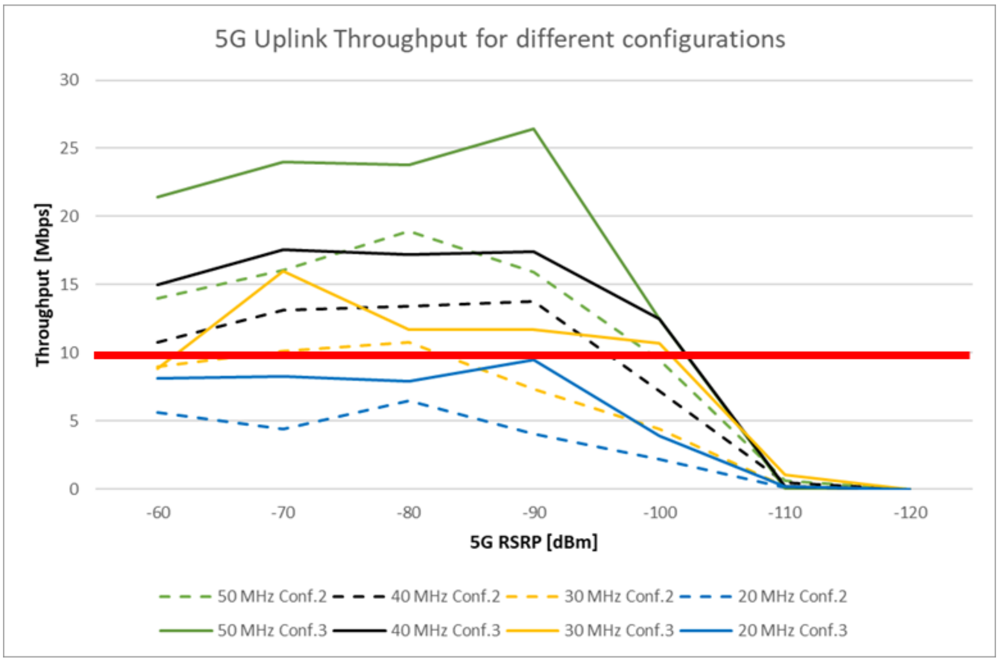


Figure 11. 5G Uplink Throughput for different bandwidths and TDD Frame configurations: "Conf.2 with 7 downlink and 2 uplink time slots; "Conf.3 with 6 downlink and 3 uplink time-slots" as generated by the measurement data from the set-up depicted in Figure 10 (results obtained by TNO in the laboratory).

Further, we see that for larger 5G bandwidths of 40 or 50 MHz (and for Conf.3 even for 30 MHz) the minimum allowed RSRP value to achieve 10 Mbps uplink throughput is not significantly influenced. Again, this observation needs to be revisited for SIMO/MIMO uplink transmissions.

2.1.3 Cellular, LPWAN and Direct-IoT-to-satellite sensor data collection

The latest IoT Analytics "State of IoT-Spring 2023" report [19] shows that global IoT connections grew by 18% in 2022 to 14.3 billion active IoT endpoints. Short-range wireless technologies (Wi-Fi, Bluetooth and Zigbee) and longer-range connectivity technologies, such as Long Range (LoRa), Narrowband IoT (NB-IoT) and Long-Term Evolution for Machines (LTE-M) are simplifying the development of IoT sensor data collection at a fair cost. However, connectivity using Low-Power Wide-Area Networks (LPWAN) is only possible where there is access to a terrestrial network, which is often not the case, for example with remote environmental sensor stations, isolated rural/farming areas, search and rescue operations and trucks fleet tracking. For these applications satellite communication is the only feasible option. Historically, only very high volume or extremely mission-critical applications could justify the high cost of satellite access. In recent years, however, the cost of access to space has been decreasing, with organizations such as Space-X or OneWeb dramatically driving down launch costs, stimulating growth in the launch numbers of small satellites, including CubeSats. This growing popularity of small satellites is opening multiple opportunities to implement satellite technologies for remote sensing.

The following COMMECT PAT will analyze the performance of standard LoRa for terrestrial communication and two IoT-to-NTN connectivity types. The first type is based on direct IoT-to-satellite connectivity technologies, using either LoRa or Iridium Short Burst Data (SBD). The second type will use LoRa for IoT-to-UAV connectivity.

2.1.3.1 LoRa, direct-IoT-to-satellite and drone-assisted solutions for farming

Description of architecture and equipment

LoRaWAN is one of the IoT LPWAN technology that can be used in the context of the COMMECT project to extend connectivity in rural areas. It can also be implemented to access sensor data in many Living Labs. Low-cost and low-power end devices can collect data in real-time and transmit it to several gateways at a long coverage range.

The network architecture is defined in a star-of-stars topology (Figure 12). Multiple sensors send data to the gateways within their communication range, and then gateways forward data to the remote LoRaWAN Network Server (LNS) and LoRaWAN Application Server (LAS) via the backhauling network (Section 2.2.2). The radio communication is based on LoRa, a derivative modulation from the Chirp Spread Spectrum (CSS).

A selection of transmission parameters (Transmit Power (P_{Tx}), Spreading Factor (SF), Coding Rate (CR), Packet size, transmission periodicity), determine the robustness of transmission against packet loss, but also data rate and energy consumption.

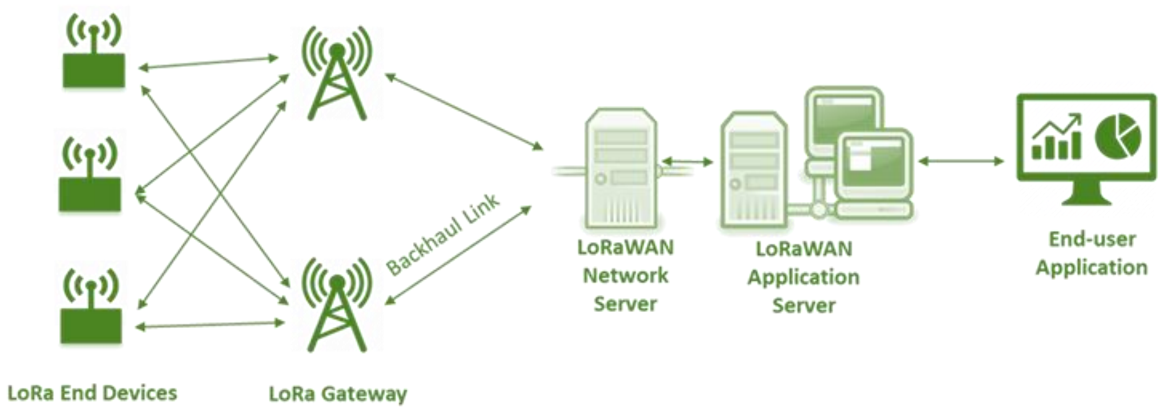


Figure 12. Architecture of LoRaWAN network testbed.

The gateway installation will define three communication scenarios that will be considered in this connectivity solution, as depicted in Figure 13. The Gateway can be deployed in the field at a fixed position (Sc1), on a flying drone to extend the connectivity in the field (Sc2) or on a LEO satellite for fields where terrestrial coverage cannot be ensured (Sc3).

Figure 13. Equipment used in different scenarios.

To test connectivity in Scenarios 1 and 2, the "Milesight EM500 (EM500-CO2 Carbon Sensors, n.d.)" [20] device will be used as a LoRaWAN sensor to send data to gateways. The transmission parameters of the device can be configured using a mobile application (via NFC) or PC software (via USB). It is a battery-powered device showing the battery status, which will help monitor the energy consumption during transmissions in different configuration set-ups.

The RAKwireless gateway will be used to collect data from sensors. It is a Raspberry Pi (RPi) based gateway with higher electromechanical and software flexibility. It allows the custom software installation and is more practical to be mounted on the drone. The power supply of the gateway for scenario 2 will be insured with a power bank.

In Scenario 3, devices like the Lacuna Space devKit LS200 [21] will be used to communicate directly with real LEO satellites. Firmware on the devices may be closed, and thus, not support set-up of new features/parameters.

Thus, in addition, to perform the direct IoT to satellite test, the satellite link emulator OpenSAND will be used. OpenSAND, described above in Section 2.1.1 emulates a GEO/LEO satellite system using three types of components: the satellite terminals, the satellites, and the satellite gateways. The three components can be executed in Virtual Machines on the same laptop, or on three different laptops. The satellite terminal will be connected via Local Area Network to the RPi LoRa gateway. In the last release, OpenSAND added the support to LEO satellites with one ISL (and delay variations representing a LEO constellation). To emulate a direct LoRa-to-satellite communication, OpenSAND will be adapted to emulate that the RPi gateway is actually pseudo-integrated in the LEO satellite component, i.e., the channel link between the satellite and the satellite terminal will be removed and the satellite terminal functions disabled to emulate direct LoRa-to-satellite communication.

Description of the performance evaluation tests

The end-to-end connectivity solution proposed above will be evaluated according to the technical requirements defined in deliverable D1.2 (particularly requirement *R1.1: Packet Delivery Ratio* and requirement *R1.2: Battery Life*).

Packet delivery ratio and energy consumption will be evaluated through experiments and simulations in the laboratory and in the field to demonstrate the feasibility of the designed system and validate its accuracy. The signal attenuation, propagation impact, noise resistance and receiver sensitivity will be tested with different transmission settings.

- **Laboratory test (Sc1): Standard LoRaWAN**

The laboratory test will be performed for connectivity in Scenario 1, a set of LoRaWAN devices will be configured to send data packets periodically to the LoRaWAN gateway in the laboratory. The gateway will forward packets to the server, where they will be stored for later processing.

In the first test, devices will be configured to send data every 15 minutes using Adaptive Data Rate (ADR). In this configuration, the SF allocation will be managed by the LoRaWAN server, where the SF is decreased for devices with a lower link budget, and increased if the link budget is high, so that the GW can receive the signal. The packet delivery ratio and SF allocation will be analyzed in this configuration.

A second test will be performed where ADR will be deactivated, and SF allocation will be programmed for every device. All devices will be configured to use the same SF, and communication performance will be evaluated for each SF. Then another distribution of SFs will be defined to have a multi-SF communication scenario.

Energy consumption will be measured for all these configurations to check the impact of SF selection on battery life.

- **Outdoor test (Sc2): IoT to UAV**

Outdoor tests will be planned to test connectivity in Scenario 2 with a flying gateway (acting as aerial wireless base station).

Devices will be distributed in different corners of the test field and the drone carrying the gateway will be flying following a predefined (and a random) trajectory. Devices will communicate at varying distances to the gateway, and signal attenuation, packet delivery ratio and energy consumption will be evaluated as a function of distance and environmental obstacles. Conclusions from the previous tests in the laboratory about the SF impact will define SF allocation strategy for devices in this scenario.

Advanced analysis of the outdoor tests will provide results about the communication performances in terms of: i) The communication range of LoRa in real environment and the optimal positioning of LoRaWAN gateways. ii) The capacity of drone assisted IoT communication infrastructures given the limited energy and flight time of the drone.

- **Simulations (Sc3): IoT to satellite**

Direct IoT to satellite communication is a promising scenario to bring connectivity where there is no terrestrial backhauling technology or when it is not possible or profitable to deploy a LoRaWAN gateway plus a backhauling network in the field. LEO satellite gateways can ensure extensive coverage of LoRaWAN devices in remote areas. However, the satellite's limited visibility necessitates efficient data packet transmission scheduling, but also limits the amount of data to be transmitted during the day.

In this task, tests will be performed to evaluate scheduling methodologies and transmission parameters to guarantee the successful transmission of queued packets. Real data traffic will be generated using prototyping devices, and will be sent to the emulated satellite gateway using different transmission configurations (SF, packet size and transmission frequency). Collected packets will be analyzed. Achievable packet delivery ratio will provide conclusions about the connectivity limitation and optimal configurations to send, efficiently, collected data in real environments.

2.1.3.2 Narrowband satellite vs XG for seamless connectivity on the road

This COMMECT PAT is a follow-up of the COMMECT PAT described in Section 2.1.1, where the seamless connectivity on the road was evaluated on broadband connectivity, but here we focus on sensor monitoring. Using broadband satellite access only for sensor data collection has not yet been justified, given the high price of broadband satellite capacity and the price of the mobile antenna for one single truck. However, as stated before, satellite operators propose dedicated transport service with cheaper equipment/antennas: either booking not priority data for this kind of traffic (like Iridium Short Data Burst service) or building dedicated constellations for sensor data collection (like Lacuna Space tested in the previous Section 2.1.3.1).

The idea here is similar to our previous work on seamless connectivity, where we evaluate multi-connectivity strategies combining two different networks or technologies to have a backup option in case cellular coverage is poor or non-existent. The backup network will be narrowband satellite access (or Short Data Burst service) using the Iridium LEO constellation (see Figure 14, showing the detailed service description) where the service will only be capable of transmitting short data (mainly sensor information, etc.). The monthly plan costs around 20€-40€ for a limited quota of 8KB-30KB, and the antenna/terminal costs around 250€.

If considered relevant, we could test a second narrowband satellite access, the Orbcomm ST6100 with an Inmarsat Data Pro plan (GEO satellite). The cost of the antenna and the monthly plan are the same as the Iridium SDB, but the limited quota is higher.

The multi-connectivity strategies here will be simplified: packet duplication or link selection depending on the availability of the links.

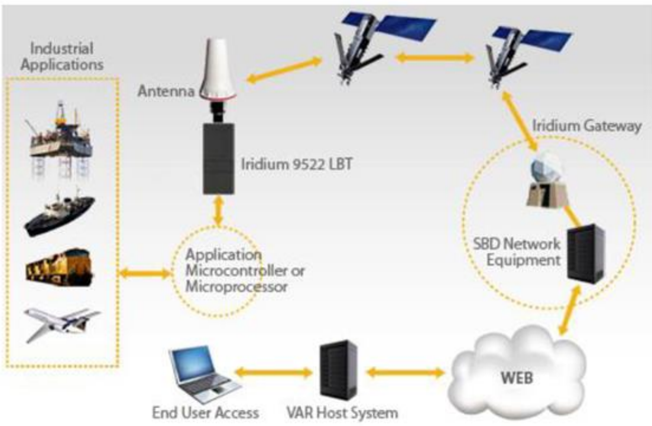


Figure 14. Iridium SBD service.

Figure 15. Iridium SBD antenna.

The mobility campaigns of this COMMECT PAT will be performed after the Mobility Campaign 2 (MC2) of seamless tests for broadband traffic, using the OSCAR truck (described previously) in rural areas near Toulouse (France). In this case, only short messages (sensor type) will be sent from the satellite terminal (uplink) as traffic to evaluate the feasibility of using narrowband satellite access on the road when XG is not available. The performance will be evaluated following the technical requirements defined in deliverable D1.2 (requirement *R3.1: UL Throughput* and requirement *R3.3: Service reliability*).

2.1.4 Network slice orchestration using Intelligent Connectivity Platform

The Intelligent Connectivity Platform (ICP) serves as an intent-driven platform for intelligent connectivity and incorporates the functionalities of managing and optimizing connectivity resources. The ICP can be defined as a “middle” platform or service orchestrator that operates only at the planning horizon level. It is placed between the Decision Support System (DST) system, which caters to non-technical users, and the Connectivity Platform layer consisting of diverse infrastructure labs. The role of the ICP is to facilitate the interaction between the DST and the available connectivity options, acting as a mediator and provider of connectivity candidates for solving user questions or requests. The purpose of ICP will be fully addressed in future deliverables D1.3[22] about COMMECT architecture and D2.3[10].

The objective of this COMMECT PAT is to integrate the ICP prototype with TNOR’s network orchestrator at TNOR’s Lab (described in deliverable D2.1[3]] and evaluate the overall performance. The idea is to first select the suitable connectivity solution based on the user requirements and then translate the selected technology in low level service order which will be transferred to service orchestrator for resource reservation. More details on it will be provided in future deliverable D2.3 and D5.4 (second version of this document).

2.2 Backhauling Network

As defined before, the backhauling network provides the transport of data traffic between the access network and a core network with the central infrastructure (located in data centers or a network operations center). They are usually links with high-capacity connections capable of carrying large amounts of traffic. In COMMECT, satellite is one of the chosen backhauling technologies that can make it feasible to offer cellular or IoT services in areas that are impossible or expensive to reach using traditional terrestrial means. In this case, the satellite network helps bringing the data from a 5G core to the 5G base station, or between the LNS and the LoRa GW.

Two COMMECT PATs are listed in Table 5 regarding the comparisons of connectivity solutions for the backhauling network, both comparing 5G to satellite networks but for different types of uplink traffic: video streaming and sensor data. Only the second COMMECT PAT is confirmed.

Main COMMECT PATs	Related WP2 tasks	Partners involved	Living Labs benefiting from this test	Confirmed test?
XG vs broadband satellite for uplink video streaming	T2.2 (Local 5G Private Networks)	TNO TNOR	All LLs	No
XG vs broadband satellite for sensor data collection	T2.3 (IoT and Edge)	LIST SES VITECH		Yes

Table 5: List of COMMECT PATs considered in the backhauling network section.

2.2.1 XG vs broadband satellite for uplink video streaming

This COMMECT PAT will focus on comparing 5G and satellite as a backhauling network for transmitting video streaming. Two partners will carry similar performance evaluation tests for uplink videos streaming but using different equipment and targeting different use cases: TNO targets the livestock loading/unloading monitoring and TNOR targets forestry use cases like situations awareness and remote control.

2.2.1.1 XG vs broadband satellite for uplink video streaming in the farm

This COMMECT PAT is a follow-up of the COMMECT PAT described in Section 2.1.2, where a comparison of Wi-Fi and 5G private network performances will be carried out to ensure the transmission of real-time video through the Last-mile network. Here, the establishment of a Transport Network (backhauling), which serves the purpose of connecting to a remote video server, is analyzed. This connection can be executed through the utilization of either a fixed terrestrial line or a wireless terrestrial line, catering to varying infrastructure needs. While the application of a satellite link is plausible, it is important to note that this approach might be more suited for controlled conditions or when equipped with satellite link emulators like OpenSAND [11] described before, due to the inherent complexities associated with satellite communication.

The quantification of transport delay over satellite links is a core consideration for this COMMECT PAT and very important to assess End-to-End (E2E) delay in various contexts:

- This parameter is significant in scenarios involving a gNB located at the farm side, with the 5G core behind the satellite transport link.
- An alternative scenario is explored, featuring the gNB and 5G core deployed at the farm side. This COMMECT PAT aims to assess whether this arrangement could mitigate potential satellite delay challenges.

2.2.1.2 XG vs broadband satellite for uplink video streaming in the forest

TNOR will compare different connectivity solutions to provide backhaul connectivity for the nomadic private networks. In particular, the backhauling network under tests will transport video streaming (video size/quality is expected to be reduced considerably by a video renderer software on the edge) and control traffic between the Network on Wheels (NoW) presented in deliverable D2.1 and the Backbone. NoW serves as a self-contained entity, encompassing radio, core, and ancillary applications within a singular, effortlessly transportable mobile framework. Its utility extends to remote locales bereft of coverage, as well as regions where prevailing connectivity infrastructure stands compromised due to the impact of natural disasters. In essence, NoW stands as a versatile and adaptive response to the challenges posed by network coverage in diverse scenarios.

The performance evaluation tests will compare different commercial network service providers and a satellite network in terms of throughput, reliability and latency (according to D1.2). In addition, different backhauling modems for traffic aggregation will also be tested. The objective is to analyze the most adapted connectivity solutions to provide situation awareness services and remote operational support for forest machine operators.

More detail on these tests will be provided in next deliverable D5.4 (second version of this document).

2.2.2 XG vs broadband satellite for sensor data collection

Description of architecture and equipment

The lack of mobile terrestrial coverage in rural, remote areas is among the challenges of deploying IoT networks. The cost per subscriber of deploying cellular networks in rural areas is high due to the low population density, thus these areas are often not well served. In this context, satellite technology is an enabler to bring connectivity to those isolated regions. The potential of integrating satellite backhauling with LoRaWAN technology to collect sensor data is highlighted in this section and will be evaluated as an alternative to terrestrial networks.

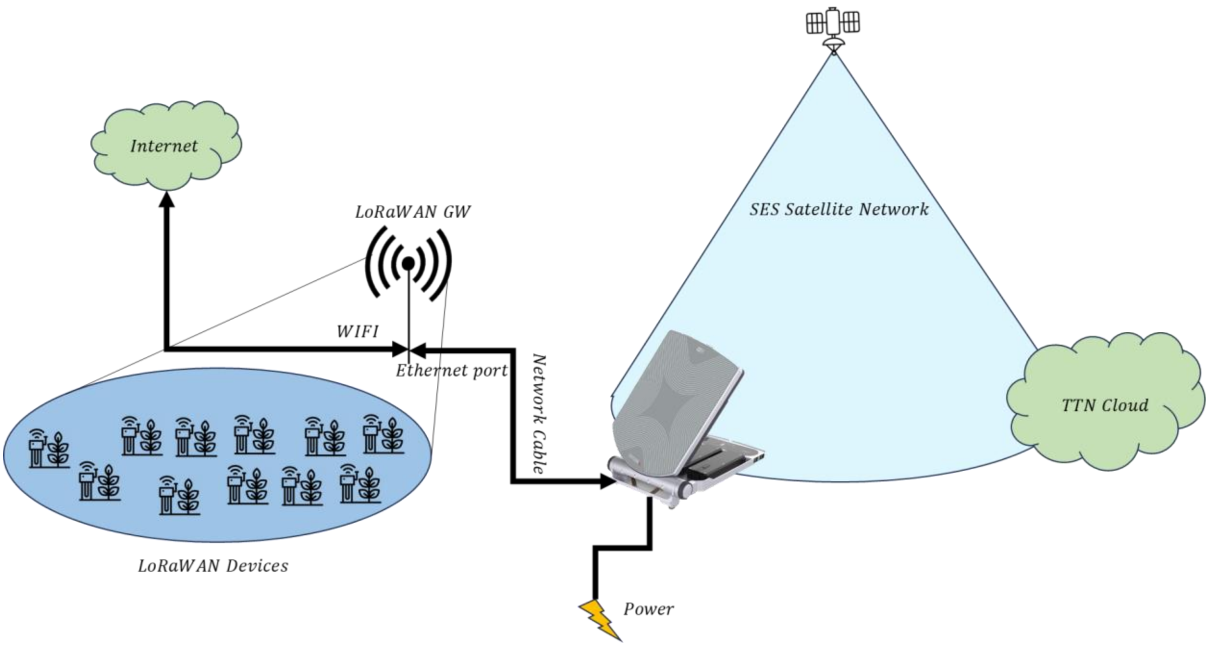


Figure 16. Satellite backhauling for sensor data collection.

The architecture related to this connectivity solution is described in Figure 16. IoT data is collected from LoRaWAN devices and transmitted to a LoRaWAN gateway deployed in the lab. The gateway is connected to the fast deployable satellite terminal via Ethernet, to upload the IoT sensor data via SES's satellite backhauling network.

The tests will be performed using the "Milesight EM500" device as a LoRaWAN sensor at the access network to send data to the Gateway. And the RAK wireless gateway will be used to collect data from sensors.

For the baseline test (scenario on the left Figure 16), the gateway will be connected to the server using the terrestrial network (ethernet cable or Wi-Fi). The terrestrial backhauling will be replaced by the satellite link using the "Satcube Ku" [23] satellite transportable terminal (scenario on the right of Figure 16), and for other detailed analysis of metrics related to the satellite backhauling, the OpenSAND emulator will be used to reproduce the satellite backhauling link.

Description of the performance evaluation tests

The proposed connectivity solution will be evaluated for end-to-end transmission of sensor data according to the technical requirements defined in deliverable D1.2 (particularly requirement *R1.3: Latency* and requirement *R1.4: Network availability*).

To initialize the comparison between real satellite and OpenSAND, the connectivity will be tested for the entire communication link (access and backhaul) including uplink and downlink paths. For this, it is essential to set OpenSAND link configuration to the same used in the real scenario using the "Satcube Ku" satellite. For instance, the capacity of OpenSAND can be initialized as 12 Mbps to emulate the ASTRA 2F satellite of SES. Under this designated emulation environment for satellite backhauling, the comparison test between OpenSAND and SES terminal is more meaningful.

The real satellite backhauling link will be used to test the end-to-end communication and evaluate the network availability and latency. However, since the allocation of resources (capacity, bandwidth, hardware installation) for this real test will be limited, it will be replaced later by the emulated link. But initial comparisons and calibrations between real and emulated testbeds are the starting point.

The first comparison tests between the real satellite and the emulated link are expected to give the same results in terms of latency introduced to the end-to-end transmission under the same configurations.

The emulated link will be used after to evaluate other advanced communication metrics under different configurations in order to meet the requirements defined for this connectivity solution. The performance achieved using satellite backhauling will be compared to the ones that can be realized using terrestrial backhauling.

3. Computing Technologies in rural areas

The COMMECT connectivity platforms should be green by design and consider new paradigms which reduce the consumption, not only at connectivity level but also at computing level (e.g., 5G private networks, mobile edge computing, zero-touch devices, etc.). This section presents COMMECT PATs that will focus on the analysis of energy consumption of services that will improve the competitivity and sustainability of rural communities.

3.1 Edge and Cloud

This section aims at evaluating the advantages and the constraints of using Edge computing for video and image processing, and when aggregating/processing traffic from different base stations. This will be done in terms of energy consumption, throughput performance, latency, etc. Two COMMECT PATs are planned but only one of them is confirmed at this stage of the project, and deliverable writing.

Main COMMECT PATs	Related WP2 tasks	Partners involved	Living Labs benefiting from this test	Confirmed test?
Energy efficiency using ML algorithms on Edge devices for processing farming images	T2.3 (IoT and Edge)	DNET	All LLs	Yes
Impact of local breakouts on 5G core energy consumption	T2.2 (Local 5G Private Networks) T2.3 (IoT and Edge)	TNOR		No

Table 6: List of COMMECT PATs considered in the Edge and Cloud computing section.

3.1.1 Energy efficiency using ML on Edge devices for processing farming images

The main objective of this COMMECT PAT is to carry out performance testing and evaluation of processing power and power consumption of Edge devices while performing real time video processing.

Execution of Machine Learning (ML) algorithms (inferencing) is often a demanding computing process that can consume significant energy. Having in mind that the Serbia LL deployments rely on portable/mobile solar plants with limited energy generation capabilities and storage capacities, it is necessary to evaluate the energy needs of ML algorithms and thus determine the price/performance options. Namely, determine the minimum energy generation capabilities to support execution of the planned ML algorithms together with the energy required for the execution of other application logic (for example, to run the irrigation equipment). The evaluation has to take into account not only the electrical energy capabilities (the number of solar panels, battery capacity) but also the configurations of edge ML devices and the characteristics of the installed Graphics Processing Unit (GPU) boards as these can significantly impact the overall costs of the deployed system.

Description of architecture and equipment

The overall architecture of LL Serbia is described in deliverable D2.1. To avoid potential issues in the field, it is necessary to define and validate the complete network and edge computing configurations. This process will further contribute to providing recommendations on the most suitable configurations, considering both technological and economic perspectives.

To that end, the lab validation will include devices that are planned to be used in field deployments (edge ML devices, video cameras), and the same networking components and configuration, thus creating a replica of the field deployment in the lab environment.

The main focus of the laboratory validation will be on determining the most suitable configurations of edge ML devices, given the planned functionality. Evaluation of different edge ML configurations (see Table 7) will be done with a focus on real-time video analysis with varying types of objects and processes detected and analyzed.

Edge ML devices	**Configurations**		
	GPU	**CPU**	**Memory**
Jetson Nano 2GB 	128-core Maxwell	Quad-core ARM A57 @ 1.43 GHz	2 GB 64-bit LPDDR4 25.6 GB/s
Jetson Nano 4GB 	128-core Maxwell	Quad-core ARM A57 @ 1.43 GHz	4 GB 64-bit LPDDR4 25.6 GB/s
reComputer J2012 Edge AI Device with Jetson Xavier NX 16 GB 	384-core NVIDIA Volta™	6-core NVIDIA Carmel ARM®v8.2 64-bit CPU 6 MB L2 + 4 MB L3	16 GB 128-bit LPDDR4x @ 59.7GB/s
ProArt Station Ubuntu-NVIDIA-01 	NVIDIA GeForce RTX 3070/PCIe/SSE2	11th Gen Intel® Core i7-11700 @ 2.50GHz x 16	80 GB

Table 7: Configuration of Edge ML devices

Solar panels will not be used during the laboratory testing. Instead, devices under evaluation will be connected to a regular electric grid as well as to batteries that are planned to be used in the field deployments. Appropriate power monitoring equipment Primera-Line energy meter / electricity meter [24] for calculating energy consumption and energy costs (energy cost device with 2 individually adjustable electricity tariffs). Video streams will be obtained from the video cameras in the lab as well as using videos generated using AI algorithms, creating scenarios expected in the field. The video camera illustrated in Figure 17 will be used for the tests:

- **Dahua Camera IPC-GS7EP-3M0WE** – provides a 5MP live monitoring with 0~340° pan and 0~90° tilt functions.

Figure 17. Dahua Camera.

A high-level overview of the laboratory networking and computing configuration is presented in the figure below. Workstation is used to run the tests and calculate processing time while power consumption is measured by Primera-Line energy meter.

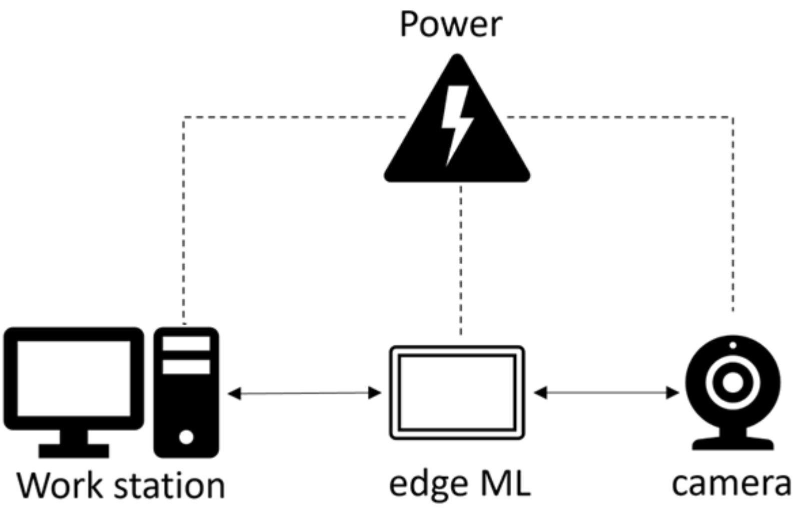


Figure 18 Lab test set-up

Description of the performance evaluation tests

Real-time video processing with complex object detection and tracking algorithms is performed on different Edge devices. Each Edge device has a GPU with specified Tera-Operations Per Second (TOPS) and built-in memory size. The processing time is observed and calculated for individual devices and the number of frames processed per second is captured. At the same time, power consumption is measured, and average kWh consumption can be estimated.

Expected Results

The following performance test metrics will be used to validate the requirements from deliverable D1.2 (mainly requirement *R5.1: Power Conversion Efficiency*):

1. Confirming the networking setup and the ability to remotely monitor the equipment installed in the field and its performance.
2. Validation of the notification systems in case of observed malfunction of the field equipment.
3. The amount of time consumed for the execution of different ML algorithms (video processing) by different types of edge ML computing devices.
4. The amount of energy utilized by GPUs for execution of different algorithms.

5. The amount of data transferred to cloud.

3.1.2 Impact of local breakouts on 5G core energy consumption

With *sustainability* high on the agenda of most (if not all) industries today, various initiatives have been in place for setting respective sustainability targets, as well as roadmaps towards achieving them. From the telco perspective, the Radio Access Network (RAN) and data centers are the major contributors to the overall energy consumption of the network [25].

Energy efficiency in the RAN is a well-studied domain in both academic and industrial research. In fact, each radio vendor has started to launch their own green radio solutions (e.g., [26]-[28], among others) in the last couple of years. Meanwhile, Beyond 5G (B5G) architectures and use cases start to go beyond the "traditional" central Cloud model, towards distributed *Edge-Cloud Continuum* paradigms [29], in which *Local Breakout Edge* implementations (e.g., with the 5G User Plane Function (UPF) at the Edge) will play a key role on keeping the traffic locally. It is interesting to study how this shift from central to distributed architectures will impact the energy consumption of the 5G core and/or UPF.

On this note, energy-aware features such as frequency scaling and low power states defined by the Advanced Configuration and Power Interface (ACPI) Specification [30] are widely supported by state-of-the-art compute servers and operating systems. Moreover, Intel's Running Average Power Limit (RAPL) interface [31] has served as basis for a number of green observability solutions (e.g., [32] and [33]). The plan is to compare scenarios with central and distributed UPFs, looking at the impact on the energy consumption – bearing in mind that in the distributed case, the load will be lower and hence, lower power states can be potentially exploited.

Particularly, we will evaluate different granularities of load aggregation and use the resulting traffic profiles as input to the 5G Core in our laboratory, then measure the corresponding energy consumption of the UPF. The centralized scenario will be emulated by using the aggregate load from all base stations. On the other hand, the distributed scenario will be emulated by the different granularities of load aggregation – from per base station to per city or region. A random topology will be used as the basis for this analysis.

The results will help evaluate different deployment options for rural communities and will assist in choosing between local break out deployment options or central core deployment options, keeping in view the energy consumption profiles.

4. Conclusions

This deliverable summarizes the first part of the work carried out in Task 5.1, where the main focus is to test and evaluate the performance of COMMECT connectivity solutions under laboratory conditions while using either real equipment in a controlled environment or simulators/emulators to replace some of the network components. In particular, this deliverable outlines the plans of the performance assessment tests, named COMMECT PATs, which are very correlated to the solutions proposed in WP2, about XG, Edge and Last-Mile Energy Efficient Solutions for coverage Extension. The WP2 solutions will be tested in T5.1, and feedback collected during the test campaign will help in further improving them. Task 5.1 can also be seen as an important step before the deployment in the Living Labs in WP4 and their validation in *Task 5.2 – Technical Validation in the Living Labs*. Inputs such as the first performance results or to know how complex is to deploy equipment in controlled laboratory conditions, can be useful for both WP4 and for Task 5.2.

We have presented the organization of the COMMECT solutions that focus on solving the communication and computing problems in rural and isolated areas. Regarding communication, the main comparisons addressed in COMMECT are terrestrial networks (XG, Wi-Fi and terrestrial IoT) vs NTN networks (satellite, UAV, etc.), in both the backhauling network and the Last-mile network, and for different user needs. Regarding computing Technologies, the main focus is to evaluate Edge solutions and to find a trade-off between service performance/quality and energy consumption. We have structured the COMMECT PATs accordingly, as: 1) Connectivity Access in Rural/Remote Areas (Terrestrial vs. Non-Terrestrial Networks) and 2) Computing Technologies in Rural Areas. Then, these COMMECT PATs are subclassified depending on the type of connectivity, the network deployment segment, the target service, etc. Each COMMECT PAT has described the objectives of the performance tests, the topology of the testbed and networks, the planned campaigns and metrics that will be used to validate the requirements detailed in Task 1.2 – COMMECT requirements and KPIs.

This deliverable helps to create synergies and cooperation among COMMECT partners outside de Living Labs, allowing to compare connectivity solutions under different conditions. It facilitates the sharing of information and results that will be very useful not only for the LLs deployment and testing, but also to provide knowledge to DST regarding the best candidate solutions adapted to each use case, sector, rural area and type of test. It should be highlighted that COMMECT PATs are mainly linked to LLs in Luxembourg, Denmark, Norway and Serbia. Regarding the LL Turkey, the connectivity solutions, network equipment and IoT devices are already (or mostly) deployed, and the performance tests will be carried out in the field, and described in Task 5.2.

Finally, it has to be noted that while the structure and organization of COMMECT PATs are finalized, the tests that are proposed herein might evolve, i.e., some new tests might be included and those that are not confirmed might be removed (or moved to Task 5.2) in the next version of the deliverable.

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