H2020 5G Dive Project
Grant No. 859881

# D1.4 Conclusions on Vertical Oriented 5G Field Trials and Future Outlook


## Abstract

This deliverable presents architecture validation and summary of the comprehensive results in this 5G-DIVE project (from 01/10/2019 to 31/12/2021), including DEEP Platform and the studied use cases, I4.0 and ADS.

This deliverable also includes information on possible way forward towards future exploitation of the platform innovations.

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# Disclaimer

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# Contents

# List of Tables

# List of Figures

# List of Acronyms

| | |
|---|---|
| **3GPP** | 3rd Generation Partnership Project |
| **4G** | 4th Generation |
| **5G** | 5th Generation |
| **5G NR** | 5th Generation New Radio |
| **5G-DIVE** | eDge Intelligence for Vertical Experimentation |
| **AC** | Alternating Current |
| **ACK** | Acknowledgement |
| **ADS** | Autonomous Drone Scout |
| **AI** | Artificial Intelligence |
| **AP** | Average Precision |
| **API** | Application Programming Interface |
| **APPs** | Applications |
| **AWS** | Amazon Web Services |
| **BASS** | Business Automation Support Stratum |
| **CDF** | Cumulative Distribution Function |
| **CNN** | Convolutional Neural Networks |
| **COVID-19** | Coronavirus Disease 2019 |
| **CPE** | Customer Premises Equipment |
| **CPU** | Central Processing Unit |
| **CRAN** | Cloud Radio Access Network |
| **D*x.y*** | Deliverable *x.y* |
| **DASS** | Data Analytics Support Stratum |
| **DC** | Data Center |
| **DCAS** | Drone Collision Avoidance System |
| **DDS** | Data Distribution Service |
| **DEEP** | 5G-DIVE Elastic Edge Platform |
| **DL** | Downlink |
| **DNS** | Domain Name System |
| **DT** | Digital Twin |
| **E2E** | Exchange-to-Exchange |
| **EAB** | Ericsson AB |
| **EagleEYE** | Aerial Edge-enabled Disaster Relief Response System |
| **EDC** | Edge Data Center |
| **EFS** | Edge and Fog System |
| **eMMB** | Enhanced Mobile Broadband |
| **eNB** | Evolved Node Base Station |
| **EPC** | Evolved Packet Core |
| **EuCNC** | European Conference on Networks and Communications |
| **E-UTRAN** | Evolved UMTS Terrestrial Radio Access Network |
| **FIM** | Fog Infrastructure Manager |
| **FOrcE** | Fog Orchestration Manager |
| **Gbps** | Gigabits per second |
| **GGC** | Greengrass Core |

| | |
|---|---|
| **GHz** | Gigahertz |
| **gNB** | 5G NR base stations |
| **GPS** | Global Positioning System |
| **GPU** | Graphics Processing Unit |
| **GUTI** | Globally Unique Temporary Identifier |
| **H2020** | Horizon 2020 |
| **HAT** | Hardware Attached on Top |
| **HD** | High Definition |
| **HTTP** | Hypertext Transfer Protocol |
| **HW** | Hardware |
| **I4.0** | Industry 4.0 |
| **ID** | Identity |
| **IDCC** | Interdigital Europe |
| **IE** | Intelligence Engine |
| **IEEE** | Institute of Electrical and Electronics Engineers |
| **IESS** | Intelligence Engine Support Stratum |
| **III** | Institute for Information Industry |
| **IIPFD** | Intelligent Image Processing for Drones |
| **IMDEA** | Madrid Institute for Advanced Studies |
| **IMSI** | International Mobile Subscriber Identity |
| **IoT** | Internet of Things |
| **IP** | Internet Protocol |
| **ITRI** | Industrial Technology Research Institute |
| **JSON** | JavaScript Object Notation |
| **K8S** | Kubernetes |
| **KPI** | Key Performance Indicator |
| **LED** | Light Emitting Diode |
| **LoRa** | Long Range |
| **LTE** | Long Term Evolution |
| **LTS** | Long Term Support |
| **LWM2M** | Lightweight M2M standard |
| **MAC** | Medium Access Control |
| **mAP** | mean Average Precision |
| **Mbps** | Megabits per second |
| **MiniPC** | Minicomputer |
| **MIRC** | Microelectronics and Information Systems Research Center |
| **ML** | Machine Learning |
| **MME** | Mobility Management Entity |
| **mMTC** | Massive Machine Type of Communication |
| **MQTT** | Message Queuing Telemetry Transport |
| **MTC** | Machine Type Communications |
| **NBI** | Northbound interface |
| **NCTU** | National Chiao Tung University |
| **NDI** | Network Device Interface |
| **NR** | New Radio |

| | |
|---|---|
| **NSA** | Non-standalone |
| **NTP** | Network Time Protocol |
| **OCS** | Orchestration and Control System |
| **OPTUNS** | SDN-based optical-tunnel-network system |
| **PER** | Packet Error Rate |
| **PHY** | Physical (Layer) |
| **PiH** | Person in need of a help |
| **PoC** | Proof of Concept |
| **PTZ** | Pan, Tilt and Zoom |
| **QoE** | Quality of Experience |
| **QoS** | Quality of Service |
| **RAM** | Random Access Memory |
| **RAN** | Radio Access Network |
| **RAT** | Radio Access Technology |
| **RF** | Radio Frequency |
| **ROS** | Robot Operating System |
| **RSRP** | Reference Signal Received Power |
| **RSSI** | Received Signal Strength Indicator |
| **RTSP** | Real Time Streaming Protocol |
| **RTT** | Round Trip Time |
| **SA** | Standalone |
| **SCTP** | Stream Control Transmission Protocol |
| **SFP** | Small Form-factor Pluggable |
| **SGW** | Serving Gateway |
| **SINR** | Signal to interference plus noise radio |
| **SQL** | Structured Query Language |
| **TBD** | To Be Determined |
| **TCP** | Transmission Control Protocol |
| **TED** | Test Dataset |
| **TELCA** | Telcaria S.A |
| **TLS** | Transport Layer Security |
| **TW** | Trained Weight |
| **UAV** | Unmanned Aerial Vehicle |
| **UC** | Use Case |
| **UC3M** | University Carlos III of Madrid |
| **UDP** | User Datagram Protocol |
| **UE** | User Equipment |
| **UI** | User Interface |
| **UL** | Uplink |
| **ULUND** | Lund University |
| **URLLC** | Ultra-reliable low-latency communication |
| **USB** | Universal Serial Bus |
| **USRP** | Universal Software Radio Peripheral |
| **VM** | Virtual Machine |
| **VPN** | Virtual Private Network |

| | |
|---|---|
| **WAN** | Wide Area Network |
| **Wi-Fi** | Wireless Fidelity |
| **WP** | Work Package |
| **ZDM** | Zero Defect Manufacturing |
| **ZMQ** | ZeroMQ |

# Executive Summary

This concluding deliverable provides the final conclusions on how the 5G-DIVE systems can provide benefit to the vertical use cases studied.

In Section 2, we verify the functionalities of each building blocks of DEEP, including BASS, DASS and IESS. The experiment results show DEEP is able to provide required features, such as system management, data dispatching, and ML/AI engines, to support the vertical applications running on top of DEEP.

In Section 3, we summarize the trial results of the use cases of Industry 4.0. Based on the trial results and performed demonstrations, we evaluate the fulfillment of objectives, conditions, business requirements, functional requirements and technical requirements, which were defined in D1.1 [5] . Most of requirements of the cases: Digital Twin, Zero Defect Manufacturing, and massive Machine Type Communications are met. Finally, we propose future developments to enhance the systems of each use cases.

In Section 4, we follow the same procedures as those in Secion 3 to assess Drone Fleet Navigation and Intelligent Image Processing for Drones. All requirements are met, and the future directions of exploiting more functions from DEEP to scale up the ADS systems are given.

Based on the assessment results, the majority of the requirements set up in D1.1 [5] have been fulfilled. The underlaying DEEP of 5G-DIVE satisfies the need of the use cases of Industry 4.0 and Autonomous Drone Scout. The future outlook is planned to disseminate DIVE to more Industry verticals.

# 1. Introduction

This concluding deliverable examines the two aspects of Dive project: i) DEEP the intelligent computing platform, and ii) the two disseminative uses cases: I4.0 the automated industrial manufacture, and ADS for quick disaster relief. The expecting architecture and features are carefully validated, the results are comprehensively interpreted, and finally the future outlook of DIVE are depicted.

For such purposes, the document is organized in the following 4 sections:

In Section 2, we make summary of experiments results from the main three components, BASS, DASS IESS, of DEEP platform. Then we verify the functionalities of expecting features. We also propose the future direction plans for applying DEEP to other industry verticals.

In Section 3, we move to the first industry vertical: I4.0 with its three use cases: Digital Twins, ZDM and mMTC. We conclude the trial results of each use cases. Next we carefully validate the requirements defined in D1.1 [5] in the following aspects of fulfilment: objective, condition, business requirement, functional requirement and technical requirement. Finally, we plan the future development to expand the capabilities of the systems built for each use cases.

In Section 4, we check the next vertical: ADS, with its two use cases: Drone Collision Avoidance System and Intelligent Image Processing for Drones. We follow the same procedures as previous section to validate whether the requirements are met.

In Section 5, we brief the achievements of this 5G-DIVE project.

# 2. 5G-DIVE Elastic Edge Platform

The DEEP platform abstracts the underlying heterogeneous networks and computing resources and provides vertical industries the right size of computing power to fit their need in terms of the given service level agreement. This section assess the abilities of DEEP's main functional blocks: BASS, DASS, to support and to meet the need the vertical use cases studied in Section 3 and Section 4.

## 2.1. BASS – Business Automation Support Stratum

The BASS is the central component of the DEEP platform, orchestrating and managing both resources and vertical services while providing smart features to ease the interaction of verticals with the infrastructure and vertical services. The following subsections report the results collected during the integration of use cases with the BASS, identify takeaways and discuss future directions for development and exploitation.

### 2.1.1. Summary of Experiments Results and Verification of Features

The BASS and its features have been thoroughly tested in two distinct phases. In the first phase, the 5G-DIVE use cases have been integrated into the BASS by leveraging remote vertical premises. In more detail, an instance of the BASS was deployed in Spain and secure connectivity was put in place to connect it with distributed resources offered by the verticals. This setup allowed for preliminary, successful verification of the BASS features while the verticals remained in full control of their resources and could perform debugging and troubleshooting on their services. In the second phase, a trial testbed has been setup at 5TONIC premises for a joint final validation of both the DEEP platform and the use-cases. More information about the executed tests and complete result reports can be found in D3.3 [3]

This is a short summary of the BASS features that have been verified successfully:

- Multi-region orchestration
- Service management
- Active monitoring

At the same time, non-functional requirements such as scalability, availability, and reliability have been verified demonstrating the high quality of the software, its stability, and its good performance.

The BASS architecture, design, and development have proved to satisfy the requirements of the vertical use cases, by providing significant advantages like simplified and abstracted service definition, lifecycle management, and monitoring out-of-the-box.

### 2.1.2. Future Directions

The BASS generates a strong interest in verticals to manage their deployment in an easy way, with best practices already implemented, and a strong focus on automating most tedious and manual tasks. One future direction for the BASS is to re-engineer it to adapt it to other industrial use cases and lay the ground as a reference implementation of a fully-featured business support system for the industry, this reference implementation could be further developed to become a commercial product. To achieve this, the next development phases would require the stabilization of the feature set and more focus on bug fixing and refactor for code quality.

A more challenging future direction is the one that sees the BASS transforming from a centralized orchestration software into a fully distributed one. From a single entity controlling several resources, it could evolve in a multitude of orchestration agents, working together as peer. The agents would have a smaller resource footprint with the respect to the actual implementation of the BASS and this would enable their deployment also in remote parts of the edge where connectivity is unstable or unavailable.

## 2.2. DASS – Data Analytics Support Stratum

The DASS is one of the components of the DEEP platform, in charge of the distributed data management including data dispatching, and data storage. The following subsections report the results collected during the integration of use cases with the DASS, identify takeaways and discuss future directions for development and exploitations.

### 2.2.1. Summary of Experiments Results and Verification of Features

The DASS functional and non-functional features have been validated for most of the use cases of the project during the field trials. The use cases have adopted it to perform data storage as well as data dispatching. More information about the executed tests and complete result reports can be found in D3.3 [3] . More specifically, the following DASS features have been verified successfully:

- Data Dispatcher
- Data Storage

The data dispatcher and data storage features were validated during the trial integration for the I4.0 use cases. The Digital Twin (DT) in the *Replay* feature exploits the functionalities made available by the DASS. The Remote Operator, with the help of the DT application and a remote-control mechanism (e.g.: joystick, web interface), remotely controls the physical robotic arm. Consequently, the robot arm in real time updates the DT to keep a tight synchronization between the physical and digital worlds. Simultaneously, the *Replay* feature continuously collects in real time the DT states from the corresponding application using the DASS Data Dispatcher, storing them in the DASS Data Storage. It's important to remark that the *Replay* feature doesn't not require any modification to the DT application nor the robot since DASS Data Storage can be plugged at runtime into the system and can automatically store target data without further intervention.

In a specific moment of the remote operation (e.g., due to robot misbehavior), the Remote Operator can request for a replay of a past sequence of movements through the Web Interface GUI by specifying the desired time interval. The *Replay* module queries the DASS Data Storage about the DT states associated to requested time interval. Once the past sequence data is obtained, the *Replay* module starts to playback the data in a loop fashion. The Remote Operator is informed that the action replay is ready via the Web Interface GUI and in that moment, he can add a new virtual replica in the Digital Twin application in order to visualize the replay data. More information about the DASS integration in DT use case can be found in the D2.3, Section 3.1.2.2[2] .

Additionally, in the ZDM use case, the service flows for telemetry data collection starts when the factory starts working. The camera starts streaming the video towards the Edge node and the factory starts working, with the cubes being placed on the running conveyor belt. The telemetry agent in the EFS uses the Zenoh protocol[1] provided by the DASS to communicate with the edge. Next, the DASS components located at the edge node, synchronize with the DASS components located at a Cloud Services Provider, forming a homogenous and integrated DASS system. By doing so, DASS can effectively direct the telemetry data from the edge into a DASS Data Storage located in the cloud.

In the massive Multiple-Type Communication (mMTC) use case, the DASS functionalities are used through the DEEP platform. For example, the mMTC use case consumes the IESS catalog and the BASS active monitoring functions, which in turn uses the DASS data dispatching and storage functionalities.

In the Intelligent Image Processing for Drones (IIPFD) use case for Autonomous Drone Scouting (ADS) trial. DASS was integrated as a data transmission protocol for streaming data from the drone to the edge. In the Drone Collision Avoidance System (DCAS) use case for ADS, the DASS provided data dispatcher, and storage solutions at the fog (aerial drone), as well as on the edge.

### 2.2.2. Future Directions

The DASS manages successfully distributed and decentralized data generated in the different use case implementations. It defines a complete data pipeline for different data sources avoiding manual configuration or patching. The future directions for the DASS component area centered on exploiting the key innovation of the DEEP platform. D2.3, Section 2.2.1[2]. In addition, to support the data gathering workflow, which is essential for the verticals to monitor the operational performance of their vertical services to collect input data for the training and cross-validation of AI/ML models.

The Eclipse Zenoh open-source project, which contains the actual implementation of the DASS components, offers multiple future directions. One of them is offering the advantage of using Zenoh to enable ROS2-to-ROS2 (Robot Operating System 2) communication over wireless technologies via the Zenoh bridge for the Data Distribution Service (DDS[2]). The Zenoh/DDS bridge has demonstrated that any DDS/ROS2 system can transparently leverage Zenoh to overcome the challenges posed by R2X communication over wireless transports, Wide Area Networks (WAN) and constrained networks in general. The focus will be on improving the communication over wireless networks, and tackle existing challenges, especially when communicating elements, such as robots, cars and race-cars, move around and more importantly, when they move fast. This can be extended to an internet scale allowing to cover a variety of robotics use cases supporting a Robot-to-Anything (R2X) communication.

[1] https://zenoh.io
[2] https://github.com/eclipse-zenoh/zenoh-plugin-dds

## 2.3. IESS – Intelligence Engine Support Stratum

The IESS is the component of the DEEP platform offering advanced AI and ML features. The goal is to facilitate the verticals in the integration of intelligence engines in their services. The following subsections report the feedback collected during the adoption of the IESS by 5G-DIVE use-cases, identify takeaways and discuss future directions for development and exploitations.

### 2.3.1. Experiment Results Summary and Feature Verification

The IESS features have been constantly tested during the development and they have been finally verified during the trials at 5TONIC premises. Testing and verification have always been performed with the involvement of the use cases in order to collect meaningful feedback. More information about the executed tests and complete result reports can be found in D3.3 [3]

More specifically, the following IESS features have been verified successfully:

- Automated model training
- Storage and retrieval of artifacts from the catalog
- Packaging and deployment of inference applications

Meanwhile, non-functional requirements such as scalability, availability, and reliability have been verified demonstrating the high quality of the software, its stability, and its good performance.

The IESS has proved to be a valuable tool for verticals. In particular, the delegation of the training pipeline to the IESS greatly simplifies the life of the vertical. The phases for the preparation of the training environment, the allocation of resources, and finally the deployment of the training job are all automated.

Furthermore, the verticals have greatly appreciated the feature offered by the IESS for exposing the model predictions as a service. The trained model is packaged in a RESTful application, deployed close to the consumers of the predictions that can request the latter through a well-defined HTTP interface. This feature solves a common problem in the machine learning field, which is making the model predictions usable in production-like environments.

Finally, the IESS catalog has proven to support successfully all the aforementioned operations, as well as providing a shared storage for reusable pre-trained models and software artifacts.

### 2.3.2. Future Directions

The IESS manages successfully to lower the technological barrier for the adoption of AI, especially at the edge. Focused on automation, it defines a complete pipeline for training, deploying, and serving intelligent applications with sane defaults and best practices included. The next step in the exploitation of the IESS would be to propose it to non-IT verticals, e.g., finance and business, which would obtain even greater benefits from this tool. With the collected feedback, the IESS could be further improved in its usability and become more user-friendly to non-technical users.

The future development of the IESS will also focus on improving energy efficiency, especially in the training phases, in order to decrease the $CO_2$ footprint of machine learning applications. Promising directions towards this goal are the design of new algorithms with efficiency as the first objective and the split and distribution of the training jobs to take advantage of coordination and data locality.

# 3. Validation and Summary of Industry 4.0 Use Cases

I4.0 is one of the two vertical application areas of this DIVE project. Three use cases are enumerated to show the merit of applying DEEP to the industry. This section concludes the achieved objectives, conditions, business requirements, functional requirements, and technical requirements specified in D1.1 [5] based on the trial results shown reported in D3.3 [3] . The future directions of development and improvement are also briefed in this session.

## 3.1. I4.0-UC1: Digital Twin

In this section, we summarize the trial results of the Digital Twin use case in 5TONIC. Based on the trial results and performed demonstrations, we evaluate the fulfillment of objectives, conditions, business requirements, functional requirements and technical requirements, which were defined in D1.1 [5] .

### 3.1.1. Summary of Trial Results and Validation of Requirements

The Digital Twin use case was deployed and integrated in 5TONIC laboratory in Madrid, Spain together with the mMTC use case, utilizing the same Edge infrastructure and 5G connectivity from 5TONIC. Figure 3-1 shows the setup deployment. The robot manipulator, a 5G HAT[3] and a mini-PC were set up in one table which covers the trial area and represented the Digital Twin fog site. The three devices were interconnected using an L2 switch, where the 5G HAT provided 5G connectivity for the Robot and the mini-PC to the Edge datacenter. The deployment of the virtual functions that are part of the Digital Twin service was distributed between the robot manipulator, the mini-PC and a VM provided in the 5TONIC datacenter. The robot manipulator hosted the Robot Drivers virtual function, the mini-PC hosted the Interface and Movement Prediction virtual function while the rest of the Digital Twin service was deployed in the Edge VM. In the trial, the robot sensor data i.e., joint state values, were read from the robot at a frequency of 20 ms and via the 5G HAT they were updating the virtual replica of the Digital Twin application. In downstream, the Digital Twin application was sending navigation commands at a frequency of 20 ms to control the physical robot. In addition to the base Digital Twin stack, a Movement Prediction function was included as part of the Digital Twin service to enhance the remote control. In the Movement Prediction virtual function, an AI algorithm based on vector autoregression (VAR) was developed to predict the robot movement when a remote-control command is delayed or lost. The designed and developed Digital Twin service was also integrated with all the components of the 5G-DIVE DEEP platform.

In the following we summarize the main achievements of the DASS, BASS and IESS integration:

[3] https://www.waveshare.com/sim8200ea-m2-5g-hat.htm

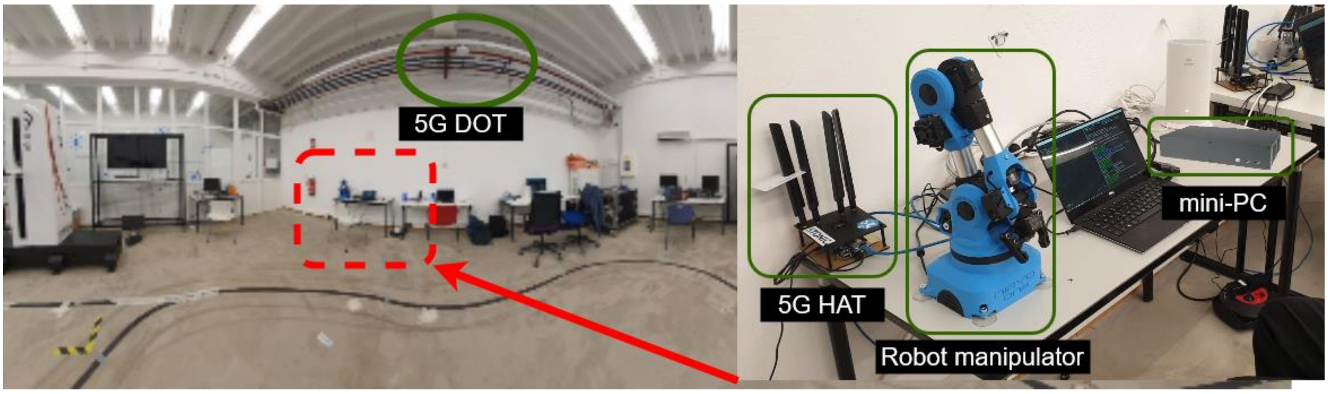


FIGURE 3-1: DIGITAL TWIN TRIAL SETUP DEPLOYMENT AT 5TONIC

- A Replay Feature was developed with the help of the **DASS** and it was successfully demonstrated in the first year of the project.
- The monitoring, life-cycle management and orchestration configuration were done through the **BASS**.
- The **SLA-enforcer** of the BASS was used to evaluate the optimal minimum memory and CPU allocation for the system in order not to violate E2E latency requirements
- The Movement Prediction AI algorithm was integrated with the **IESS**. A generated dataset was uploaded in the IESS Training Catalog and was used during the IESS training procedure. Once the model was trained, a Movement Prediction inference instance was deployed using the BASS.

Finally, the setup of the trial was also used to perform experimental analysis and validation of deployed Digital Twin service. It is worth mentioning that in the first year of the project we focused on the experimental validation and demonstration of 5G connectivity and Edge computing in Digital Twin services, while in the section year of the project our focus was on AI/ML features for Digital Twin services. The summary of the obtained results is presented in the following, while more details are provided in D3.2 [4] and D3.3 [3] :

- The 5G NSA network is excellent at achieving RTT latency of 6.5 (± 1.04) ms, jitter of 0.46 (± 0.18) ms, 0% of packet loss, UL throughput of 96 (± 1.81) Mbps and DL throughput of 600 (± 13.50) Mbps during the experiments performed.
- The performance of the designed Digital Twin system was excellent when we used 5G connectivity and computational offload to the Edge. This was not possible using 4G connectivity where the complete system experienced serious degradation.
- An adaptive control mechanism was presented that adapts the robot control frequency to the network latency. The results showed that this kind of adaptive control mechanism can improve the synchronization accuracy between the physical robot and its virtual replica with respect to a fixed control mechanism.
- The Movement Prediction results show the improved QoE when a robot is remotely controlled via a wireless link that suffers from unpredictable delays or packet loss. The accuracy of the movement predictions can be further improved by using the delayed packets that are

discarded by the robot. In addition, the results show that the Movement Prediction model is light enough to run in an RPi 3 providing prediction in 1.60 ± 0.16ms.

- The BASS SLA-enforcer results show that for different E2E application latency requirements of the Digital Twin, the SLA enforcer learns the best values for CPU and RAM that satisfy the vertical service SLA. The SLA enforcer learned how to stabilize the E2E application latency after the first 14500 training timesteps.
- Computation offload results show that approximately 30% of CPU and 27% of RAM can be saved on the robot device by offloading the robot stack in the edge.
- Robot vertical scaling results show that the high CPU load (load of above 80%) of the Edge node that hosts the Control virtual function has a direct implication on the end-to-end application latency. Migration or Scaling measures should be taken in order to avoid these high load scenarios.

#### 3.1.1.1. Objective Fulfillment

The fulfillment of the objectives described in D1.1 [5] is discussed in the following. Based on the trial results and executed demonstrations, all objectives are considered as achieved.

- **Objective 1: To demonstrate 5G performance for interconnecting a real robot to its digital twin. For such a purpose, the digital twins, sharing the computing resources and the software, will virtually replicate the same function.**

  During the mid-term review the 5G performance for interconnecting a real robot to its digital twin was demonstrated showing the advantages it can offer with respect to 4G. The demonstrated system was composed of 7 virtual functions that were automatically deployed using the BASS over-sharing computing resources enabling replication of the virtual functions. In the second year of the project, during the 5TONIC trials we moved from 5G NSA to 5G SA solution where we tested the performance of the Digital Twin service through experimental analysis. Therefore, Objective 1 is considered as achieved.

- **Objective 2: To provide advanced network connectivity with low latency inside the Fog/Edge and Cloud, distributing the computational needs across the different tiers in order to reduce the reaction time of the digital twin.**

  The Digital Twin service distributed the virtual functions computational needs across the Fog and Edge tiers providing excellent synchronization between the physical robot and the digital replica. We were able to demonstrate a control frequency of 20 ms by the Digital Twin application and to show the potential on device resource savings that can be achieved by distributing the computation. Therefore, Objective 2 is considered as achieved.

- **Objective 3: To monitor the operation of the physical robot in order to detect critical conditions and take adaptive measures to mitigate them.**

  The Digital Twin service was integrated with the DEEP platform exploiting the monitoring functionality of the BASS. After the integration, the remote operator had access to the BASS monitoring dashboard where the monitoring data for the virtual functions (e.g., container status, CPU load, RAM and network usage) and the physical robot (e.g., sensor state, operating temperature, level of vibrations) is available. This data can be used by a Predictive Maintenance ML model that we describe in D2.3 [2] to predict when HW malfunctioning will occur and schedule maintenance. Therefore, Objective 3 is considered as achieved.

- **Objective 4: To mitigate latency variations in the remote control in order to correctly operate the physical device.**

  The Movement Prediction function in the Digital Twin service is based on AI technologies and its main goal is to mitigate the latency and packet loss variations in remote control applications that are due to the unpredictable and variable wireless channel. Therefore, Objective 4 is considered as achieved.

- **Objective 5: To demonstrate automation capabilities for driving up the business value and reducing operational costs.**

  The automation capabilities of the Digital Twin service were demonstrated in the first year mid-term review where the Digital Twin service deployment was automated using the BASS. In addition, the SLA enforcer of the BASS was used by the Digital Twin service to fulfill the pre-defined SLAs. Finally, in the second year, we enhanced the automation capabilities by integrating the Movement Prediction AI module with IESS that provided auto-packaging and auto-deployment of an intelligence application. Therefore, Objective 5 is considered as achieved.

#### 3.1.1.2. Condition Fulfillment

The fulfillment of the conditions described in D1.1 [5] is discussed in the following. Based on the trial results, all conditions are considered as fulfilled.

- **Condition 1: 5G radio must be available at the plant and must be able to collect data from many PLCs guaranteeing no perceived delay in the virtual representation.**

  In the trial site at 5TONIC, 5G radio was available and the results and demonstration showed the clear benefits of using 5G connectivity for Digital Twin applications. Moreover, during the mid-term demonstrations, it was shown how the remote operator can control the physical robot by using its virtual representation in real-time guaranteeing with no perceived delay.

- **Condition 2: High bandwidth and low latency communications must be provided for the on-time delivery of the information of the sensors to the virtual twin and for the interaction with the digital model.**

  Low latency of approximately 6 ms and high bandwidth of 96 (± 1.81) Mbps for UL and 600 (± 13.50) Mbps for DL were achieved using a 5G NSA configuration that is sufficient for the uninterrupted interactions between the physical object and the virtual twin.

- **Condition 3: Computing resources must be located both on premises and externally at the Fog/Edge for the correct operation of the use case.**

  The trial site results at 5TONIC show that the Robot manipulator, 5G HAT and mini-PC resources deployed on the premises and the VMs provided in the 5TONIC datacenter were sufficient to correctly operate the Digital Twin use case

#### 3.1.1.3. Fulfillment of Business Requirements

The fulfillment of the business requirements defined in D1.1 [5] is discussed in the following. It is worth mentioning that it is not possible to evaluate the exact numbers stated in the business requirements directly by doing experimental evaluation in the trial sites. In this section, we perform a short analysis based on the trial results and perform demonstrations that can be directly related to the business requirements. Based on this analysis we can conclude that all the business requirements that concern the Digital Twin use case are fulfilled.

- **BR-I4.0-UC1-01: Reduce technicians' travels by 30% of allowing them to remotely control the physical robot**

  The trials and demonstrations showed the possibility to remotely control the physical robot using its virtual replica with a low control frequency of 20 ms and high movement precision of 0.01 rad. This enables industrial technicians to perform remotely a variety of industrial tasks such as pick and place, assembly or even welding. In addition, the automation capabilities that were shown in the trials limit the technicians to events when a specific hardware component needs to be replaced at the factory floor. Considering the aspects discussed above, it is reasonable to estimate that at least 30% of the technicians' travels can be reduced by enabling remote control and automation. Therefore, this business requirement is considered as fulfilled.

- **BR-I4.0-UC1-02: Reduce failure rate at least of 20% with objective 90%**

  The remote-control Digital Twins are very sensitive to failures and all of them implement the so called dead man's switch[4] which is used as a form of fail-safe method. They stop the robot when the operator loses the real-time remote-control capabilities. In the trials, we implemented and integrated the Movement Prediction AI module for repetitive industrial tasks that aim to recover from remote control failures and extend the trigger of the dead man's switch. The results show that Movement Prediction can successfully reduce the failure rate of control commands. It is worth mentioning that the Movement Prediction also implements a dead man's switch that is triggered at the moment before the remote operator can detect that remote control became predictive control. Considering the aspects discussed above, it is reasonable to estimate that at least 20% of the control command failure rate can be decreased by using the Movement Prediction feature. Therefore, this business requirement is considered as fulfilled.

[4] Switch that is applied in industry in the form of fail-safe where it stop a machine with no operator from a potentially dangerous action or incapacitate a device as a result of accident, malfunction or misuse.

- **BR-I4.0-UC1-03: Improve service response time by 30%**

  The Digital Twin service is virtualized in a cloud-native way based on microservice architecture. The deployment, instantiation, life cycle management and termination of the service are done with the help of the BASS utilizing two orchestration drivers: lightweight Kubernetes (k3s) for the virtual functions and fog05 for the robot drivers. The trials results and demonstration show the simplified automation feature when requesting deployment and instantiation of the Digital Twin service. The simplified management interface and system automation features which are validated in the trials can help to improve the service response time with respect to traditional and rigid Digital Twin applications that are usually executed as static native applications. Considering the discussion above, it is reasonable to estimate that the deployment and instantiation service response time can be improved by 30%. Therefore, this business requirement is considered as fulfilled

As a summary, Table 3-1 shows the evaluation of the fulfillment of business requirements.

TABLE 3-1: BUSINESS REQUIREMENTS I4.0-UC1

| BR – ID | Description | Fulfilment |
|---|---|---|
| BR-I4.0-UC1-01 | Reduce technicians travels by 30% by allowing them to remotely control the physical robot | Fulfilled |
| BR-I4.0-UC1-02 | Reduce failure rate at least of 20% with objective 90% | Fulfilled |
| BR-I4.0-UC1-03 | Improve service response time by 30% | Fulfilled |

#### 3.1.1.4. Fulfillment of Functional Requirements

The fulfillment of the functional requirements described in D1.1 [5] is discussed in the following.

- **FR-I4.0-UC1-01: Leverage AI to automate procedures, enable predictions and provide recommended actions accordingly.**

  The trials results obtained from the AI-based SLA enforcer applied to the Digital Twin service show how AI can be used to automate the SLA procedure and provide recommended CPU and memory allocation actions to the BASS orchestration drivers. In addition, the Movement Prediction AI module enables movement predictions that are available as recommended actions to the Digital Twin application. Therefore, this functional requirement is considered as fulfilled.

- **FR-I4.0-UC1-02: Provide E2E 5G connectivity inside the plant and to the outside public network**

  As described before, during the duration of the project, E2E 5G connectivity (SA and NSA) was provided for development, integration, experimentation, and demonstration. Results clearly show the benefits of having 5G connectivity for this use case, such as low delay allowing different splits of robot control logic between the edge and the robot. Therefore, this functional requirement is considered as fulfilled.

- **FR-I4.0-UC1-03: Guarantee information updates with unnoticeable delay**

  Trials results and past demonstrations show that with the combination of 5G connectivity and Edge computing we can distribute the Digital Twin service computation and provide controlled local environment that can guarantee the updates of the virtual replica in real-time with unnoticeable delays. Therefore, this functional requirement is considered as fulfilled.

- **FR-I4.0-UC1-04: Support remote control protocols using wireless as an alternative to cable today**

  The Digital Twin service was implemented using Robot Operating System (ROS) as middleware and the used remote-control protocol relies on TCP. Our experimental results show that we used different wireless technologies (e.g., 5G, LTE, Wi-Fi) to support such remote-control protocol as an alternative to cable today. Therefore, this functional requirement is considered as fulfilled.

As a summary, Table 3-2 shows the evaluation of the fulfillment of functional requirements.

TABLE 3-2: FUNCTIONAL REQUIREMENTS I4.0-UC1

| FR – ID | Description | Fulfillment |
|---|---|---|
| FR-I4.0-UC1-01 | Leverage AI to automate procedures, enable predictions and provide recommended actions accordingly | Fulfilled |
| FR-I4.0-UC1-02 | Provide E2E 5G connectivity inside the plant and to the outside public network | Fulfilled |
| FR-I4.0-UC1-03 | Guarantee information updates with unnoticeable delay | Fulfilled |
| FR-I4.0-UC1-04 | Support remote control protocols using wireless as an alternative to cable today | Fulfilled |

#### 3.1.1.5. Fulfillment of Technical Requirements

The fulfillment of the technical requirements described in D1.1 [5] is discussed in the following. Note that the technical requirements are formulated to cover the network-related segments. As mentioned before, our testbed in 5TONIC was developed to support 5G connectivity for the duration of the whole project. The Digital Twin use case was focused on investigating the impact of 5G connectivity and Edge computing in the first year of the project and this was demonstrated in the mid-term review. Experimental results from this investigation were presented in D3.2 [4] where most of the technical requirements were fulfilled.

- **TR-I4.0-UC1-01: Reference Availability of more than 99.9999%**
  The availability, in this case, refers to network availability. The definition of network availability is the ratio between the amount of uptime of a network and a specific time interval. This usually requires very long-term measurements. In the trials, we measured more than 4 weeks with different types of tests running on the network. Given the trial time, the Digital Twin service was stable and no network outage events have been observed. In addition, the virtualized nature of the Digital Twin service allows for different redundancy techniques to increase service

availability. For example, the service can be replicated in two separate nodes so when a node fails the other one can continue the service running. By doing so the service availability can be increased from 99.9% to 99.9999%. Considering the trials observations and the redundancy analysis above, this technical requirement can be considered as fulfilled.

- **TR-I4.0-UC1-02: Reference Reliability of more than 99.999%**
  In the trials, the command loss rate (CLR) was measured over a long-time term. The measured CLR is about 0.01% without application retransmissions. When we applied application retransmission this CLR was reduced from 0.01% to 0.0001%, which means that the reliability increased from 99.99% to 99.9999%. Given the analysis of the trial results of CLR, this technical requirement can be considered as fulfilled. In addition, through the use of the Movement Prediction Module, the loss of a command will not affect the performance of the DT, pushing the reliability to unprecedented boundaries.
- **TR-I4.0-UC1-03: Reference E2E latency of less than 20ms**
  As shown in the experimental results in D3.2 and D3.3, both 5G systems (5G SA and 5G NSA) in combination with edge computing archive E2E latency less than 20 ms. In the case of 5G NSA the E2E latency was 6.5 (± 1.04) ms while for the SA was 7.5 (± 4.03). Based on these results, this technical requirement can be considered as fulfilled.
- **TR-I4.0-UC1-04: Remote control bandwidth per instance (DL) of more 100Kbps**
  In the trials, the DL bandwidth was measured for both 5G NSA and 5G SA. The 5G NSA reported values of 600 (± 13.50) Mbps while the 5G SA of 790 (± 29.30) Mbps. The required remote-control bandwidth is quite low mainly because it is composed only of navigation instructions. Based on these results, this technical requirement can be considered as fulfilled.
- **TR-I4.0-UC1-05: Video bandwidth per instance (UL) of more than 5Mbps**
  In the trials, the UL bandwidth was measured for both 5G NSA and 5G SA. The 5G NSA reported values of 96 (± 1.81) Mbps while the 5G SA of 100 (± 29.22) Mbps. Although in the developed use case we never used a video camera, the presented results show that this technical requirement can be considered as fulfilled.
- **TR-I4.0-UC1-06: Reference connection density of more than 1000 devices per Km2**
  This technical requirement was not possible to be evaluated and verified in the trials mainly due to the limited hardware resources. As described in D3.3, in the trials we had 4 available UEs that were providing 5G connectivity. Moreover, we cannot afford to have a testbed where we can deploy 1000 devices. However, if this requirement can be fulfilled by a hardware-based system, in 5G DIVE we developed a completely virtualized Digital Twin system that would support even higher connection density, considering the scalability and flexibility offered by the Edge.

- **TR-I4.0-UC1-07: Local Reference Converge using one cell with no handovers**
  In the trials, as described in D3.3 [3] we deployed a single cell that was providing local reference coverage for all the use cases. In addition, in the first year of the project, we also used a single cell that was locally available in the 5TONIC laboratory. Given the setup of the trials and the obtained results, this technical requirement is considered as fulfilled.

As a summary, Table 3-3 summarizes the evaluation of the fulfillment of technical requirements.

TABLE 3-3: TECHNICAL REQUIREMENTS I4.0-UC1.

| TR - ID | Description | Value | Fulfilment |
|---|---|---|---|
| TR-I4.0-UC1-01 | Reference Availability | 99.9999% | Fulfilled |
| TR-I4.0-UC1-02 | Reference Reliability | 99.999% | Fulfilled |
| TR-I4.0-UC1-03 | Reference E2E Latency | 20 ms | Fulfilled |
| TR-I4.0-UC1-04 | Remote control bandwidth per instance (DL) | 100 Kbps | Fulfilled |
| TR-I4.0-UC1-05 | Video bandwidth per instance (UL) | 5 Mbps | Fulfilled |
| TR-I4.0-UC1-06 | Reference Connection density | Less than 1000 devices per $Km^2$ | Not possible for trial evaluation (but considering to be fulfilled) |
| TR-I4.0-UC1-07 | Reference Coverage | Local using one cell, no handover | Fulfilled |

### 3.1.2. Future Directions

In 5G-DIVE, we developed a virtualized Digital Twin network service that was integrated with the 5G-DIVE DEEP platform. Through the project, the Digital Twin network service verified the feasibility and benefits of using the three main tiers of the 5G DIVE project, namely: 5G Connectivity, Edge computing and AI technologies. It also showcased the benefits of using the DEEP platform through the integration with the BASS, DASS and IESS. The following list describes some of the possible future works after the 5G-DIVE project.

- Investigating the tradeoff between potential resource savings by computational offload in the edge and performance loss in Operational Digital Twins
- Investigate the concept of Robot-as-a-Service where the same robot can be re-used for performing different tasks by deploying virtual functions on the fly
- Investigate the vertical autoscaling and if the latency budget offered by 5G can be used in order to save resources on the edge nodes
- Investigate ML algorithms that can use the big data available in the digital world in order to predict malfunctioning

## 3.2. I4.0-UC2: Zero Defect Manufacturing

In this section, we summarize the trial results of the ZDM use case in Interdigital Labs using the Vodafone 5G test network, London. Based on the trial results and performed demonstrations, we evaluate the fulfillment of objectives, conditions, business requirements, functional requirements and technical requirements, which were defined in D1.1 [5] .

### 3.2.1. Summary of Trial Results and Validation of Requirements

In the context of 5G-DIVE, The ZDM use case utilizes the enhanced capabilities of Fog and Edge for supporting real-time analysis of HD video streamed from production to the edge over 5G, in order to detect possible defects, which is shown in Figure 3-2. The key idea here is to incorporate state-of-the-art technologies, such as 5G and AI with the DEEP platform to meet the requirements from the vertical industries.

This trial took place in Interdigital Labs, London with 5G SA test network provided by Vodafone and edge capabilities from Amazon. This setup is detailed in D2.3 [2] , where the production line is deployed in the lab and connected to the edge side (i.e. Amazon Wavelength) over the Vodafone 5G network.

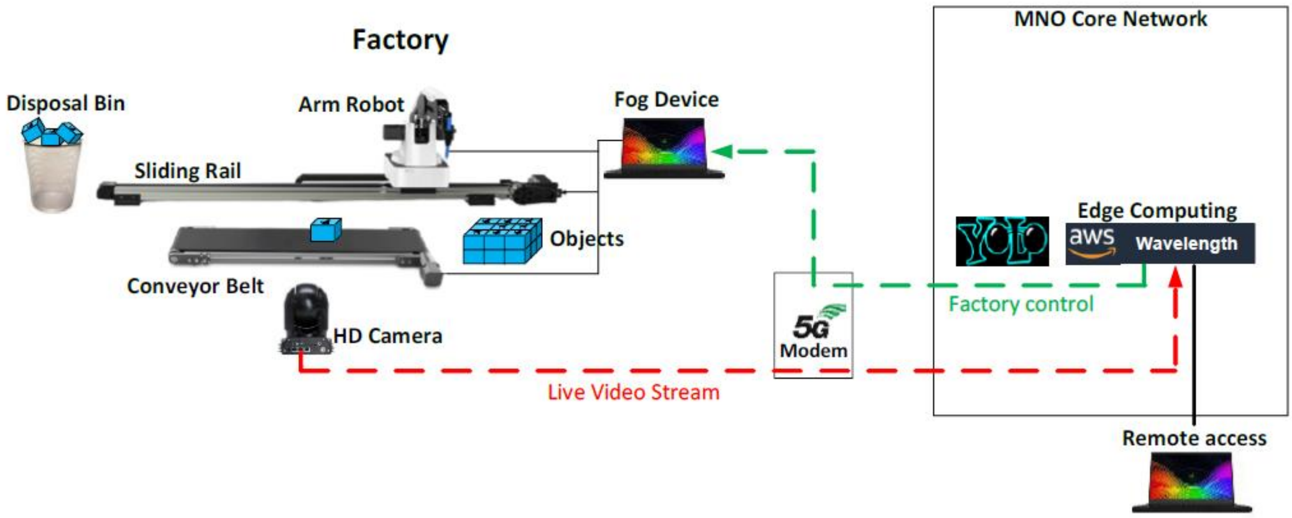


FIGURE 3-2: ZDM SETUP WITH 5G TEST NETWORK FROM VODAFONE AND EDGE CAPABILITIES FROM AMAZON

The ZDM use case trials have proven the significance of integrating the 5G-DIVE components with the DEEP platform. Specifically, the adoption of the Fog-Edge paradigms while relying on 5G connectivity allowed an intelligent control of the production line at an end-to-end latency of 11ms and a high-resolution video transmission over 35.3 Mbps of available uplink bandwidth This demonstrates improved performance compared to 4G connectivity, which attained 41ms (end-to-end latency) and 10.1 Mbps as reported in D3.2[4] . Additionally, the measurement software reported an application latency of 564.7ms and 473.6ms for transmitting the video stream from the camera (production line side) to the edge side for a resolution of 1080p60[5] and 720p50, respectively. These measurements are optimal in terms of providing a real-time video stream over the 5G network, which includes buffering, encoding, decoding and Network Device Interface (NDI) encapsulation, hence the increased latency. Furthermore, the control mechanism at both the fog and edge sides, as well as the AI object detection at the edge side, were all automated with the BASS that enables the whole stack to deploy and to start in a few seconds.

In the context, three sets of requirements were defined, business, functional and technical in D1.1 [5] . The functional requirements describe the functionality of the ZDM setup in order to meet the business requirements. The business requirements of Table 3-4 in D1.1 [5] show five main requirements. In the context of the 5TONIC trials, the number of defective objects to the non-defective objects at the output of the production line will be reported. This number was proven in previous trials to attain zero scrap output (i.e. 0% defective objects at the output). This would have a direct impact on the number of customers' visits, given that the quality of assurance of the produced goods is monitored via an AI-aided defect detection. Additionally, the customer is capable of remotely monitoring the production line and the condition of each of the produced goods (i.e. defective and non-defective). Furthermore, given the AI monitoring capability, the ZDM system is capable of achieving a 100% defect detection (all defective items are correctly identified) as a result of disposing of any non-defective object detected at the production stage. All these requirements will be covered in the following sections.

#### 3.2.1.1. Objective Fulfilment

The fulfillment of the objectives described in D1.1 [5] are discussed in the following. Based on the trial results and executed demonstrations, all objectives are considered as achieved.

- **Objective 1: To demonstrate 5G performance for delivering high-bandwidth traffic coming from the camera towards a monitoring application able to identify defective pieces.**
  The 5G performance for delivering high-bandwidth traffic coming from the camera towards the monitoring application at the edge was demonstrated showing the advantages it brings to the ZDM use in terms of identifying the defective pieces. Therefore, Objective 1 is considered as achieved.
- **Objective 2: To demonstrate 5G and Edge capability to deliver low latency required to reduce reaction between the identification of the defective piece and its removal of the production line.**
  In the final trials of ZDM, 5G connectivity was used to demonstrate its capability to deliver low latency required to reduce reaction between the video capturing of the object and the identification and removal of the defective objects. The application layer measurement software reported an application latency of 564.7ms and 473.6ms for transmitting the video stream from the camera located at the production line side to the monitoring application at the edge side for a resolution of 1080p60 and 720p50, respectively. This latency measures the end-to-end video streaming that includes encoding/decoding, buffering and NDI encapsulation/decapsulation. Therefore, Objective 2 is considered as achieved.

[5] https://en.wikipedia.org/wiki/1080p

- **Objective 3: To highlight critical conditions inferred by the camera data and provide alarms and preventive maintenance information.**
  In the ZDM setup, the video stream coming from the camera towards the edge side goes into an AI-based object detection application (i.e. YOLO[6]). The YOLO engine was trained to detect a specific type of defectiveness (i.e. black circular marks) and send removal commands to the production line. Hence, after detecting a defective object, it will be removed and disposed by the robotic arm. Therefore, Objective 3 is considered as achieved.
- **Objective 4: To provide plant managers with actual information about the status of the production lines, predicting future failures or bottlenecks, giving the opportunity to move up actions and prevent problems thanks to the monitoring process.**
  In the ZDM use case, the video stream of the production line can be access by the plant manager at the edge side (i.e. refer to Figure 5-21 in D3.3 [3] ). This allows the manager to monitor the production process and gives the manager access to information about the product in progress (i.e. the plant manager can monitor the product being placed on the conveyor belt and can see the output of the AI engine as well as the command sent to the fog). Therefore, Objective 4 is considered as achieved.

#### 3.2.1.2. Condition Fulfilment

The fulfillment of the conditions described in D1.1 [5] is discussed in the following. Based on the trial results, all conditions are considered as fulfilled.

- **Condition 1: 5G must be available at the plant facilities and must be able to interconnect all the different hardware in the production line (e.g., cameras, conveyor belt, removal tool, etc.).**
  In the trial site at the interdigital labs, 5G network was available and was utilized for providing connectivity between the fog and edge sides, where results showed the clear benefits of using 5G connectivity for the ZDM use case. Furthermore, the production line components (robotic arm, conveyor belt and sliding rail) were connected to the fog device, which is connected to the edge node over 5G, while the camera is connected to the edge device (e.g. monitoring application) directly over 5G.
- **Condition 2: High bandwidth and low latency communications must be provided for the on-time delivery of the information of the video camera to the monitoring application and, afterwards, its interaction with the removal tool.**
  The 5G connectivity provided an intelligent control of the production line at an end-to-end latency of 11ms and a high-resolution video transmission over 35.3 Mbps of bandwidth.
- **Condition 3: The video camera equipment shall be present in the conveyor belt installation in order to feed the monitoring platform with real time data.**
  The high-resolution camera was deployed at the production line for capturing and providing a video stream of the production process to the edge side in real-time.

[6] https://pjreddie.com/darknet/yolov2/

#### 3.2.1.3. Fulfilment of Business Requirements

The fulfillment of the business requirements defined in D1.1 [5] is discussed in the following.

- **BR-I4.0-UC2-01: Reduce cost of production by 10%**
  In the trials, an AI-based identification and control of the production process in the ZDM use case was employed, which allows enhanced defect detection and removal of defect objects. Additionally, the ZDM setup enables remote monitoring of the production process as well as of the decision produced at the edge side. Both aspects can make the production process more intelligent and interoperable. Hence, they decrease the cost of the company resources that should be allocated -inside the factory- to monitor production processes in terms of management and post-processing of the defective objects. Hence, it is reasonable to estimate that at least 10% of the cost of production can be reduced. Therefore, this business requirement is considered as fulfilled.
- **BR-I4.0-UC2-02: Increase the production throughput by 15% by improving the detection rate of defective pieces in production**
  As described previously, the ZDM use case employs a newly trained model for detecting defective and non-defective objects. The newly trained system was tested in the trials and was demonstrated to achieve zero defects at the output of the production line, where all defect objects were successfully detected and removed then disposed from the production line. This improves the productivity of the factory, which is defined as the throughput of high-quality goods. In the context of the ZDM use case, only high-quality goods were able to make it to the final stage of the production line. Hence, it is reasonable to estimate that the production throughput can increase by at least 15%. Therefore, this business requirement is considered as fulfilled.
- **BR-I4.0-UC2-03: Reduce customer visits by 40% by reducing the number of trips of the customer to the factory for quality assurance of the produced goods**
  The trials of the ZDM use case demonstrated that the production process can be remotely monitored in real-time using the 11ms latency provided by the 5G connectivity. Furthermore, the PTZ (i.e. pan, tilt and zoom) capabilities of the camera allow the customer to remotely control the camera and direct it towards any part of the production line. Additionally, the real-time defect identification and the interactions between the edge and fog sides can be also monitored remotely, which provides the customer with the information required about any piece being processed in the production line. Hence, it is reasonable to estimate that at least 40% of the customer visits can be reduced. Therefore, this business requirement is considered as fulfilled.

- **BR-I4.0-UC2-04: Reduce scrap of at least 10% with an objective of achieving 0 scrap**
  The ZDM use case employs an AI-based monitoring application (i.e. YOLO) at the edge side, which identifies and exchanges information and commands with the fog node. This allowed the system to remove all defective objects from the production line and dispose of them when detected. Hence, the ZDM was capable of achieving a zero scrap output from the production line using the newly trained objects (i.e. plain cubes were trained as non-defected, while cubes with black circular marks were trained as defected). Therefore, this business requirement is considered as fulfilled.
- **BR-I4.0-UC2-05: Detect up to 30% of form and/or welding errors so anticipative measures may be deployed to mitigate these errors**
  As mentioned before, the ZDM use case allows remote monitoring of the production process at the factory side as well as the condition of the product (defective/non-defective) and commands produced at the edge side. This allows the technician to detect any errors that might occur at both sides and can deploy anticipative measures, such as improving the trained model, remotely debugging and fixing the control scripts at both the production line as well as the edge side. Hence, it is reasonable to say that using the remote monitoring and controlling capabilities in the ZDM use case that anticipative measures can be deployed for mitigating at least 30% of errors. Therefore, this business requirement is considered as fulfilled.

Note here that it is not possible to assess the numbers suggested in the business requirements directly by doing the experimental evaluation. However, we provided our input above by performing a short analysis based on the trial results that are directly related to the business requirements. Based on this analysis we can conclude that all the business requirements shown in Table 3-4 are fulfilled.

TABLE 3-4: BUSINESS REQUIREMENTS I4.0-UC2.

| BR - ID | Description | Fulfilment |
|---|---|---|
| BR-I4.0-UC2-01 | Reduce cost of production by 10% | Fulfilled |
| BR-I4.0-UC2-02 | Increase the production throughput by 15% by improving the detection rate of defective pieces in production | Fulfilled |
| BR-I4.0-UC2-03 | Reduce customer visits by 40% by reducing the number of trips of the customer to the factory for quality assurance of the produced goods | Fulfilled |
| BR-I4.0-UC2-04 | Reduce scrap of at least 10% with an objective of achieving 0 scrap | Fulfilled |
| BR-I4.0-UC2-05 | Detect up to 30% of form and/or welding errors so anticipative measures may be deployed to mitigate these errors | Fulfilled |

#### 3.2.1.4. Fulfillment of Functional Requirements

The fulfillment of the functional requirements described in D1.1 [5] is discussed in the following.

- **FR-I4.0-UC2-01: Leverage AI to automate procedures, enable prediction and provide recommended actions accordingly**
  The ZDM use case, the video captured by the camera is streamed over 5G towards the edge node, which employs an AI-based object detection application (i.e. YOLO) to detect defective and non-defective objects. For every object detected (regardless of whether it is a defect or non-defective), a control script monitors the output of the YOLO engine and sends accordingly commands to the factory through the fog node requesting it to either keep the non-defective object or to remove the non-defective object from the production line. Therefore, this functional requirement is considered as fulfilled.
- **FR-I4.0-UC2-02: BASS will be able to scale up and down the system in order to guarantee SLAs**
  The automation capabilities of the ZDM use case were demonstrated in the trials with 5G connectivity, where the ZDM setup was fully automated using the BASS. This includes the automation of the factory control capabilities at the fog as well as the AI-based detection procedures and the edge control loop at the edge side. After the BASS integration, a remote operator can access the BASS monitoring dashboard and can activate and/or deactivate different components of the ZDM setup. In case of scaling up the monitoring capabilities at the

production line (such as increasing the number of cameras at different stages of the production process) and the control procedures at the edge side (such as having multiple AI-detection instances and independent control procedures for each camera stream running at the edge), the BASS will be able to automate and monitor each part in terms of activating and deactivating each of these components. Therefore, this functional requirement is considered as fulfilled.

- **FR-I4.0-UC2-03: Provide E2E 5G connectivity inside the plant facilities and outside to the public network**
  As described earlier, throughout the project, a 5G connectivity was employed with SA and NSA for development, integration, experimentation and demonstration of the ZDM use case. The demonstration results showed the benefits of having 5G connectivity over 4G for this use case. Therefore, this functional requirement is considered as fulfilled.
- **FR-I4.0-UC2-04: Guarantee the delivery of information from the cameras to the monitoring application with minimal delay**
  The final trial as well as past demonstrations show that with employing 5G for connecting the factory side to the edge side, very low latency of 11ms was measured. An additional delay was introduced by the application layer video processing (i.e. encoding/decoding, buffering and NDI encapsulation/decapsulation), but still provided a minimal delay for video transmission. Therefore, this functional requirement is considered as fulfilled.
- **FR-I4.0-UC2-05: Support remote control protocols using wireless as an alternative to cable today**
  The ZDM was employed using two main components, the control component and the AI-detection component. The control component is employed using python code at both the fog node (direct control of the production line) and the edge side (decision sent to the fog side), while the AI component runs at the edge side using YOLO. All data/command exchange for the control components rely on the TCP connectivity between the edge and node. Our experimental results from all demonstrations and trials show that we used different wireless technologies, namely Wi-Fi, 4G and 5G to support the remote control protocols as an alternative to cable today. Therefore, this functional requirement is considered as fulfilled.

As a summary, Table 3-5 summarizes the evaluation of the fulfillment of functional requirements.

TABLE 3-5: FUNCTIONAL REQUIREMENTS I4.0-UC2.

| FR - ID | Description | Fulfilment |
|---|---|---|
| FR-I4.0-UC2-01 | Leverage AI to automate procedures, enable prediction and provide recommended actions accordingly | Fulfilled |
| FR-I4.0-UC2-02 | BASS will be able to scale up and down the system in order to guarantee SLAs | Fulfilled |
| FR-I4.0-UC2-03 | Provide E2E 5G connectivity inside the plant facilities and outside to the public network | Fulfilled |
| FR-I4.0-UC2-04 | Guarantee the delivery of information from the cameras to the monitoring application with minimal delay | Fulfilled |
| FR-I4.0-UC2-05 | Support remote control protocols using wireless as an alternative to cable today | Fulfilled |

### 3.2.1.5. Fulfillment of Technical Requirements

The fulfillment of the technical requirements described in D1.1 [5] is discussed in the following.

- **TR-I4.0-UC2-01: Availability of 99.9999%**
  The availability here refers to network availability, which can be defined as the ratio between the amount of uptime of a network to a specific time interval. This requires a very long-term measurement in order to obtain accurate measurements. In our trials, we employed the 5G connectivity using Vodafone's 5G SA testbed, which was stable overall executions. Additionally, for the Vodafone-Wavelength solution, the edge is virtualized in a cloud base system, which allows the system to switch to a different virtualized environment in case. Similarly, when using standalone edge devices, the system can be executed with multiple running nodes, which allows switching to a different node in case one link goes off. Hence, with this design, when one node fails, the other node continues to function. The availability is increased from 99.9% to 99.9999%. Therefore, this technical requirement can be considered as fulfilled.
- **TR-I4.0-UC2-02: Expected Reliability of 99.9999%**
  As a result of using the Vodafone 5G test network. The link-level reliability wasn't available for testing. Hence, this technical requirement can be considered as unfulfilled.
- **TR-I4.0-UC2-03: Reference E2E Latency of 10ms**
  As shown in the experimental results in D3.3, the Vodafone 5G SA test network was used to provide connectivity between the factory and the edge side. This system provided an E2E

latency of 11ms. Based on these results, this technical requirement can be considered as partially fulfilled.

- **TR-I4.0-UC2-04: Remote control bandwidth per instance (DL) of 100Kbps**
  In the trials, the DL bandwidth was measured for the 5G connectivity at 47.3 Mbps (spans between 32.5 Mbps and 53 Mbps). The required remote-control bandwidth is quite low mainly because it is composed only of sending a command from the edge side to the fog device (i.e. the edge sends either 'Y' or 'N' as commands to the fog node). Based on these results, this technical requirement can be considered as fulfilled.
- **TR-I4.0-UC2-05: Video bandwidth per instance (UL) of 5Mbps (per camera)**
  In the trials, the UL bandwidth required for high-resolution video transmission was measured for 5G at 35.3 Mbps (with a maximum of 40.9 Mbps). Hence, the presented results show that this technical requirement can be considered as fulfilled.
- **TR-I4.0-UC2-06: Reference Connection density of <1000 device per Km2**
  This technical requirement was not possible to be evaluated in the trials mainly due to the limited hardware resources. In the trials, we had one UE that was providing 5G connectivity for both the camera and the control links. Additionally, it would not have been possible to use multiple high-resolution cameras with NDI capabilities due to the high cost of the PTZ camera used. However, if this requirement can be fulfilled by a hardware-based system, the ZDM system was built in a flexible way that allows multiple cameras, independent control loops and 5G UEs. Hence, the presented results show that this technical requirement can be considered as fulfilled.
- **TR-I4.0-UC2-07: Reference Coverage locally using one cell, no handover**
  The ZDM trials took place in the Interdigital Labs, where available UEs could connect to a single cell, which was providing local reference coverage for all the use case executions. Given the setup of the trials and the obtained results, this technical requirement is considered as fulfilled.

As a summary, Table 3-6 summarizes evaluation of the fulfilment of technical requirements.

TABLE 3-6: TECHNICAL REQUIREMENTS I4.0-UC2.

| TR - ID | Description | Fulfilment |
|---|---|---|
| TR-I4.0-UC2-01 | Availability of 99.9999% | Fulfilled |
| TR-I4.0-UC2-02 | Expected Reliability of 99.9999% | Unfulfilled |
| TR-I4.0-UC2-03 | Reference E2E Latency of 10ms | Partially Fulfilled |
| TR-I4.0-UC2-04 | Remote control bandwidth per instance (DL) of 100Kbps | Fulfilled |
| TR-I4.0-UC2-05 | Video bandwidth per instance (UL) of 5Mbps (per camera) | Fulfilled |
| TR-I4.0-UC2-06 | Reference Connection density of <1000 device per $Km^2$ | Fulfilled |
| TR-I4.0-UC2-07 | Reference Coverage locally using one cell, no handover | Fulfilled |

### 3.2.2. Future Directions

Future direction for the ZDM use case includes scalability of the edge monitoring of the production line, where multiple cameras can be deployed at different stages of the production. This motivates further enhancement of resource management at the edge side to provide an independent AI-aided control for each stage at the production line.

## 3.3. I4.0-UC3: massive Machine Type Communications

In this section, we first summarize the trial results of massive MTC use case in 5TONIC. Based on the trial results, we evaluate the fulfilment of the requirements in terms of objectives, conditions, business requirements, functional requirements, technical requirements, which are described in D1.1 [5] .

### 3.3.1. Summary of Trial Results and Validation of Requirements

During the week of November 15-19, 2021, the massive MTC trial setup was deployed and integrated in 5TONIC in Madrid, Spain, together with the digital twin trial setup, utilizing the same Edge infrastructure from 5TONIC data center. Figure 3-3 shows the setup deployment. Note that a block diagram for more details can be seen in section 5.3 in D3.3 [3] . We deployed one mMTC radio head on a table which covers the trial area. Seven IoT nodes based on the IEEE 802.15.4 protocol are deployed at 3 locations. Each IoT node has a temperature sensor. An mMTC service acting as an IoT gateway (GW) is deployed in a Kubernetes cluster which are deployed on the three VMs provided by 5TONIC data center. The mMTC service provides the full stack of the IoT GW based on the IEEE 802.15.4 protocol from PHY layer (L1) to application layer (LWM2M server). LWM2M client is installed in each IoT node. Therefore, the end-to-end application layer connection between the mMTC service in the edge date center and each IoT node deployed in the trial field is established based on LWM2M. In the trial, the sensor data, i.e. temperature values, were read from the IoT nodes at a certain frequency, e.g. 1 reading per minute per IoT node, configured on the mMTC service side. In addition to the IoT GW stack, an RF fingerprinting function is included as part of the mMTC service as well to enhance the network security. In the RF fingerprinting function, an AI-based algorithm based on deep neural network D2.3 [2] [7] is developed to for intruder detection when a false IoT node (e.g. an attacker) tries to get access to the network. The mMTC service is also integrated with 5G-DIVE DEEP platform. For example, the life-cycle management and orchestration configuration are done through BASS in DEEP. During the system integration and deployment phase, the system functionalities and configurations were validated and verified. Then the system was configured to run for a long time, at least several days for each trial measurement. We measured the IoT application layer performance in Data Loss Rate (DLR) and Round-Trip Time (RTT) over either Ethernet or 5G network, the RF fingerprinting performance regarding accuracy to detect normal or intruder nodes, and the performance regarding orchestration and automation features such as service restart, pod-level redundancy, and node-level redundancy. The trial results are summarized the following, while more details can be seen in D3.3 [3] .

- The application layer performance over Ethernet network is excellent with is high reliability, i.e. low DLR of 0.7% and below 300 ms RTT in average. Note that we have two types of IoT nodes based on two different platforms, i.e. nRF52840 platform and Zolertia Firefly platform, used in the trial. The two nodes based on Zolertia Firefly platform performed much better than the other 5 nodes based on nRF52840 platform. If we only count the results of Zolertia Firefly nodes, the measured DLR is 0.005%, which we believe should better reflect the performance in the field where performance certified nodes are usually used.
- The application layer performance over 5G network performs as well as that over Ethernet network. But the RTT is increased by about 100ms in average due to the impact of increased latency of 5G network compared with Ethernet.

- RF fingerprinting results show high intruder detection accuracy of 90% when one packet is used for detection. Intruder here denotes the unauthorized nodes which may attack the IoT network. The accuracy can be further improved by using multiple packets together. For example, using two packets for detection can increase the accuracy to 99%.
- The orchestration and automation tests show that the mMTC service is quite robust against pod-failure event. When no redundancy is configured in the system, the pod is automatically restarted after the pod failure detected. The pod restart time is about 3 seconds. The IoT service is interrupted for 3 seconds. If there are data transmitted in this time, these data will be lost. This is much better than that for a hardware based IoT GW, which may even need a manual restart. However, with configured pod-level redundancy or node-level redundancy with two container replicas, no service interruption and no data losses have been measured. The robustness is improved significantly.
- Autoscaling features were also tested in the measurement regarding scalability investigation. Both vertical scaling and horizontal scaling are supported.

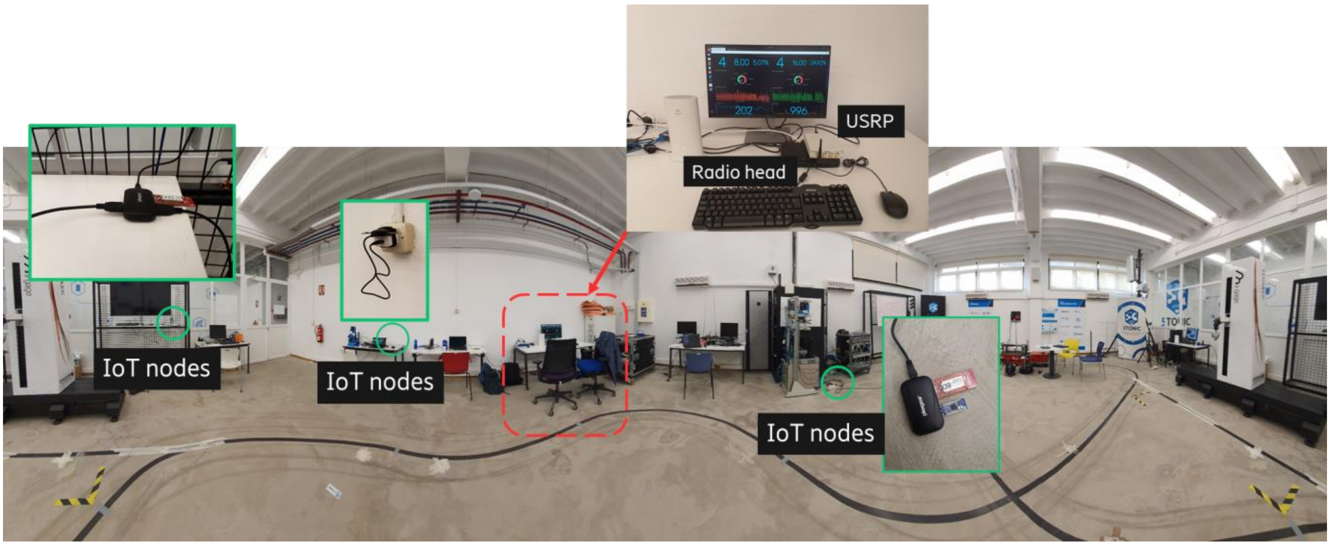


FIGURE 3-3: MMTC TRIAL SETUP DEPLOYMENT IN 5TONIC

### 3.3.1.1. Objective Fulfilment

The fulfilment of the objectives described in D1.1 [5] are discussed in the following. Based on the trial results, all objectives are considered as achieved.

- **Objective 1: To demonstrate connectivity performance of virtualized IoT gateways for supporting dense deployments of IoT sensors.**

  As described previously, the mMTC service deployed in 5TONIC data center acts as an IoT GW. The trial results show it works as expected. The design is able to support many IoT devices in a dense deployment. Therefore, objective 1 is considered as achieved.

- **Objective 2: To demonstrate the orchestration and automation features of the IoT connectivity services.**

As described previously, orchestration and automation features such as auto pod restart, pod-level redundancy, node-level redundancy, and autoscaling have been successfully tested in the trail. Therefore, objective 2 is considered as achieved.

- **Objective 3: To demonstrate the intelligence features of the virtualized IoT gateways.**

  The RF fingerprinting function in the mMTC service is based on AI technologies. An AI model based on a deep neural network is developed for security enhancement. The RF fingerprinting function was successfully tested in the trial. Therefore, objective 3 is considered as achieved.

- **Objective 4: To demonstrate a service-based data pipeline architecture for providing sensor data about the status of plant and workflows.**

  The mMTC service are designed using microservice-based architecture. The mMTC service comprises of 3 microservices which provides the end-to-end IoT connectivity between the mMTC service and the IoT nodes. In the trial, temperature data as an example of sensor data are reported from the IoT nodes at certain frequencies, for example, 1 reading per minute per IoT node. Therefore, objective 4 is considered as achieved.

#### 3.3.1.2. Condition Fulfilment

The fulfilment of the conditions described in D1.1 [5] are discussed in the following. Based on the trial results, all conditions are considered as fulfilled.

- **Condition 1: Fixed or wireless network infrastructure are available to provide network connectivity between radio heads and virtualized IoT gateways at the Edge or in Cloud.**
  In the trial, we tested with both Ethernet network and 5G networks. The results show that they work properly.
- **Condition 2: Network bandwidth and latency fulfils the requirement of specific RATs used.**
  Same as the condition 1, the trial results show that the network bandwidth and latency of Ethernet network and 5G network are sufficient for IEEE 802.15.4 used in the trial.
- **Condition 3: Adequate computing, network and storage resources are available in the Edge and Cloud infrastructure for hosting virtualized IoT gateways and applications.**
  The trial results show that the VMs provided by 5TONIC data center are sufficient for the mMTC use case.
- **Condition 4: Large number of wireless sensors and/or actuators with different RATs are deployed at the factory premises.**
  In the trial, we used 7 IoT nodes (all nodes we have available). Given the coverage area of the trial site, it is considered as sufficiently many.
- **Condition 5: Radio heads are deployed to provide coverage of the factory premises where wireless sensors and/or actuators are deployed.**
  In the trial, we deployed one radio head, which is sufficient to cover the trial site area.

#### 3.3.1.3. Fulfilment of Business Requirements

The fulfilment of the business requirements described in D1.1 [5] are discussed in the following. Note that it is not possible to evaluate the exact number stated in the business requirements directly by the trial results. Here, we give a short analysis based on the trail results which are related to the business requirements. Based on the analysis, all business requirements are considered as fulfilled.

- **BR-I4.0-UC3-01: Reduce IoT network deployment cost by 25%.**
  The trial shows the possibility to deploy the IoT stack completely in software in the edge. Reusing the existing edge infrastructure would not need extra costs for purchasing HW. Therefore, HW costs can be saved for the IoT stack part. And less functions are needed in the radio head. The radio head can be designed at a lower cost. Radio heads can be also designed to support multiple IoT RATs (radio access technologies) simultaneously. In this case, the number of deployed radio heads can be reduced since no parallel deployments are needed for different RAT. Intelligent functions can be added to the system easily by adding them into the edge. This would be much more costly if intelligent functions are integrated into the HW-based GWs. Considering the aspects discussed above, it is a reasonable estimation of more than 25% reduction in deployment cost. Therefore, this business requirement is considered as fulfilled.
- **BR-I4.0-UC3-02: Reduce IoT network operational cost by 20%.**
  The IoT stack is completely softwarized in a cloud-native way based on microservice architecture. The life cycle management is done with proven orchestration frameworks, such as Kubernetes used in the mMTC use case. In the trial, the operation is further simplified by utilizing BASS in the DEEP platform. The operations are streamlined and unified with one user interface and simplified service descriptors which are easy to use and understand. The trial results show the automation features such as pod-restart, pod-level redundancy and node-level redundancy enhance the service robustness automatically without the need of manual handling (e.g. labor works) when service failures happen. Therefore, the simplified management interface and system automation features which are validated in the trials can help reduce the operational cost of the mMTC services. Considering the analysis above, it is a reasonable estimation that the IoT network operational cost can be reduced by more than 20%. Therefore, this business requirement is considered as fulfilled.
- **BR-I4.0-UC3-03: Reduce mean time between failures by 50%**
  As described before, the automation features validated in the trial can increase the system robustness against service failures. For example, with a node-level redundancy configured, the system continues to operate when some nodes are malfunctioning. Further Kubernetes-based orchestrator has autohealing features. For example, when a pod or a service is unresponsive, Kubernetes will automatically restart the pod or the service. The restart time is much quicker than that if manual operations are needed, which would happen in traditional systems. For example, in the trial, a pod restart only takes about 3 seconds during which the service is interrupted. After 3 seconds, the service is resumed. Based on the trial results, the number of failures can be significantly reduced and the time between failures can be also significantly reduced. It is a reasonable estimation that the mean time between failures would be reduced more than 50%. Therefore, this business requirement is considered as fulfilled.

As a summary, Table 3-7 summarizes evaluation of the fulfilment of business requirements.

TABLE 3-7: BUSINESS REQUIREMENTS I4.0-UC3

| BR – ID | Description | Fulfilment |
|---|---|---|
| BR-I4.0-UC3-01 | Reduce IoT network deployment cost by 25% | Fulfilled |
| BR-I4.0-UC3-02 | Reduce IoT network operational cost by 20% | Fulfilled |
| BR-I4.0-UC3-03 | Reduce mean time between failures by 50% | Fulfilled |

#### 3.3.1.4. Fulfilment of Functional Requirements

The fulfilment of the functional requirements described in D1.1 [5] are discussed in the following.

- **FR-I4.0-UC3-01: Orchestration with automated life cycle management.**
  As described before, the mMTC service design is based on microservice architecture using Kubernetes framework. BASS in DEEP are integrated with Kubernetes to further simplify the life cycle management. Kubernetes together with BASS provides the orchestration of the mMTC service with automated life cycle management. The system can be self-healed with service automatic restart. Autoscaling is also supported to scale the system resources according to the amount of IoT traffic. These functions are validated in the trial and lab tests. Therefore, this functional requirement is considered as fulfilled.
- **FR-I4.0-UC3-02: Orchestration with load balancing and auto-scaling.**
  In the system design, we use MetalLB[7] as the load balancer to perform load balancing. The auto-scaling are supported also via Kubernetes. These functionalities are validated in the trial and lab tests. Therefore, this functional requirement is considered as fulfilled.
- **FR-I4.0-UC3-03: Virtualized IoT RAN supporting multiple RATs**
  The mMTC testbed is designed to support both IEEE 802.15.4 full stack and LoRa PHY. Both have been validated in lab tests. For the trial to have a full stack end-to-end server-client application, we focused on IEEE 802.15.4. But the system support both RATs. Therefore, this functional requirement is considered as fulfilled.
- **FR-I4.0-UC3-04: Orchestration optimization with ML/AI**
  Originally, ML/AI technologies are planned to be leveraged for orchestration optimization. However, the focus was changed for security enhancement with RF fingerprinting instead. The developed RF fingerprinting function showcases that the AI/ML techniques can be easily introduced and integrated in the mMTC system design based on the microservice architecture. The trial results show that the developed AI model based on deep neural network is very effective to detect intruder nodes, which can significantly enhance the IoT system security. Even though this functional requirement is considered not fulfilled, the original idea to utilize AI/ML technologies in the mMTC service is achieved.

[7] https://metallb.universe.tf/

As a summary, Table 3-8 summarizes evaluation of the fulfilment of functional requirements.

TABLE 3-8: FUNCTIONAL REQUIREMENTS I4.0-UC3

| FR – ID | Description | Fulfilment |
|---|---|---|
| FR-I4.0-UC3-01 | Orchestration with automated life cycle management | Fulfilled |
| FR-I4.0-UC3-02 | Orchestration with load balancing and auto-scaling | Fulfilled |
| FR-I4.0-UC3-03 | Virtualized IoT RAN supporting multiple RATs | Fulfilled |
| FR-I4.0-UC3-04 | Orchestration optimization with ML/AI | Not fulfilled (but ML/AI is used for security enhancement instead.) |

#### 3.3.1.5. Fulfilment of Technical Requirements

The fulfilment of the technical requirements described in D1.1 [5] are discussed in the following. Note that the technical requirements were formulated to cover both cellular IoT and non-cellular IoT segments. Particularly, cellular IoT is also referred to as LPWAN (Low-Power Wide-Area Network) or LPWA (Low-Power Wide-Area), which features long range, low power and low cost. The examples of typical LPWAN RATs are Sigfox, LoRa, NB-IoT, LTE-M etc. And non-cellular IoT is also referred to as LP-WPAN (Low Power Wireless Personal Area Network) which features short range, low power and low cost. The examples of typical LPWPAN RATs are IEEE 802.15.4 and Bluetooth. As mentioned, there are many RATs in each mMTC segment. It is impossible in 5G-DIVE to verify all of them. In this work, we picked IEEE 802.15.4 as a representative RAT of LPWPAN and LoRa as a representative RAT of LPWAN, for mMTC development and performance evaluation. Therefore, our testbed is developed to support both IEEE 802.15.4 and LoRa, which are further developed on the top of several open-source software, e.g. IEEE 802.15.4 PHY[8] [8] , LoRa PHY[9], Contiki[10] etc. As mentioned before, we have a full-stack implementation of IEEE 802.15.4, which is suitable for the trial in 5TONIC, as reported in D3.3 [3] , while we have the LoRa implementation focused on LoRa PHY, which is more suitable for scalability studied in D2.1 [6] , [7] . Nevertheless, in this work, it is reasonable that we evaluate the fulfilment of the technical requirements based on the trial results of IEEE 802.15.4, which are reported in D3.3 [3] and lab test results of LoRa, which are shown in D2.1 [6] , [7] for non-cellular IoT and cellular IoT, respectively.

- **TR-I4.0-UC3-01: Application layer end-to-end latency less than 10 s for cellular IoT (5G requirement) and less than a few 100s ms for non-cellular IoT.**
  As shown by the test results in [7] , maximum latency of LoRa PHY is less than 250 ms when 58 cells are served by the full resource of one CPU core. For IEEE 802.15.4, the trial results show 90% of RTT is less than 400 ms, while maximum RTT is about 1000 ms. If we consider one-way latency, it should be 200 ms and 500 ms, assuming the latencies in two directions are symmetric. Based on these results, this technical requirement is considered as fulfilled.

[8] https://github.com/bastibl/gr-ieee802-15-4
[9] https://github.com/rpp0/gr-lora
[10] https://github.com/contiki-ng/contiki-ng

- **TR-I4.0-UC3-02: Air interface bit rate in the range of a few 10s bps – a few100s kbps for cellular IoT and a few 100s kbps to 2 Mbps for non-cellular IoT.**
  The LoRa implementation supports spreading factor 7-12 corresponding to bit rate range of about 0.3 kbps to 5.5 kbps. The 802.15.4 implementation support 250 kbps bit rate. The lab and trial results show the link performance at these bit rates are reliable. Therefore, this technical requirement is considered as fulfilled.
- **TR-I4.0-UC3-03: Connection density up to 1 million devices/km2 for cellular IoT (5G requirement).**
  This technical requirement is difficult to evaluate and verify in a trial. For example, no one can afford to deploy 1 million IoT devices in the trial field. However, if this requirement can be fulfilled by a hardware-based system, a cloudified system as envisioned in the mMTC use case in 5G-DIVE would support even higher connection density, considering the scalability and flexibility offered by Cloud. Even though this is not tested in the trial, this requirement is considered as fulfilled in principle based on the discussion above.
- **TR-I4.0-UC3-04: Coverage of 164 dB maximum coupling loss at a rate of 160 bps for cellular IoT (5G requirement) and 10-100 meters for non-cellular IoT.**
  For a cellular IoT system to meet this requirement, it requires a base station with very high transmit power and the UEs supporting long range feature with high number of transmit repetitions. This is not possible for this project to arrange such systems. In this project, the idea is to softwarize the IoT stacks in a cloud environment. The current trend of Cloud RAN approach shows that even NR can be run at full performance using a COTS (commercial off-the-shelf) server. Therefore, there is no doubt that less-complex cellular IoT stacks like NB-IoT can be implemented in software achieving the same coverage performance as the system based on special-purpose hardware components. For non-cellular IoT, the trial results show that the implemented 802.15.4 stack support more than 10 meters coverage. Therefore, this technical requirement is considered as fulfilled.
- **TR-I4.0-UC3-05: Availability larger than 99.99%**
  The availability here refers to as network availability. The definition of network availability is the ratio between the amount of uptime of a network and a specific time interval. This usually requires very long-term measurement. In the trial, we measured more than 4 weeks with different types of tests. Given the trial time, the mMTC network service was stable and no network outage events have been observed. Additionally, the cloud-grade hardware, i.e. servers, normally has availability of 99.9%, in comparison to 99.999% of telecom-grade equipment. However, cloud system uses redundancy to increase availability. For example, with node-level redundancy of two nodes (i.e. deploying the services on two nodes with load balancing. When one node fails, the other node continues to function.), the availability is increased from 99.9% to 99.9999%. Considering the trial results and the node-level redundancy analysis above, this technical requirement is considered as fulfilled.
- **TR-I4.0-UC3-06: Link reliability is high, e.g. 99.9%**
  In the trial, the data loss rate (DLR) was measured over a long term. The measured DLR is about 0.7% without application layer retransmission. If applying one time retransmission in case of a data loss event (e.g. time-out of the response reception), the data loss rate would be reduced from 0.7% to 0.005%, which means the reliability is increased from 99.3% to 99.995%. As described previously,

another observation in the trial is that the nodes based on Zolertia Firefly platform performed much better than the other nodes based on nRF52840 platform. If we only count the results of Zolertia Firefly nodes, the measured DLR is 0.005%. It indicates that the reliability of the good nodes, e.g. Zolertia Firefly nodes, is 99.995%. Given the analysis of the trial results of DLR, this technical requirement is considered as fulfilled.

As a summary, Table 3-9 summarizes evaluation of the fulfilment of technical requirements.

TABLE 3-9: TECHNICAL REQUIREMENTS I4.0-UC3.

| TR - ID | Description | Value | Fulfilment |
|---|---|---|---|
| TR-I4.0-UC3-01 | Application layer end-to-end latency | Less than 10ms for cellular IoT (5G requirement), Less a few 100ms for non-cellular IoT. | Fulfilled |
| TR-I4.0-UC3-02 | Air interface bit rate | A few 10bps to a few 100kbps for cellular IoT, a few 100s kbps to 2 Mbps for non-cellular IoT. | Fulfilled |
| TR-I4.0-UC3-03 | Connection density | Up to 1 million devices/km2 for cellular IoT (5G requirement). | Not possible for trial evaluation (but considered to be fulfilled in principle) |
| TR-I4.0-UC3-04 | Coverage | 164 dB maximum coupling loss at a rate of 160 bps for cellular IoT (5G requirement),<br>10-100 meters for non-cellular IoT. | Fulfilled (verified for non-cellular) |
| TR-I4.0-UC3-05 | Availability | 99.99% | Fulfilled |
| TR-I4.0-UC3-06 | Link reliability | High (exact value TBD, massive MTC requires lower reliability than eMBB and URLLC) | Fulfilled |

### 3.3.2. Future Directions

In 5G-DIVE, we built a cloudified mMTC network service integrated with 5G-DIVE DEEP platform. It verifies the feasibility and benefits of using Cloud RAN approach for mMTC services. It also showcases that the operations can be simplified via orchestration and DEEP integration. The following list some possible future works after 5G-DIVE project.

- Investigating more advanced autoscaling features, e.g. considering the tradeoff between resource utilization and latency.
- Investigating energy efficiency performance and optimize energy consumption in cloud environment.
- Continue to investigate data-driven approaches to enhance IoT security.
- Investigating more IoT features which would benefit from AI/ML and big data capabilities.

# 4. Validation and Summary of Autonomous Drone Scout Use Cases

ADS is the other vertical application area in 5G-DIVE project. This section gives a summary of trial results, evaluates the fulfillment of ADS requirements, and depicts the future outlook of the following use cases. In particular, Section 4.1 and Section 4.2 presents the trial results summary of ADS-UC1 and ADS-UC2, respectively. Since both use cases share most components of the same platform and thereby have the same KPI requirements, we address the ADS requirement validation jointly for both use cases in Section 0. This includes the fulfillment of the objectives, conditions, as well as business, functional, and technical requirements that are described in D1.1 [5] . Finally, Section 4.4 presents the future direction for the ADS use cases.

## 4.1. ADS-UC1: Trial Results Summary of Drone Fleet Navigation

Drone fleet navigation is an important functionality needed during a disaster relief mission. During the disaster relief mission of the drone fleet, the drone navigation server and Drone Collision Avoidance System (DCAS) function is applied to support drones for executing missions. In 5G-DIVE, numerous drone fleet trials have been conducted to validate the robustness of drone fleet navigation managed by a server deployed on the edge infrastructure and communicating over a 5G-NSA network. In addition, two features are crucial in order to use drones for providing aerial support in aerial disaster relief response missions. The DCAS has been validated by deploying the application logic both at the fog (i.e., drone) and at the edge. The feature performed well in both cases. However, drone operators are advised to adopt it at the edge, especially if the number of drones in the fleet is large. Besides, iDrOS (Internet Drone Operating System) has been proved the ability to migrate application components from drone to edge. This feature is useful for rapid deployment during missions based on the available hardware resources at fog and edge. Moreover, a stress test has been performed for the designed drone navigation server while utilizing 5G-NSA and it shows that it can support 50 emulated drones for several missions. The ADS-UC1 with the given features will pave the road for other public safety applications or other industrial applications.

It is important to highlight that the 5G-DIVE DEEP platform assists the orchestration of both the edge and fog infrastructures (e.g. Kubernetes, FogO5), and provides advanced features to enhance the overall performance of the drone fleet. In particular, the DASS provides a high throughput publishing framework for sensory data from drones to the edge. The BASS provides a monitoring service which is a good tool for disaster relief mission operators. Also, it can support the rapid deployment of intelligent applications in the fog. Based on the collected sensory data and other infrastructure data, side by side with 5G-DIVE DEEP platform, we executed several successful autonomous drone fleet missions.

The trial results are summarized as follows, while more details of the trial results can be found in D3.3 [3] .

- With the utilization of 5G communication network, we are able to support more drones in the mission. Without 5G, fewer drones will be supported. Apart from that, drones will not be able to provide low latency which is necessary for services such as DCAS. In the trial, three drones are supported simultaneously.

- DCAS can perform collision avoidance in a real-time fashion. DCAS has been adopted at the fog or the edge based on the drone operator's needs. In addition, the updated design of the drone navigation server is able to provide a more user-friendly interface for multiple drones at the same web control simultaneously. When DCAS is deployed at the edge, 5G-NSA network is used for drone-edge communications. If DCAS is deployed at the fog (drone), the drone to drone communication is used.
- IDrOS provide the feature of software mobility between fog and edge, this is very useful and dynamic feature taking into account the computing capabilities at the drone, the latency to the edge and signal strength.
- Scalability of Drone fleet navigation has been tested with different periods and a large number of drones (i.e. 20/50 emulated drones). The drone navigation is tested also with three drones in real-time and demonstrated successfully the DCAS service and the functionality for a battery swap.

## 4.2. ADS-UC2: Trial Results Summary of Intelligent Image Processing for Drones

During the months of October and November 2021, numerous ADS trials have been conducted. The trials were using the complete end-to-end deployment of the 5G-enabled edge infrastructure as well as intelligent application in supporting the aerial disaster relief response mission. Figure 4-1 shows the complete end-to-end deployment of the aerial disaster relief response system. In the system, three aerial drones are utilized to provide aerial video surveillance of the mission area. This video surveillance is fed to the edge via a 5G NSA network. At the edge, the video surveillance is consumed by the intelligent engine application, in this case, EagleEYE, and EagleStitch. Here, EagleEYE is used to provide for Person in need of Help (PiH) detection and localization service. While EagleStitch is used to provide for 2D panorama stitching of the surrounding area. Apart from that, the 5G-DIVE DEEP platform is also fully integrated at the edge and fog (i.e. drone) to enhance the overall performance of the disaster relief response system. Figure 4-2 highlights the features that the 5G-DIVE DEEP platform brings to the ADS-UC2. The DASS provides for data preprocessing, and storage solutions at the fog (aerial drone), as well as at the edge. The IESS provides for automatic AI model training and model storage framework. The BASS provides a simplified and unified interface for application lifecycle management. With that said, the trial results are summarized as follows, while more details of the trial results can be found in D3.3 [3] :

- With the utilization of 5G network, providing for more bandwidth and better network latency, we are able to support more drones in the mission. Not only that, the drones will also be able to transmit aerial video surveillance footage with better quality. In the trial, we run the mission with three drones simultaneously.
- EagleEYE is able to perform PiH detection and localization in a real-time fashion. The processing latency for PiH detection and localization in a single image frame coming from the drone is 47.14 ms. With pipelining and parallelization techniques in EagleEYE, we can provide for PiH detection and localization in real-time.

- The scalability of EagleEYE is also investigated and tested. In the testing with simulated drone video surveillance footage, up to 6 simultaneous drone streams are able to be processed by EagleEYE. Technically, more drones can be supported but the test performed is limited by the hardware where the system is deployed.
- EagleStitch is able to provide 2D panorama stitching of the surrounding mission area to provide for more insight to the rescue team. The processing latency for this task is 0.757 ms for stitching two aerial images taken by the aerial drone.

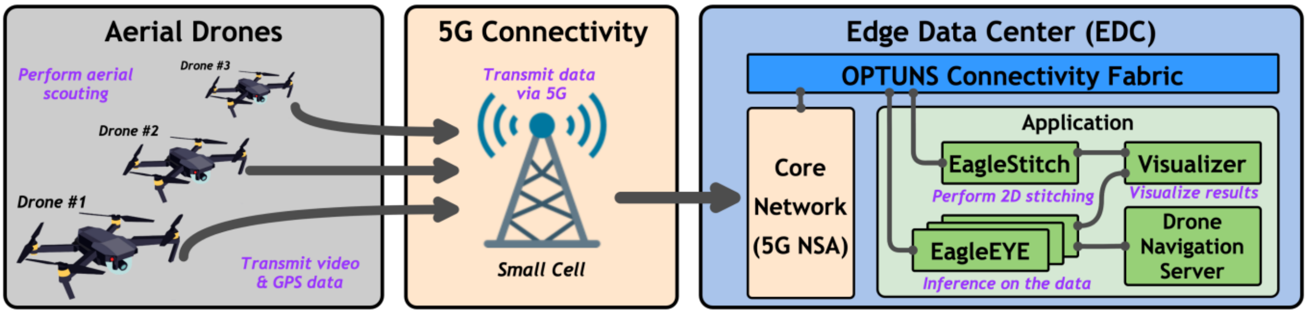


FIGURE 4-1: COMPLETE END-TO-END DEPLOYMENT OF AERIAL DISASTER RELIEF SYSTEM

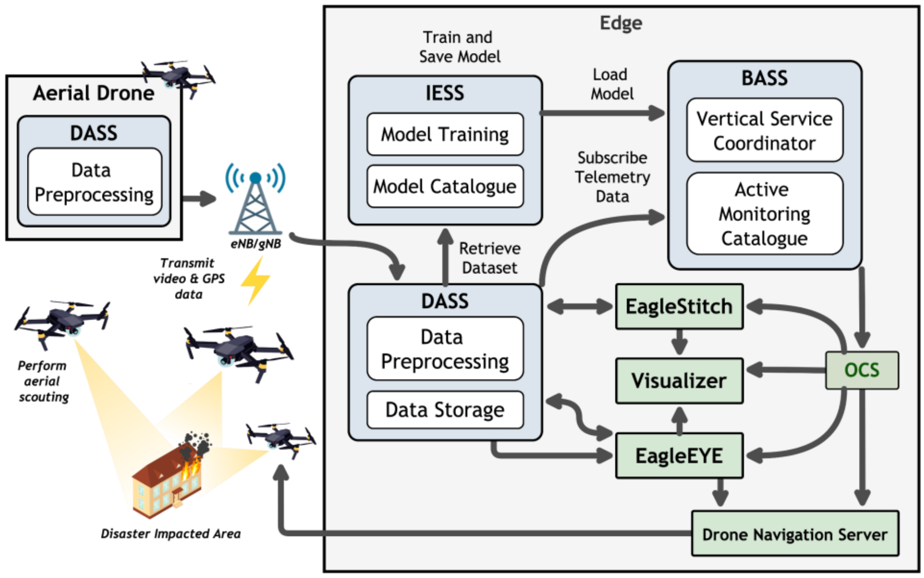


FIGURE 4-2: INTEGRATION OF AERIAL DISASTER RELIEF RESPONSE SYSTEM WITH 5G-DIVE DEEP

## 4.3. ADS Validation of Requirements

Below are the evaluation of objectives, conditions, as well as business, functional and technical requirements of ADS-UC1 and ADS-UC2. Note that both ADS use cases shares the same Business, Functional, and Technical Requirements as described in D1.1 [5]

### 4.3.1. Objective Fulfilment

- **ADS Objective 1: To demonstrate the performance of 5G system integrating intelligent edge in connecting and navigating a fleet of drones seamlessly. The collected data from drones is transmitted over 5G for processing at the edge.**
  5G-NSA supports for multiple drones video streaming and sensory data required for drone fleet navigation, as well as intelligent image processing for drones. More details are reported in D3.3 [3] . Therefore, objective 1 is fulfilled.
- **ADS Objective 2: To provide low latency inter-server connectivity at the edge for drone fleet navigation and intelligent image processing**
  As shown previously in Figure 4-1, OPTUNS [10] edge data center network architecture has been utilized in ADS-UC2 to provide high bandwidth and ultralow latency network for rack-to-rack and server-to-server communication. Experiment results provided in [10] showcase OPTUNS performance in this regard. With that, objective 2 is fulfilled.
- **ADS Objective 3: To monitor drones flight status in order to detect and avoid collisions during rescue missions through intelligent drone-to-drone collaboration.**
  New drone navigation server supports the view and management of multiple drones at the same web control. The drone navigation server can manage the drones directly through the 5G-NSA network or it can depend on the relay functionality from drone-to drone. Also, DCAS is using the drone-to-drone network if it is enabled in the drone itself. If it is enabled at the edge, the drone operator can use the 5G-NSA network. With that, objective 3 is fulfilled.
- **ADS Objective 4: To demonstrate the benefits of automation and scalability for drone fleet navigation.**
  Obviously, the automation especially in disaster relief missions will enable the response team to deploy new drone service quickly, in particular, BASS is supporting the deployment of EagleEYE services even within a different region. The scalable design of services such as EagleEYE and the drone navigation server demonstrated the user-friendly services, reliable and available all the time as depicted in D3.3 [3] . With that, objective 4 is fulfilled.
- **ADS Objective 5: To adjust drone trajectory based on the detected hazards**
  As shown previously in Figure 4-2, during the execution of the PiH detection and localization mission of ADS-UC2, whenever EagleEYE detects a PiH, the GPS location of the detected PiH will be recorded and sent to the Drone Navigation Server for autonomous trajectory update of the drone. With that, objective 5 is fulfilled.
- **ADS Objective 6: To provide 2D-image stitching capabilities in order to provide more information to the relief team**
  As shown previously in Figure 4-2, during the execution of the PiH detection and localization mission, one of the drones in the drone fleet will perform a maneuver to capture video surveillance

of the surrounding area. This video footage will be received by EagleStitch at the edge to perform 2D stitching of the area. The stitched image is then displayed to the relief team via the visualizer to provide more insight of the area. With that, objective 6 is fulfilled.

### 4.3.2. Condition Fulfilment

The fulfillment of the conditions described in D1.1 [5] is discussed in the following. Based on the trial results, all conditions are considered as fulfilled.

- **ADS Condition 1: High bandwidth is required for on-time delivery of the information (sensing, imaging, and control) among drones and between drones and the edge.**
  In the trial, we adopted 5G-NSA solution, this enabled us to provide a high bandwidth especially for Uplink (i.e. from drone to the edge). This uplink is used mainly for transmitting high quality images and sensory data with low latency suitable for disaster relief response. The field trials, show the detection of EagleEYE is accurate, the drone navigation server connected all the time to the drone fleet.
- **ADS Condition 2: The weather condition shall satisfy the minimum requirement for safe drone piloting. This includes wind speed for drone handling and clear visibility.**
  In this matter, we had to reschedule some of the field trial to avoid the extremely windy weather. If the speed of the wind is high, this is a risk for the public safety. However, we still had suitable wind condition to carry the field trials for ADS-UC1 and ADS-UC2.
- **ADS Condition 3: The edge computing resources shall always be available to ensure seamless operation and scalability.**
  In the trial, we used OPTUNS edge data center network architecture to provide high bandwidth and ultra-low latency network. We did not report any event of failure. The results show that they work properly.

### 4.3.3. Fulfillment of Business Requirements

The fulfillment of the business requirements described in D1.1 [5] is evaluated in this subsection. Note that it is not possible to evaluate the exact number stated in the business requirements directly by the trial results. Here, a short analysis based on the trial results related to the business requirements is presented. Based on the analysis, all business requirements are considered as fulfilled.

- **BR-ADS-UC1-01: Reduce the data collection time by at least 50%**
  Different components of ADS end-to-end solution enhance the overall performance and lead to satisfying this business requirement. Starting from iMEC, it contributed to the reduction of data collection by supporting local breakout of UE traffic for lower latency, supporting container-based and VM-based virtualized servers with GPU pass-through; and supporting scale out of compute nodes for more virtual servers running at a time. Also, 5G-NSA solution contributed to the decrease of the data collection especially with high bandwidth or low latency. Therefore, a reduction of data collection time by at least 50% can be expected.

- **BR-ADS-UC1-02: Reduce the time of the staff hours by at least 50% to 90%**
  With the utilization of EagleEYE, EagleStitch, DCAS, as well as the BASS to aid in the disaster relief response, we can expect a reduction in staff hours in two areas. First, in the total deployment time required to deploy the full service stack of the disaster relief response system. The BASS automates the deployment while also reducing the deployment complexity. Second, in the total time required to response to a disaster. The combination of 5G connectivity, edge and fog computing, on top of the DEEP platform, provides the disaster response team with additional resources and information to make more agile decision, compared with the legacy system, where all the operation are executed manually. Therefore, a reduction of at least 50% of staff hours can be expected.
- **BR-ADS-UC1-03: Increase at 3X- 5X productivity**
  5G EPC used in 5G-NSA part, will enhance the system productivity, especially with the following features. Increase in UE attachment rate to 20 UEs per second, with 50 thousand simultaneous users in total; support for MME auto scale-out for accommodating a large number of users; support 3GPP EN-DC functionality; support of SmartNICs to accelerate packet processing time to less than 300us. Moreover, with the 5G-NSA solution, the flexible design of EagleEYE and the updated drone navigation server we believe productivity can increase significantly. Therefore, an increase of at least 3x in productivity can be expected.
- **BR-ADS-UC1-04: Increase safety at 55% by using drones to inspect dangerous areas**
  With their small size and agile nature, drones can be used to perform aerial video surveillance of a dangerous area to shield the risk imposed to the rescue team personnel. With EagleStitch to provide a panorama view of the surrounding area, the response team can be informed of the current situation of the area to make an informed decision that ensures safety while doing the rescue mission. Apart from that, drone fleet navigation with multiple drones allows covering a wide area in the disaster relief area. This will defiantly reduce the risk of harming the response team. Therefore, an increase in staff safety by at least 55% can be expected.
- **BR-ADS-UC1-05: Decrease the time for the detection of risks to humans by 50%**
  Thanks to careful planning, quick and intelligent applications, and automation processes, the time to detect the risk is decreased significantly. In particular, thanks to the newly updated drone navigation server and the scalable design of object detection, where multiple drones can operate simultaneously. In addition, multiple PiH detection and localization features are used in the trials. With the aforementioned features, detection of PiH in multiple areas is possible. Therefore, a decrease of 50% in the time needed to detect risks to human can be expected.

As summary, Table 4-1 summarizes evaluation of the fulfilment of the business requirements.

TABLE 4-1: BUSINESS REQUIREMENTS ADS-UC1

| BR - ID | Description | Fulfilment |
|---|---|---|
| BR-ADS-UC1-01 | Reduce the data collection time by at least 50% | Fulfilled |
| BR-ADS-UC1-02 | Reduce the time of the staff hours by at least 50% to 90% | Fulfilled |
| BR-ADS-UC1-03 | Increase at 3X- 5X productivity | Fulfilled |
| BR-ADS-UC1-04 | Increase safety at 55% by using drones to inspect dangerous areas | Fulfilled |
| BR-ADS-UC1-05 | Decrease the time for the detection of risks to humans by 50% | Fulfilled |

### 4.3.4. Fulfilment of Functional Requirements

The fulfilment of the functional requirements previously described in D1.1 [5] are evaluated in the following.

- **FR-ADS-UC1-01: High bandwidth and low latency through 5G are required for on-time delivery of the information (i.e. sensory data such as images, GPS location, etc.) to the edge.**
  With the utilization of 5G network, more network bandwidth, as well as low latency communication is made available for the mission. Allowing for more drones to be supported during mission execution in the field. With an uplink of 99.1Mbps, as well as round-trip latency of 39.5ms. gNB/eNB, 5G UE, iMEC, EagleEYE, 5G EPC can be used to support a wide range of deployment models, use cases and 5G advanced services. In addition, they can promote the deployment of high-performance, openness, flexibility, secure and reliability private networks in an efficient manner to enable customers to carry out rapid 5G application transformation. The functional requirements are satisfied and ensure that ADS use case services are available, multi-connectivity system, accurate GPS, etc. With that, this requirement is considered fulfilled.
- **FR-ADS-UC1-02: High availability of the Drone connection including redundant connection to guarantee the communication in case of failure and Drone collision avoidance.**
  To provide for this functionality, the drone navigation server has been updated to allow for multiple drone control at the same console. This feature has been stress-tested in the second year of the project with up to 50 emulated drones. It has been shown that the system is capable of maintaining connection for all of the drones. In addition, we allow the DCAS to be enabled at the edge or at the fog using different connectivity modes for redundancy (Wi-Fi, or 5G NSA). With that, this requirement is considered fulfilled.

- **FR-ADS-UC1-03: Support programmability and virtualization (Native application if not possible) to enable flexible and dynamic reconfiguration.**
  EagleEYE is designed with microservices architecture in mind, allowing for flexible and dynamic reconfiguration during runtime. This feature is also demonstrated in the BASS integration phase, where a predefined descriptor of EagleEYE can be reconfigured in different configurations to suit for different mission. With that, this requirement is considered fulfilled.
- **FR-ADS-UC1-04: Support flexible deployment options of the core network (remote, local)**
  They 5G NSA setup follows the 3GPP EN-DC Option 3X procedures for the UE (a drone) to switch its connectivity to 5G when the signal is strong enough and otherwise fall back to 4G. Moreover, the traffic local breakout by iMEC can reduce end-to-end latency for the targeted services, such as EagleEYE, EagleStitch, and DCAS. With that, this requirement is considered fulfilled.
- **FR-ADS-UC1-05: Support different levels of accuracy of image recognition of Drone to cater for the different factors of distance, height, and all environmental conditions.**
  The Dual Object Detection module inside of EagleEYE system is responsible for the detection of ‘flag’ and ‘person’ object to make up the detection of a PiH. The object detection model itself is trained with various ‘flag’ and ‘person’ object in various environment and setting with varying distance and height to accommodate for this requirement. During the trial, this requirement is tested and validated as EagleEYE is able to detect PiH from the drone aerial surveillance footage taken from different angle and altitude. With that, this requirement is considered fulfilled.
- **FR-ADS-UC1-06: Support two-way communications between drones (Drone-to-Drone)**
  In case the drones can’t communicate with the edge due to signal quality or any other reasons, the drone-to-drone communication is available and can be used to relay information including communication, and sensory data back to the edge. DCAS can be deployed at the edge or at the fog. In case of the fog deployment, it is important to use the drone-to-drone communication. This has been tested in the first year successfully. With that, this requirement is considered fulfilled.

As a summary, Table 4-2 summarizes the evaluation of the fulfillment of the functional requirements.

TABLE 4-2: FUNCTIONAL REQUIREMENTS ADS-UC1

| FR - ID | Description | Fulfilment |
|---|---|---|
| FR-ADS-UC1-01 | High bandwidth and low latency through 5G are required for on-time delivery of the information (i.e. sensory data such as images, GPS location, etc.) to the edge. | Fulfilled |
| FR-ADS-UC1-02 | High availability of the Drone connection including redundant connection to guarantee the communication in case of failure and Drone collision avoidance. | Fulfilled |
| FR-ADS-UC1-03 | Support programmability and virtualization (Native application if not possible) to enable flexible and dynamic reconfiguration | Fulfilled |
| FR-ADS-UC1-04 | Support flexible deployment options of the core network (remote, local) | Fulfilled |
| FR-ADS-UC1-05 | Support different levels of accuracy of image recognition of Drone to cater for the different factors of distance, height, and all environmental conditions. | Fulfilled |
| FR-ADS-UC1-06 | Support two-way communications between drones (Drone-to-Drone) | Fulfilled |

### 4.3.5. Fulfillment of Technical Requirements

The fulfillment of the technical requirements previously described in D1.1 [5] are evaluated in the following.

- **TR-ADS-UC1-01: Uplink data rate (Drone to Network)**
  In the trial, iperf3[11] is installed on both a drone and a server running on iMEC. Iperf3 generates a testing TCP flow from the drone to the server for measuring the uplink rate. 99.1Mbps is recorded and has been shown to be sufficient to support for the operation of multiple drones in the publishing of video data and sensory data in a disaster response mission. With this, this requirement has been fulfilled.
- **TR-ADS-UC1-02: Downlink data rate (Network to Drone)**
  In the trial, a testing TCP is transmitted from the server to drone. The downlink rate of 177Mbps is recorded and has been shown to be sufficient to support the data transmission for drone navigation server commands for drone control. With this, this requirement has been fulfilled.
- **TR-ADS-UC1-03: Uplink Latency (Drone to Network)**
  In the trial, Wireshark[12] is installed on the drone and the server used in TR-ADS-UC1-01. Both devices had synchronized to a public Network Time Protocol (NTP) server. We opened a terminal on the drone, and then emit a ping request to the server. The time duration between the ping request shown on Wireshark log of the drone and the server is taken as uplink latency. 20ms is recorded and has been shown to provide real-time transmission of data. With this, this requirement has been fulfilled. This is crucial for real-time execution of the services in particular EagleEYE, DCAS in performing the disaster relief mission. With this, this requirement has been fulfilled.
- **TR-ADS-UC1-04: Downlink latency (Network to Drone)**
  Continuing the ping test performed in TR-ADS-UC1-03, the time duration between the ping response shown on Wireshark log of the server and the drone is taken as downlink latency. 19.5ms is recorded and has been shown to provide real-time transmission of data. With this, this requirement has been fulfilled. The smaller downlink latency can be considered that less retransmission happened on MAC layer because the radio power is stronger on downlink direction than the power on uplink direction. This is crucial for real-time execution of the services in particular EagleEYE, DCAS in performing the disaster relief mission. With this, this requirement has been fulfilled.
- **TR-ADS-UC1-05: Positioning accuracy**
  During trial, positioning accuracy of 1.5 meter has been recorded. Different positioning mechanism has also been tested to improve the accuracy as reported in D1.1 [5] Appendix B. Also, the Real-Time Kinematic (RTK) is adapted as a reference point. This can be very helpful especially if the mission is located near a blocking building. With this, the requirement has been fulfilled.

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[11] iPerf - The TCP, UDP and SCTP network bandwidth measurement tool, https://iperf.fr/
[12] Wireshark · Go Deep., https://www.wireshark.org/

- **TR-ADS-UC1-06: Altitude**
  During the trial, the drone has been tested to fly at up to 30m of altitude. This attitude is good enough to cover the entirety of a high-rise building and perform a disaster relief mission. With this, this requirement has been fulfilled.
- **TR-ADS-UC1-07: UE Speed**
  During the trial, the drone has been tested to fly at a speed of 5m/s. This speed provides a good balance between speed, while also maintaining the camera focus of the drone and still having sharp images. With this, the requirement has been fulfilled.
- **TR-ADS-UC1-08: Number of UEs**
  During the trial, 3 drones have been tested to fly simultaneously in the disaster relief mission. With 3 drones, we can cover a large area and make the disaster relief response more efficient. Emulation with 50 drones simultaneously running has also been done successfully. With this, the requirement has been fulfilled.
- **TR-ADS-UC1-09: Image Quality**
  In the trial, the drone surveillance footage is captured and streamed to the edge at Full HD 1920 x 1080 resolution. This resolution provides a good balance between image fidelity as well as network bandwidth consumption for supporting multiple drones. With that, this requirement is considered fulfilled.
- **TR-ADS-UC1-10: Service Reliability**
  The disaster relief response system used in ADS-UC1 and ADS-UC2 has also been tested in a 2-hour long disaster relief mission simulation to test for service reliability. During the whole test duration, the system is confirmed to be able to provide a disaster relief response service. In general, disaster relief response missions will only last around 20 minutes due to the limitation in drone battery capacity. In the case where a longer mission happens, the disaster relief response system will be able to keep running and provide service. In case one of the drone fleets faces low battery, we consider the drone swapping mechanism while using DCAS (providing the shortest path). This has been described in detail in D3.3 [3] . Also, the drone navigation server is able to support multiple drones for different missions without any issues, the stress test results have proven it. With that, this requirement is considered fulfilled.

Table 4-3 summarizes the evaluation of the fulfillment of the technical requirements.

TABLE 4-3: TECHNICAL REQUIREMENTS ADS-UC1/ADS-UC2

| TR - ID | Description | Value | Validation |
|---|---|---|---|
| TR-ADS-UC1-01 | Uplink data rate (Drone to Network) | 50 Mbps | ✓ 99.1Mbps |
| TR-ADS-UC1-02 | Downlink data rate (Network Drone) | 150 Mbps | ✓ 177Mbps |
| TR-ADS-UC1-03 | Uplink Latency (Drone to Network) | 100ms | ✓ 20ms |
| TR-ADS-UC1-04 | Downlink latency (Network to Drone) | 20ms | ✓ 19.5ms |
| TR-ADS-UC1-05 | Positioning accuracy | 10m | ✓ Tested and around 1.5m |
| TR-ADS-UC1-06 | Altitude | 15m to 100m | ✓ 30m |
| TR-ADS-UC1-07 | UE speed | 0 to 10m/s | ✓ Tested up to 5m/s |
| TR-ADS-UC1-08 | Number of UEs | 3 to 5 | ✓ 3 drones/UEs |
| TR-ADS-UC1-09 | Image quality | 1080p | ✓ 1080p |
| TR-ADS-UC1-10 | Service reliability | 99.99% | ✓ Tested up to 2hours |

## 4.4. Future Direction

In the future, we believe the integration of IDrOS will add special benefits for drone fleet missions in ADS-UC1. For example, DCAS can utilize the IDrOS to migrate its services in real-time from fog to edge. Also, other applications can be migrated from edge to drone. This process can be fully automated using the BASS platform. As for ADS-UC2, first, further development into the scalability of the ADS-UC2 intelligent application, specifically for EagleEYE is underway. In D3.3 [3] , an updated architecture design of EagleEYE that supports scalability is presented. Initial internal testing shows that the updated architecture can handle multiple concurrent drone streams. Second, the integration with the BASS monitoring feature as well as SLA Enforcement, with which horizontal/vertical scaling of EagleEYE can be automated. This feature will allow EagleEYE to support the processing of more drone streams. Third, the full integration with IESS for enhanced functionality in terms of automatic AI model training.

# 5. Conclusion on 5G-DIVE

5G-DIVE aims to enhance the management and automation of business processes by adopting data analysis and Artificial Intelligence running on top of the evolved 5G-CORAL platform, which is for edge and fog computing. This concept materialized in a new building block called 5G-DIVE Elastic Edge Platform (DEEP).

Two vertical pilots: (i) Industry 4.0 and (ii) Autonomous Drone Scout are built and examined to show the technical merits and business value proposition of 5G technologies.

For I4.0, the use case Digital Twin shows the capability of real time control. The second use case proves automatic detection of defects in production lines can be benefited by adopting AI/ML algorithms with the help of edge/fog computing. The third use case, mMTC, shows the feasibility and flexibility of softwarized protocol stacks in the IoT domain.

For Autonomous Drone Scout, the first use case, the drone fleet navigation has been validated with three drones' trial, DCAS is running at the fog and the edge. Besides, the newly updated drone navigation server is stress tested with 50 emulated drones. The second use case presents the detection and localization of PiH with EagleEYE, as well as 2D panorama stitching of disaster impacted area with EagleStitch. In the ADS use case, 5G connectivity solution, AI/ML techniques, the DEEP platform, as well as the edge/fog infrastructure are utilized to provide for a complete end-to-end disaster relief response solution. Apart from that, we have validated that the ADS use case fulfills the business, functional, technical requirements.

This deliverable has focused on and answered the key questions defined in the proposal phase. Base on the assessment on DEEP platform, as well as the systems that integrate DEEP and vertical-specified applications for each use cases, the majority of the requirements set up in D1.1 [5] have been fulfilled. Thus, we can conclude that the 5G connectivity and the developed DEEP platform very well satisfy the need of the trials.

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