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INTRODUCTION TO THE 5G-HEART PROJECT

The Horizon 2020 project 5G-HEART (5G HEalth AquacultuRe and Transport validation trials) developed and executed large scale healthcare, transport and aquaculture vertical trials on top five European 5G test facilities. It focused on realising 5G trials and validating 5G Key Performance Indicators (KPIs) using vital use cases from the targeted vertical domains. The project experimented with eMBB, URLLC and mMTC services in different setting as illustrated in the figure below. 5G-HEART labelled each use case with an H, T, or A prefix for healthcare, transport, and aquaculture verticals, respectively.

In healthcare, we have selected three major use cases for e-health which will challenge the performance and availability of 5G services. All the use cases share a common vision of remote care or “hospitals without walls”: Use case H1: Remote interventional support, Use case H2: Automatic pill camera anomaly detection, and Use case H3: Vital-sign patches with advanced geo-location.

In transport, we have focused on various advanced use cases with enhanced wireless connectivity and increased automation, paving the way to fully connected mobility and autonomous driving: Use case T1: Platooning, Use case T2: Autonomous/assisted driving, Use case T3: Support for remote driving, and Use case T4: Vehicle data services.
In aquaculture, the one main use case have been trialled on top of two test facilities. One of the trial site was located in Greece and the other one in Norway. The main aquaculture use case was called: Use case A1: Remote monitoring of water and fish quality.

<table>
<thead>
<tr>
<th>Project call</th>
<th>ICT-19-2019: Advanced 5G validation trials across multiple vertical industries</th>
</tr>
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<td>Project number</td>
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</tr>
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<td>Action type</td>
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<td>Project duration</td>
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<td>Project team</td>
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<tr>
<td>Project website</td>
<td><a href="http://www.5gheart.org">www.5gheart.org</a></td>
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**Project partners:**

VTT  TELENOR  ICOM  OTE  SKIRONIS  MI  REDZINC  TUC  DYNNIQ  WINGS  TNO  SEALAB  ACTA  OUS  ERICSSON  CEA  NTUA  EPI  UOS  POLAR  PHILIPS  OCC
HEALTHCARE VERTICAL TRIALS

This section provides an overview of the healthcare vertical trials of the 5G-HEART project. E-health is identified as a priority in the European digital agenda, but it puts strict requirements on ICT in terms of latency, reliability, bandwidth, security, and mobility. On this backdrop, 5G and healthcare is a good match, since 5G can provide essential levels of connectivity to enable a new health system. It could also transform and improve all critical components of healthcare. 5G can support the transformation of the healthcare sector from volume-based to value-based care and is essential to build the “digital base” in healthcare by providing network security and data privacy, which are paramount for healthcare.

The healthcare vertical trials in the 5G-HEART project are structured under three high-level use cases divided into nine subcases. The H1 “Remote Interventional support” focuses on using remote assisted or controlled ultrasound, advanced video, and augmented reality in different clinical situations. The subcases of this use case comprise “Educational surgery”, “Remote ultrasound examination – Congenital heart disease”, “Remote ultrasound examination – Robotics”, “Paramedic support”, and “Critical health event”. The H2 “Automatic pill camera anomaly detection”, comprise one subcase focused on developing a colon wireless capsule endoscopy system with automatic polyp detection for early detection of colon cancer with high mortality. The H3 “Vital-sign patches with advanced geolocation” focuses on the development of a prototype single-use vital-sign patch and accurate geo-location technology. It includes the subcases “Vital-sign patch prototype”, “Localizable tag”, and “Aquaculture remote health monitoring”.

The overarching vision of the healthcare use cases is to investigate how to realize a “Hospital without walls”, using 5G technology. The healthcare vertical trial use cases cover almost all situations in healthcare delivery both in- and outside the hospital as shown below:

The presented trials have been conducted in four locations utilizing the 5G-VINNI (Oslo, Norway), 5G-EVE (Athens, Greece), 5GTN (Oulu, Finland) and 5Groningen (Groningen, Netherlands). Some trials have also been conducted by using commercial 4G and 5G in Norway and the Netherlands, and by utilizing a LPWA test network in Grenoble, France.
The presented trials have been conducted in four locations utilizing the 5G-VINNI (Oslo, Norway), 5G-EVE (Athens, Greece), 5GTN (Oulu, Finland) and 5Groningen (Groningen, Netherlands). Some trials have also been conducted by using commercial 4G and 5G in Norway and the Netherlands, and by utilizing a LPWA test network in Grenoble, France.
H1A – EDUCATIONAL SURGERY
Involved partners: VTT (Lead partner), REDZINC, OULU UNIVERSITY

Introduction
Advanced 5G technology with real-time video can extend in-hospital coverage and enable faster reaction times. It can be used for primary treatment, novel and safer ways for consulting and education. We studied the feasibility of using 5G in educational surgery using advanced mobile video solutions.

Medical education requires demonstration of medical procedures to students. Normally, students need to visit the hospital premises to get this specialized training. The presence of many students in-hospital premises has associated costs and presents many challenges such as overcrowding in small hospital rooms, inconvenience to the patients/hospital staff, contagion risk and others. Virtual demonstration of medical procedures to remote students via real-time video offers to address these challenges along with other added benefits.

The usage of dedicated cameras can introduce more freedom both from the user’s as well as from the viewer’s perspective. The use of 360° camera setup with additional more focused single lens cameras enable improved depth of field. Wearable video camera solution enables seeing the medical procedures step-by-step through the operator’s eyes. These camera technologies combined with the fast 5G capability can provide significant advantage in terms of response times for the live streaming utilisation for educational purposes.

Objectives
The objectives for this use case include:

- Application- and network level testing the feasibility of 360, single lens cameras, and wearable camera technology in remote education utilising live streaming;
- Testing and verification the benefits of 5G in live low latency streaming using VTT's 5G Test Network;
- Piloting the use case in real hospital environment

Key results
RedZinc Services collaborated with VTT and Oulu University Hospital to test if RedZinc’s BlueEye wearable video technology can support in delivering the medical demonstrations to remote students via video.
The BlueEye wearable video platform consists of a lightweight wearable camera (worn around the educator’s head for point-of-view video) integrated with a secure cloud-based video platform. Two-way audio transmission means the students can interact with the educator and fellow students.

Oulu University Hospital used wearable video in the pilot to train remote paediatrics students using live video. The remote students were able to attend the tutorials from home and were able to see the medical procedure from the trainer’s point of view giving an optimum view of the procedure. This view is not even possible in the face-to-face training, as the student would have to look over the shoulder of the educator.

BlueEye wearable video ensured the medical tutorials were delivered to the students despite COVID restrictions. In a survey conducted by Oulu University Hospital post the pilot, 89% of the 26 respondents agreed that BlueEye wearable video can be used for teaching or training that would otherwise not be possible and 82% of the 27 respondents felt that BlueEye wearable video could replace traditional face-to-face teaching wholly or partly.

VTT deployed the research-oriented experiments with the 360- and multicamera setup with extensive evaluation in the 5G laboratory using low latency streaming techniques. The evaluation focused on assessing mobile (4G, 5G) uplink capacity in terms of delay and throughput in relation to experienced end-to-end latency.
According to the evaluation results published in several publications, 5G can reduce the network delay at the level of 5-15ms in steady throughput scenarios. It was noticed that high network congestion increases the delay, but use of proper network configuration and video adaption techniques can maintain the experienced E2E latency at desired level.
H1B – REMOTE GUIDED/CONTROLLED ULTRASOUND OF THE HEART

Involved partners: PHILIPS (Lead partner), OUS, TELENOR

Introduction

Ultrasound examination of the heart is a complex task, demanding substantial experience from the healthcare professional to correctly perform and interpret the examination. In smaller healthcare centres, the availability of these trained and experienced healthcare professionals is scarce, especially outside of daytime. Neonates with signs and symptoms warranting ultrasound examination of the heart, are born in healthcare centres across the globe at a steady pace. This creates the problem of meeting the demand for ultrasound examinations of the heart, compared to the supply of healthcare workers competent of properly performing the examination.

With this background we sought to assess remotely guided ultrasound of the heart, over the cellular network, where an expert in cardiac ultrasound can sit in one geographical location and give an experienced opinion to a colleague examining a patient elsewhere (see figure below). In addition, a tele-operated robotic system using master-slave configuration to perform ultrasound examinations of the heart in a similar setting was developed with the remote expert sonographer manipulating the robot via 5G connection.

Objectives

The main aim of the trials was to evaluate the usability of remote guidance of novice or relatively inexperienced sonographers to perform ultrasound examination of the heart. To do this we designed two different studies.

1. Remote guidance of novice medical students to perform a simple ultrasound examination on healthy volunteers compared with manual, gold standard, examination. Examination time, image quality, ability to assess important cardiac structures and the precision of measurements of cardiac function are the parameters investigated.
2. Remote guidance of healthcare professionals without experience in congenital heart defects to examine neonates with possible critical congenital heart defects. With remote guidance by a paediatric cardiologist, the remote guidance team is to figure out if the neonate in question has a heart defect which necessitates transfer to a tertiary paediatric surgery centre. The conclusion of the remote guidance team is then compared to the plan of the responsible paediatric cardiologists after preceding gold standard ultrasound examination.

In addition to these clinical studies, the possibilities for future enhancements of the remote collaboration solution have been explored in Eindhoven through incorporation of AR and 3D capturing, to show ultrasound images and spatial probe positioning.

Another objective was to develop a tele-operated robotic system for remote-controlled ultrasound examination of the heart. To evaluate the success of this project we used the robot to examine 23 healthy volunteers and compared the “diagnostic usability”, quality and precision of measurements from the images to manual, gold standard examination.

**Key results**

**Remote guided ultrasound of the heart**

Study 1: The examination time from the remote guidance was on average 6.1 times longer than the reference examination. The image quality was significantly lower in the student examination compared to the reference examination, 2.37 vs 1.62 on a scale of graded image quality where 0 is “unusable”, 1 is “low”, 2 is “medium” and 3 is “good quality”. Of the images 30% were graded as of low or unusable quality and 30% of the cardiac structures were deemed not assessable (see figure below).
The measurements of cardiac function did not show any systematic errors compared to the gold standard, but showed a considerable variation coefficient of around 15%, outside clinical adequacy. The results of the remote guidance of medical students performing ultrasound examination of the heart for the first time, seemed to point to the direction that it could not be appropriately used in clinical working life. Remote guidance seemed to be very well suited for educational purposes and further studies should be performed to further illuminate the possibilities.

Study 2: So far 15 neonates have been included, where six were in need for transfer to a paediatric heart surgery centre. All six of these were identified in the remote guided examinations. Out of the rest, only one neonate was incorrectly proposed for transfer and the remaining eight neonates were correctly identified as not in need of transfer. On the examining end, there were anaesthesiologists, adult cardiologists, resident doctors of paediatrics and adult cardiology. The sample size is too small to make significant conclusions, but from our experience this method is definitely worth further exploration and academic work.

AR and 3D visualisation: The enhancement with 3D telepresence for heads-up display of ultrasound images or for a more spatial accuracy when guiding positioning of the probe to acquire good quality ultrasound images is well appreciated as a concept, however technically not mature enough to really meet usability expectations and requirements. The required network KPIs are far beyond the capabilities of the currently available 5G facilities.

Remote-controlled ultrasound of the heart

The robot used is a collaborative, industrially available robot from Universal Robots, of model UR5. It is controlled with a haptic device, from SensAble technologies, model: Phantom Omni. There is a force-torque sensor mounted on the robot, enabling haptic force feedback to the controller. The ambient video is relayed by to webcams showing the position of the robot end-effector, where the ultrasound probe is mounted, relative to the healthy volunteer’s body, laying on a bench. See Images 1 and 2.
The ultrasound examination was made up of a simplified but comprehensive imaging of the left heart side. The robotic examination lasted for 26.4 minutes on average and was 1.92 times longer than the reference exam. There was a significant difference in rated image quality, where the reference reached a mean value of 2.5 and the robotic examination 1.5 on a predefined scale where grade 0 was “unusable quality”, 1 was “low quality”, 2 was “medium quality” and 3 was “good quality” (see figure below).

A total of 12% of images made by robot examination was rated as of low or unusable quality, compared to 1% in the reference examination. The amount of important cardiac structures deemed unassessible was 22% in the robotic examinations and 5% in the reference.
The measurements of heart function showed measurements made by robot to be approximately 10% lower than the reference and with 17% variation coefficient, which is considered outside clinical adequacy.

These preliminary tests show that the precision of robotic examinations cannot quite measure up to reference, gold standard examination, but is in no means useless and highly hypothesis generating and stimulates further research and development.
H1C – PARAMEDIC SUPPORT

Involved partners: TNO (Lead partner), REDZINC, AMBULANCEZORG GRONINGEN

Introduction

Ambulance services are striving towards healthcare with higher quality and possibly better cost-effectiveness. Increasingly more and more ambulance services wish to improve pre-hospital triage, and for this purpose it is important to make correct and timely decisions in emergencies.

The Chief Medical Officer (CMO) of an ambulance service may be remotely consulted for decision-making in rare or difficult emergency situations. At present, this is only possible via an audio connection (telephone) or through a dedicated communication channel via the dispatcher. The CMO has thus no visual feed of the patient information for more effective assessment. Therefore, the ambulance crew often makes conservative decisions (over-triage), propagating the risk and confidence in diagnosis/treatment to the emergency department. This results in a high percentage of cases that are brought to hospital while treatment in situ would suffice, resulting in lower availability of emergency services for more acute cases as well as unnecessary costs and burden on the healthcare system.

If a paramedic can use wearable video/audio and share a patient’s vital parameters or even ultrasound images, the remote CMO can see the same patient context that the paramedic sees, help accelerate diagnosis and improve decision-making. This will lead to accelerated patient treatment, improved outcomes, reduced travel, cost savings and higher efficiencies.

Objectives

The objectives of this study include:

- Application-level testing and verification to test and verify how usable remote video services are for use by ambulance professionals;
- Testing and verification of how well 5G may deliver video traffic;
- Testing and verification of how 5G network slicing may guarantee radio network resource for the delivery of video traffic in co-existence with other competing traffic.
Key results

It was verified that the decision making was quicker and more accurate when the remotely based Chief Medical Officer of an ambulance service received real-time video-audio complimented with vital patient data (for example electrocardiogram) from the paramedic. This meant that the pre-hospital triage significantly improved accelerating patient treatment and avoiding unnecessary conveyance to the hospital.

While the video quality from the camera headset was deemed be sufficient in general for the trialed scenario cases, snapshots with a higher resolution allowed the CMO to have a sharper image of the patient, particularly the points of interest.

Recommendations are also given addressing the observed implementation constraints in the perspectives of camera headset position, camera headset microphone and background noise cancellation.
The study has further validated the role of 5G in enabling the use of real-time video communication between the paramedic and the remote CMO, both in (more or less) ideal (with an indoor 5G SA network, with little competing mobile traffic) and more practical conditions (with an outdoor 5G SA network, on-move, with significant competing mobile traffic). The study has also shown that 5G network slicing is able to guarantee sufficient radio resource for the delivery of video-audio streams and vital data of the ambulance service.
H1D – URBAN SEARCH AND RESCUE
Involved partners: REDZINC (Lead partner), OUS, TELENOR

Introduction
As a part of the 5G-HEART project, RedZinc collaborated with Oslo University Hospital to evaluate if wearable video can improve decision-making and outcomes in Urban Search and Rescue (USAR) scenarios.

RedZinc provided BlueEye wearable video solution and Oslo University Hospital conducted a pilot with the paramedics especially trained in USAR. During the pilot, Telenor’s 4G commercial network was used for internet connectivity in Oslo.

Objectives
RedZinc’s BlueEye wearable video transmits real-time point of view video to remote locations. It is used for training, support and collegial work. BlueEye wearable video platform consists of a lightweight wearable camera integrated with a secure cloud-based video platform. An in-field searcher or technician needing support wears the BlueEye camera near their eye and starts video streaming via the BlueEye app in the attached smartphone. A remote incident commander or expert, logs in to the secure BlueEye hot desk to access live video with first-person perspective.

Oslo University Hospital used BlueEye Wearable Video to support paramedics playing the roles of searchers and technicians with remote Incident Commanders. The incident commander can see the situation through the searcher’s eyes and can interact with the searcher. The live point-of-view video enables the remote commander to immerse themselves in the situation. As a result, the remote commander can supervise and support the searcher with improved decision making.
Key results

The trials show that searcher support from the remote commander using wearable video, improves decision-making. It also increases team confidence, avoids travel by the incident commander and leads to improved outcomes in critical health events. Wearable Video can also be used to collaborate with and get support from other Emergency Services such as Ambulance, Fire brigade and Police.

The two-day pilot including 12 runs suggested that wearable video improved situational awareness of the remote commanders and helped them to immerse themselves into the situation. The remote commanders were able to instruct and guide the in-field searchers and technicians, resulting in enhanced decision making and increased team confidence.

The remote commanders appreciated the video quality that they received via BlueEye and rated the video quality as ‘good’.

Here are some of the comments from the users of the BlueEye video technology:

“The use of video is the future. I was able to comprehend the situation from home”
- Incident Commander, Oslo University Hospital

“This is perfect for achieving situational awareness”
- Incident Commander, Oslo University Hospital


H2A – AUTOMATIC PILL CAMERA ANOMALY DETECTION

Involved partners: OUS (Lead partner), TELENOR

Introduction

Colon cancer, which is mostly developed from polyps, is the second most common cause of cancer mortality. Early detection and removal of polyps in the colon is crucial for prevention.

As the most sensitive method for early detection of precancerous pathology, colonoscopy is time-intensive and can only be performed by specialised physicians, making the method suboptimal for a population screening program. There is a strong need for a cost and time-effective, accurate screening method, so that the colonoscopy expertise may be utilised for interventional procedures such as polypectomy and tissue sampling.

Capsule endoscopy (Pill Camera or Pillcam) has been available for small bowel visualisation for more than a decade. Recently, a colon capsule has been introduced for selective colon visualisation. Using post-processing algorithms that make real-time automatic polyp detection possible, one can modify momentarily the operative parameters of PillCam, such as frame rate or lighting spectrum to improve the diagnosis and save battery for the entire session. Such post processing algorithms are computationally expensive, but it can be executed in the Cloud or on the Edge.

5G enables real-time usage of such computing resources, and it can be the key for the creation of an effective infrastructure that can automatically transmit videos from the pill camera to a secure cloud where an AI-based detection algorithm performs real-time detection and provides feedback to the pill camera to optimise image capturing.

Objectives

The objectives of this study include:

- To develop PHY1 for human body backscatter communication at 433 MHz.
- To develop an AI-based real-time polyp detection algorithm.
- To establish a bridge via a 5G network connecting the PillCam and an Edge computing power where the AI-based algorithm is located.
- To measure end-to-end latency for video streaming over the 5G network from the PillCam to the Edge including the processing time required by the AI-based algorithm per frame.
An in-house backscatter radio system was developed to support the high data rate system up to 16 Mbps. The backscatter reader is a quite complicated subsystem with controlling units for antennas, received signal sensing, RF power controlling, coupling reduction circuits, etc. The system was working at 434 MHz, where only a tone signal emission was the radiation in the environment and the data signal level was below the spectral limits that couldn’t be detected in a couple of centimeters from the body surface. The system supports up-to 6 transmitters and 6 receivers antennas in total 12 antennas that can be selected by an RF switch and using the communication protocol of the system. The figure above shows the array antenna configuration on the body worn. The output of the backscatter system can be arranged to be connected to an in-house FPGA based system to stream the data via UDP or TCP protocols.

The following table demonstrates the performance of three transmission protocols used for video streaming. The RTP is a UDP protocol which is connectionless. RTP was the fastest with end-to-end latency of 46.74 ms.

<table>
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<tr>
<th>Protocols</th>
<th>Latency [ms]</th>
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<tr>
<td>UDP-RTP</td>
<td>46.74</td>
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<tr>
<td>TCP-RTSP</td>
<td>466.48</td>
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<tr>
<td>TCP-HTTP</td>
<td>240.16</td>
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</table>

When we used the HTTP for the video stream. We experienced a latency delay of ~200 ms. HTTP is a TCP protocol which is connection-oriented. It is noteworthy to mention that the End-to-End latency also includes the processing time required by the AI-based detection model per frame which was measured to be 10 ms on NVIDIA RTX 3090.

Key results

The following figure shows the overall setup to investigate the feasibility of video streaming over a 5G network from a PillCam, receive and analyse the streamed video at the Edge, and provide feedback to the PillCam, all with acceptable latency.
The following figure presents our proposed method to detect polyps in a one-shot manner. The method is developed based on a 2D CNN encoder-decoder network.

The figure below shows sensitivity and precision measurement of the proposed method for all four scenarios. When the current frame is examined alone, AlbuNet34 can provide high sensitivity (91.27%) but struggles to offer the same level of performance for precision (67.21%) due to the generation of a substantial number of FPs. When extracted features from the first previous frame are concatenated with the extracted features of the current frame, the model enjoyed a 1.5% sensitivity increase while the increase in precision is as high as 21.4%. This result indicates that integrating information from one previous frame can benefit the model to increase both measures by slightly increasing the number of TPs and eliminating a large number of FPs.
H3A – VITAL-SIGNS PATCH
Involved partners: PHILIPS (Lead partner)

Introduction

A Direct-to-Cloud (D2C), vital-signs patch is a smart band-aid that measures a patient’s vital-signs 24/7 and communicates these directly through the cellular network. This way doctors can keep a tab on their patients, no matter where they are, potentially supported by AI algorithms running in the cloud.

Devices today use Wi-Fi or Bluetooth requiring a gateway box or mobile phone to forward their data to the cloud. Setting this up is complex for a patient, leading to errors and consequently a lack of treatment compliance. Direct-to-Cloud communication through the cellular network avoids these errors. It works out-of-the-box and takes the gateway or mobile phone out of the equation, enabling ubiquitous connectivity, anytime and anywhere.

One potential application is post-surgery monitoring. Patients are monitored on the general ward and, subsequently, when they return to the comfort of their own home. This will improve outcomes and patient experience, and it will lower the cost of care due to shortened – or even avoided – hospital stays.

Objectives

The key objective was to assess the feasibility of the D2C vital-signs patch concept, addressing the key challenges of battery life and coverage. Particularly, different RATs (LTE-M and NB-IoT), IETF protocols and protocol options were explored to assess their impact on these two inter-dependent KPIs (i.e., energy usage and coverage).

Rigorous energy measurements were conducted on life commercial LTE-M and NB-IoT networks, using an in-house developed test framework.
Repetitive measurements can be performed automatically, while varying RATs, protocols, protocol options, and attenuation (to simulate poorer coverage). Detailed power traces are obtained to understand energy usage and its breakdown into several phases.

Key results

Selection and optimization of upload protocols

A vital-signs patch connecting directly to the cloud via LTE-M has been shown to be feasible, even when using HTTPS / OAuth 2.0, a relatively inefficient cloud-native protocol. As the vital-signs payload to be sent can be as small as 150 bytes, energy usage is dominated by connection setup: network attach at the cellular layer, followed secure IP connection setup (e.g., OAuth 2.0 authentication and TLS handshake).

Several opportunities to reduce that overhead have been identified and many of them have been explored experimentally. Specifically, an extended OAuth 2.0 token lifetime and the use of TLS session resumption are very helpful in extending battery life, while realizable within the context of contemporary cloud service offerings. Beyond that, developments like TLS 1.3, CoAP over DTLS and QUIC might offer further improvements, if and when they will be adopted by both cloud and modem vendors.
The opportunities for energy improvements at the cellular layer (i.e., attach) are more limited. However, once RAI for LTE-M gets deployed by MNOs and modem vendors alike some improvements can be expected.

**Addressing coverage concerns**

Although LTE-M promises a significant coverage enhancement over plain LTE, its deepest mode of coverage – CE Mode B – is optional and not supported by most operators. In addition, antenna performance for a tiny, body-worn device is lower than that of a phone. Therefore, coverage is not better than that of a phone, possibly worse.

Considering that for NB-IoT all coverage enhancement modes (CE0, CE1 and CE2) are mandatory, a 15-20 dB coverage enhancement was expected relative to typical LTE-M deployments. However, this improvement would come at the expense of severely limited bandwidth, not allowing for cloud-native protocols.

Experiments have been conducted comparing LTE-M using HTTPS / OAuth 2.0 to NB-IoT using a very simple and efficient upload protocol. These have shown that a gain of about 10.5 dB is possible of which 4 dB can be attributed to the simplified protocol and 6.5 dB to the RAT. The gap between expectation and results is probably a consequence of MNO deployment decisions.
H3B – LOCALIZABLE TAG
Involved partners: CEA (Lead partner)

Introduction
Wearable health monitoring has emerged as an effective way for improving the quality of life of the patient, as it provides seamless remote diagnoses and monitoring. The project objective is to evaluate the feasibility of a reliable and low cost, low power localisation technique to complement the cloud connectivity of Vital-patch Prototype (H3A use case). The research work hence focuses on providing a lightweight and accurate radio-localisation feature on wearable health monitoring patches without embedded stringent power consumption GNSS modules.

Objectives
The purpose of the field trials is to validate the narrowband radio-localization approach with real signals and in a realistic environment (outdoor/indoor, rural/urban). The field test plan is articulated in three phases:

1. Lab experimentations: Validation of a hardware platform based on RF and digital COTS.
2. Preliminary tests on CEA campus: Performance assessment of an intermediate version of the narrowband LPWA location algorithm over the air in a more realistic environment.
Key results

Lab experimentations and Preliminary tests on CEA campus

A coherent Multi Frequency-Phase Difference of Arrival solution (MF-PDoA) has been evaluated in the context of a NB-IoT evolution.

Performances (compared with classical Time Difference of Arrival (TDoA)) show that for an SNR of 10dB, the standard deviation error of MF-PDoA is equal to approximately 2m while the standard deviation error of TDoA is equal to 150m. A floor performance behaviour is observed when the synchronization between receivers is relaxed. The TDoA performance is much worse than MF-PDoA (i.e., larger than 120m) than the error due to time synchronization (i.e., 21m).

Field trials on the CEA campus complete the performance results where the performance gain of the new technique was achieved. In an outdoor environment, 30m accuracy was measured under multipath propagation environment (NLOS) with the new technique in comparison to 250m using SoTA ToF approaches.
Advanced field tests in the city of Grenoble

Field tests in the city of Grenoble (urban and particular strong multipath environment) have been conducted in order to be able to predict, evaluate, the location algorithms accuracy. For these tests, a proprietary network infrastructure composed of 6 LPWA Base Stations has been deployed around the city.

During the field trials, radio metrics (SNR, RSSI, TOA) has been collected via crowd sourcing. The measurement database (more than 1.8 million samples) has been exploited in conjunction with a priori know LOS/NLOS propagation statistics to predict a Localization Accuracy Map (LAM).

The accuracy prediction has been computed through the Cramer Rao Lower Bound (CRLB) and compared with experimental field trials measurement for different propagation conditions (LOS, NLOS, base station position). One can verify a very good match between the CRLB and the Maximum Likelihood Estimation (MLE) errors with only 12% of difference regarding the P68 metric and very similar CDF, which is the main purpose of this study.
During the field trials, radio metrics (SNR, RSSI, TOA) has been collected via crowd sourcing. The measurement database (more than 1.8 million samples) has been exploited in conjunction with a priori know LOS/NLOS propagation statistics to predict a Localization Accuracy Map (LAM). The accuracy prediction has been computed through the Cramer Rao Lower Bound (CRLB) and compared with experimental field trials measurement for different propagation conditions (LOS, NLOS, base station position). One can verify a very good match between the CRLB and the Maximum Likelihood Estimation (MLE) errors with only 12% of difference regarding the P68 metric and very similar CDF, which is the main purpose of this study.

Such conclusion permits to compute LAM in order to be able to predict tag localization accuracy as well as its position. As expected, the convex hull formed by the base stations corresponds to the best accuracy area, whereas the precision degrades out of this zone. According to this map, the positioning error should not exceed 300m in the analysis zone that can be verified.
H3C – AQUACULTURE REMOTE HEALTH MONITORING

Involved partners: WINGS (Lead partner)

Introduction

Health status and safety of workers within the aquaculture industry, particularly in low- and middle-income countries (LMICs), has not been given due importance to date. Farm hands and other workers in aquaculture are susceptible to many occupational diseases and injuries in the course of their work. Especially in Greece, where marine aquaculture ranks first in the aquaculture sector, the workplace hazards to which aquaculture workers are exposed, should be mitigated.

The WINGS remote health monitoring system aims at providing real-time monitoring and constant situational awareness of the health status of the workers and/or vulnerable people in remote locations, such as aquaculture sites.

Objectives

The Aquaculture Remote Health Monitoring solution (an instantiation of the WINGS STARLIT remote health monitoring system) comprises: a) Wearable devices for heart rate, oxygen saturation (SpO2) and sinus rhythm monitoring (ECG) and Smart Glasses, b) intelligence for identification of current issues, forecasting of future issues and health emergencies and notification, and c) a dashboard for providing the health care professionals with visualization of health monitoring data, notifications and alerts. Aquaculture workers are equipped with the wearable devices. Supervisors of the aquaculture area and/or professional caretakers are equipped with smart glasses to remotely obtain a view of the workers if necessary and provide additional insights to the professional caregivers /medical experts. They are: a) informed of the workers status, b) alerted if the system identifies any abnormality in usual patterns of oxygen saturation or forecasts time periods with increased risk and c) facilitated in their work due to the automated decision making and the videocalls (from the dashboard and through the smart glasses) with the subjects, as well as the forecasting and visualization techniques.
Key results

Testing has focused on the performance of the intelligence components as well as the overall system. The table below shows the intelligence components performance validation results.

<table>
<thead>
<tr>
<th>KPI</th>
<th>Target values</th>
<th>Measurements (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECG Accuracy</td>
<td>90.2%</td>
<td>98.31%</td>
</tr>
<tr>
<td>ECG Sensitivity</td>
<td>96.52%</td>
<td>92.11%</td>
</tr>
<tr>
<td>ECG Specificity</td>
<td>85.14%</td>
<td>99.12%</td>
</tr>
<tr>
<td>ECG Precision</td>
<td>83.84%</td>
<td>93.27%</td>
</tr>
<tr>
<td>SpO2 Accuracy</td>
<td>85.26%</td>
<td>82.03%</td>
</tr>
<tr>
<td>SpO2 Sensitivity</td>
<td>60.36%</td>
<td>61.4%</td>
</tr>
<tr>
<td>SpO2 Specificity</td>
<td>91.71%</td>
<td>89.5%</td>
</tr>
<tr>
<td>SpO2 Precision</td>
<td>N/A</td>
<td>70%</td>
</tr>
</tbody>
</table>

The overall system performance validation results are shown in the table below.

<table>
<thead>
<tr>
<th>KPI</th>
<th>Target values</th>
<th>Measurements (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTT Latency</td>
<td>10 &lt; Medium &lt; 100 ms</td>
<td>27</td>
</tr>
<tr>
<td>User experienced DL throughput</td>
<td>Guaranteed: 10 Mbps (per user) Maximum: 50 Mbps (per user)</td>
<td>134</td>
</tr>
<tr>
<td>User experienced UL throughput</td>
<td>Guaranteed: 1 Mbps (per user) Maximum: 5 Mbps (per user)</td>
<td>37</td>
</tr>
<tr>
<td>Service availability</td>
<td>99.99%</td>
<td>100%</td>
</tr>
<tr>
<td>Service reliability</td>
<td>99.99%</td>
<td>99.994%</td>
</tr>
</tbody>
</table>
TRANSPORT VERTICAL TRIALS

This section provides an overview into the transport vertical trials of the 5G-HEART project. Communication between vehicles, infrastructure, the cloud and other road users is crucial to increase the safety of future automated vehicles and their full integration in the overall transport system. 5G is expected to meet the requirements of various advanced use cases of the transport vertical through enhanced wireless connectivity and increased automation, which would pave the way to fully connected mobility and autonomous driving.

The transport vertical trials in the 5G-HEART project are structured under four high-level use case categories, i.e., “T1: Platooning”, T2: Automated/assisted driving”, “T3: Support for remote driving” and “T4: Vehicle data services”. The individual trial scenarios within these four categories are further divided into two main groups. The trials in the so called transport vertical core scenarios focus on the large-scale implementation and in-depth trialling of the key 5G functionalities and KPIs of the transport vertical use cases. The supplementary scenarios provide additional insight into the 5G performance by providing trial results for specific technology enablers.

The core scenarios in the transport vertical are “T2S1: Smart junctions and network assisted & cooperative collision avoidance (CoCa); Trial track”, “T2S4: Human tachograph”, “T3S1: Tele-operated support (TeSo)”, “T4S5: End-to-end (E2E) slicing” and “T4S6: Vehicle sourced high-definition (HD) mapping”. They provide a comprehensive view into the capabilities of the current 5G technologies to support the four high-level use case categories investigated in the project. All of the core scenarios have implemented the service components and network technology enablers required to deploy the tested service in the field. Using these live trial setups, the core scenarios have performed large-scale trials and extensive measurement campaigns to assess and validate the performance of state-of-the-art 5G networks as the connectivity platform for the tested services.

The supplementary scenarios in the transport vertical are “T1S1&T1S2: High bandwidth in-vehicle situational awareness and see-through for platooning”, “T2S2: Smart junctions and network assisted & cooperative collision avoidance (CoCa); Simulation track”, “T2S3: Quality of service (QoS) for advanced driving”, “T4S1: Vehicle prognostics”, “T4S2: Over-the-air (OTA) updates”, “T4S3: Smart traffic corridors”, “T4S4: Location based advertising” and “T4S7: Environmental services”. The supplementary scenarios have studied and trialled the suitability of varying 5G configurations in a smaller scale using different experimental methods ranging from field and lab-based trials to simulations and emulations. The results achieved in the supplementary scenarios complement the results gathered from the large-scale core scenario trials and complete the picture when it comes to commercial 5G networks serving the needs for the transport vertical.
The presented trials have been conducted by utilising mainly the 5GENESIS (Surrey, UK), 5Groningen (Groningen, Netherlands) and 5GTN (Oulu, Finland) trial facilities. Some trials results have also been collected by using a dedicated automated driving trial site in Chemnitz, Germany.
T1S1&T1S2 – HIGH BANDWIDTH IN-VEHICLE SITUATIONAL AWARENESS AND SEE-THROUGH FOR PLATOONING

Involved partners: UOS (Lead partner)

Introduction

This scenario involves support for high bandwidth in-vehicle streaming serving situational awareness/collision warning and see-through applications for platooning scenarios. When driving in a platoon with very close distances between vehicles, the passengers will most likely feel more secure when they can see what is happening ahead of the platoon leader. One way of facilitating this is by providing HD video stream from the platoon leader to the other members. Providing such a video stream requires the availability of high-bandwidth at high-mobility, as platoons tend to move at significant speeds.

Objectives

The aim of demonstrations is to evaluate performance of HD video streaming, over LTE and LWA; Considered metrics : mean DL throughput.

Key results

First, the experimental LTE setup depicted in figure below is used, where LTE operates on band 7 (2.6 GHz) with a bandwidth of 5 MHz. An HD video is streamed from the video server to the OAI UE with a fixed data rate of 15 Mbps. Two snapshots i.e. the original (on the left) and received (on the right) videos are shown in the figure below. It can be clearly seen that the perceived QoE is not acceptable. In fact, in the considered scenario, LTE does not have the capacity to sustain the required bitrate of the HD video stream.

Average downlink throughput was 43 Mbps for the LWA-mode and 14 Mbps for LTE.
Next, the LWA setup described in the figure below is used, where LTE operates on licensed band 7 (2.6 GHz) at a bandwidth of 5 MHz and WiFi operates at 2.4 GHz ISM band with a bandwidth of 20 MHz. The same HD video is streamed from the video server to the OAI UE. Recall that, compared to LTE, LWA simultaneously exploits the LTE and WiFi interfaces. Figure below shows a snapshot of the received video stream side-by-side the original counterpart. The results indicate that, compared to LTE-only, the perceived QoE is now significantly improved. The aggregated LTE and WiFi capacities enable sustaining the required bitrate of the considered HD video stream, thus demonstrating the capability of the experimental setup used, in support of the see-through functionality.

Average downlink throughput was 43 Mbps for the LWA-mode and 14 Mbps for LTE.
T2S1 – SMART JUNCTIONS AND NETWORK ASSISTED & COOPERATIVE COLLISION AVOIDANCE (COCA); TRIAL TRACK

Involved partners: TNO (Lead partner), PEEK TRAFFIC by DYNNIQ

Introduction

A high percentage of all traffic accidents occur at intersections, where there is a high density of vehicles and vulnerable road users (e.g. cyclists and pedestrians). The Smart Junctions scenario provides network assisted safety information towards vehicles to prevent traffic accidents and assist cooperative automated driving functions when vehicles pass through an intersection.

This safety information may involve the exchange of precise digital maps of intersections, the status of traffic signals, green wave priority requests, vehicle information (e.g. location, speed and trajectory) and information on vulnerable road users for example. Besides at intersections, such network-assisted collision warning and avoidance services can also be beneficial on other road segments like highways.

Objectives

This work aims to evaluate to what extend a 5G standalone network is able to deliver the network performance requirements as required by a time-critical safety service like a smart junction, when such a time-critical service is not the only service operating on said 5G standalone network.

Hence this work compares network performance of a 5G standalone setup with and without network slicing configured.

Key results

It was verified that by configuring and enabling 5G standalone slicing, the 5G network can guarantee and deliver the network performance requirements of multiple time-critical safety services at the same time.

To validate this, the evaluation simultaneously conducted the trials of two different verticals on the same 5G network, namely the T2S1 Smart Junctions trial together with the H1C Paramedic Support trial. The H1C trial adds additional load on the network as it facilitates remote real-time video delivery for effective situational assessment between local ambulance personnel and remotely located Chief Medical Officer (CMO).

When simultaneously running the trials on the 5G standalone network without slicing enabled, one can see that the background traffic on the network (depicted in the figure below by the red line) suppresses the time-critical vehicle traffic (the traffic of T2S1 and H1C). This is undesirable as these time-critical safety services depend on the network for the services to function.
To mitigate these problems, the 5G standalone network was configured with three different slices, each slice with absolute priority over the other slice, as depicted in the figure below.

- A default priority slice for regular consumer internet traffic
- A medium priority slice for the H1C video traffic towards the Chief Medical Officer
- A high priority slice for the T2S1 time-critical vehicle traffic

With this slice configuration enabled one can see, in the figure below, that both the traffic for T2S1 (depicted by the green line) as well as the traffic for H1C (depicted by the blue line) have priority over the background traffic (depicted by the red line) and are no longer suppressed by the background traffic.
T2S2 – SMART JUNCTIONS AND NETWORK ASSISTED & COOPERATIVE COLLISION AVOIDANCE (COCA); SIMULATION TRACK

Involved partners: CEA (Lead partner)

Introduction

Cooperative Collision Avoidance (CoCA) service consists in the exchange of sensor information between vehicles to ensure efficient navigation through different driving situations: lane changing, overtaking or entering/exiting highways and intersections à Collective perception.

CoCA system provides network-assisted safety information to connected / automated vehicles via C-V2X or 5G NR connectivity.

Based on on-board sensors (e.g. radar, LiDAR, camera) to detect and integrate obstacles, vehicles can exchange information about their surrounding environment via:

- Occupancy maps messages (occupancy map models the scene perceived by the vehicle with pixels representing a zone occupied by an obstacle with an associated probability), or
- Collective Perception Messages – CPM (list of obstacles)

Objectives

This work aims to complement the field trials by evaluating large-scale performance by simulations. We focus on the evaluation of the V2X connectivity of a CoCA system based on 4G C-V2X and 5G NR network in a road intersection scenario.

The main objective is then to evaluate the impact of the V2X connectivity performance on the fusion of local occupancy maps and CPMs and to define the best compromises between the communication configuration and obstacle detection capabilities.

Key results

The overall system architecture supporting a CoCA system based on V2X connectivity evaluated and simulated in T2S2 is shown in the hereunder figure (left) with the developed simulation framework (right).
C-V2X connectivity combined with occupancy map messages

Evaluation of the potential and the limitations of C-V2X aided cooperation for improving road safety.

Results show the trade-offs in terms of capacity, range, reliability and latency for each type of link (V2I or V2V) depending on the density of vehicles:

- It is better to send the local occupancy maps in UL using MCS-7 (resp. MCS-15) when the network presents a low UEs (resp. high UEs) density.
- RSU has to send the global occupancy map in DL using MCS7 to reach the UEs in all the intersection.
- Occupancy map messages size of 1685 Bytes with 4 bits/pixel is suitable for global occupancy maps in terms of obstacle mis-detection ratio.
- Message periodicity should be set to 100 ms whenever the number of vehicles does not exceed 70, and to 200 ms otherwise.

C-V2X connectivity combined with CPM messages

- Proposal of a fusion algorithm that can merge Collective Perception Messages in order to generate a global CPM that contains more reliable information about vehicles environment.
- The proposed fusion algorithm is simple to implement, with low complexity compared to literature approaches.
- Evaluation of the impact of C-V2X connectivity on the CPM fusion results; Effectiveness of our fusion algorithm in terms of obstacles detection capabilities.
- This algorithm can also cope with packets losses caused by C-V2X connectivity performance degradation; The use of CPM is more advantageous than occupancy maps in our scenario.
5G NR connectivity combined with CPM messages

- Show potential and limitations of 5G-NR connectivity for supporting CoCA service.
- The good reliability of the 5G link allows to obtain good performances in terms of obstacle detection required for the CoCA service.
- E2E latency of the UL CPM messages involved in a latency-critical service such as CoCA is shown to be not problematic under high traffic density.
- Radio access latency has been shown to dominate other higher-level latency components present in the budget (backhaul, core network).
**T2S3 – QoS for Advanced Driving**

**Involved partners:** TUC (Lead partner), UOS

**Introduction**

Modern connected and automated vehicles (CAV) may operate on different levels of automation (LoA). While higher levels of automation (SAE Level 3-5) are generally preferred over lower levels (SAE Level 0-2), their availability might depend on many factors like the vehicle specific operational design domain (ODD), environmental factors and the availability of supporting infrastructure. The need to switch to lower LoAs is considered undesirable.

Advances in algorithmic support might enable an older CAVs to operate on higher LoAs even in situations where the original ODD would have been reached, but the available hardware might not be able to support those. One hypothetical solution is to offload algorithmic computation into the cloud for situations, where the vehicle alone would not be able to support a high LoA.

**Objectives**

The objective is to trial a hypothetical support service that enables an automated vehicle to maintain a higher level of automation in situations where it was not designed to operate originally. The trialled test-case focuses on the enhancement of object detection in video streams that allows a vehicle to continue to operate on a high LoA when entering an urban area. This is done by deploying a state-of-the-art machine learning algorithm to the cloud and communicating the detected objects back to the vehicle which then performs trajectory planning using these objects.

The KPIs of interest are bandwidth requirements, latency, reliability and the possibility to detect QoS changes to abort potentially dangerous operations as soon as possible.
Key results

The described application has been successfully built, deployed and trialled using a currently available commercial network over 4G and 5G NSA in real-world traffic. A totality of 23 measurement runs with a net duration of 2.75h have been performed. The following key results have been achieved:

<table>
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<th>4G</th>
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<td>Latency</td>
<td>44.4 ms</td>
<td>51.9 ms</td>
</tr>
<tr>
<td>User experienced DL throughput</td>
<td>0.017 Mbps</td>
<td>0.017 Mbps</td>
</tr>
<tr>
<td>User experienced UL throughput</td>
<td>2.139 Mbps</td>
<td>1.879 Mbps</td>
</tr>
<tr>
<td>Reliability</td>
<td>98.50 %</td>
<td>95.03 %</td>
</tr>
</tbody>
</table>

A detailed analysis exposed instances with low reliability and high latencies. Correlation with other measurement data revealed, that these were caused by low RSSI in those areas. This leads to the conclusion that with current technology such service may not be viable yet with this network setup.
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<td>Reliability</td>
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</tr>
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</table>

A detailed analysis on the latency distribution exposed instances with very high latencies. Correlation with other measurement data revealed, that these were caused by low RSSI in those areas. This leads to the conclusion that with current technology such a service is not viable yet.
**T2S4 – HUMAN TACHOGRAPH**
Involved partners: VTT (Lead partner), POLAR

**Introduction**

The human tachograph service utilises wearable sensors to monitor the biosignals of professional drivers and provides guidance to prevent fatigue and improve wellbeing. Unlike most of the existing driver fatigue detection systems, human tachograph tracks both the live biosignals during driving as well as sleep and physical activity in long-term. The information from the human tachograph application can also be shared with other drivers and vehicles. For this purpose, a 5G-based traffic warning system has been implemented, which triggers anonymised warning messages towards other road users and road traffic safety systems based on the human tachograph driver condition analysis.

**Objectives**

The human tachograph use case scenario studies and analyses the collection of monitoring data related to the professional driver’s condition status throughout the day and define the most useful data sets for different driver safety applications. Furthermore, it studies different fatigue risk management strategies, which provide tools to improve the driver’s physiological status related to driving.

The transfer of the monitoring data from the wearable sensor devices to the service platform at the network edge is trialled and validated with different service and 5G network configurations. The key 5G connectivity challenges are related to the end-to-end latency and reliability with specific focus on the 5G uplink direction when transferring the raw sensor data to the network edge for processing.

**Key results**

The overall functionality of the human tachograph service on top of 5G network was divided into two parts, i.e., wearable sensor data collection and transfer in the uplink direction, and warning message triggering and distribution in the downlink direction. The most important KPIs measured from the human tachograph data traffic during the trials were end-to-end latency and reliability, which are the main KPIs determining if the information provided by the service is up-to-date when it is shared with other road users or road safety systems in the form of the anonymised warning messages.
The measured end-to-end latency during the trials was only taking into consideration the communication delays and did not contain the time required for the processing and analysis of the sensor data. This approach was chosen because depending on the service deployment architecture, the sensor data processing and warning message triggering can be performed in different locations in the user device or the network. The uplink and downlink reliability was assessed as the percentage of successfully delivered data packets within the defined one-way latency limit.

The target value for the end-to-end latency was set to 10 ms. As one of the aims for the human tachograph trials was to assess if 5G enables the service functionality to be shifted from the end user devices and remote clouds to the network edge, the end-to-end path contains both the 5G uplink and downlink. Hence, the one-way delay target was 5 ms for both the uplink and downlink. The target value for communication reliability was set to 99.99%. Both target values are based on the requirements to support advanced driving use cases as defined by 3GPP.

When it comes to the one-way latencies achieved with the human tachograph service traffic, the main challenges with the current 5G technologies are in the uplink. The measurement results shown in the figure below reveal that the average uplink latency achieved with 5G non-standalone and standalone configurations is 5.5-9.0 ms. The results also show that there are big differences in the achieved performance between different user equipment models. However, compared to the average 4G uplink latency of 16.5 ms measured with the same service setup, the 5G uplink performs significantly better. In downlink direction, the measured average one-way latencies are 5.5 ms for 4G and 4.0-6.0 ms for 5G, depending on the configuration and user equipment model in use.

![Latency Measurement Results](image_url)
As the one-way latency results above already show, the measured latency variation, i.e., jitter, is still quite high especially for the 5G uplink. As the packet data scheduling algorithms in the current 5G equipment are not optimised for continuous uplink traffic, the achieved reliability as function of the latency target is well below the 99.99% requirement defined by the 3GPP. Even in the downlink direction, the achieved reliability for the strict 5 ms one-way delay target is 99% at best.
**T3S1 – TELE-OPERATED SUPPORT (TESO)**

**Involved partners:** NTUA (Lead partner), TUC, UOS

**Introduction**

Tele-operated support (TeSo) refers to the remote control of a vehicle using the available mobile network infrastructure. A human operator located remotely sends control commands to the vehicle over the network, while at the same time, information about the vehicle’s state and its surroundings is properly transferred and visualized back to the operator.

The architecture of the developed TeSo service prototype consists of:

- Four cameras mounted on each side of the vehicle (front-back, left-right), several sensors recording ambient and operational data, and actuators transforming the remote-control commands into physical movements.
- An On-Board Unit (OBU) that aggregates the sensor data and transforms the proprietary data structures into predetermined standard formats and vice-versa (for the remote-control commands).
- The Remote Operations Center – Gateway (ROC-GW), which orchestrates the bidirectional communication with the Remote Operations Center (ROC) over the network.
- The ROC Graphical User Interface (GUI) application located at the remote site that displays the received video streams and sensor data to the human operator, while accepting as input the remote-control commands that must be transmitted to the vehicle.

**Objectives**

This work proceeded to the actual trialing of the TeSo service prototype in a real pilot over a 5G network. A research vehicle properly equipped with sensors and actuators was actively controlled remotely from a distance of around 36km. Approximately 500 minutes of raw measurements and video recordings were collected, while conducting the following maneuvering scenarios:

- TC01: Straight maneuver
- TC02: Turn right maneuver
- TC03: Lane change maneuver
- TC04: Parking maneuver
• TC01: Straight maneuver
• TC02: Turn right maneuver
• TC03: Lane change maneuver
• TC04: Parking maneuver

The collected data was analyzed to calculate the achieved throughput, latency, jitter, and packet loss rate in both downlink and uplink and assess the 5G network infrastructure’s effectiveness and efficiency in supporting TeSo.

**Key results**

The collected data captured the outgoing and incoming traffic at the two devices hosting ROC-GW and ROC, and regards the following data streams:

- JPEG-encoded frames of the four cameras
- Vehicle’s velocity [m/s] -> Vehicle state
- Steering wheel angle [rad], and throttle and brake percentage [%] -> Automation state
- Geographic coordinates (GNSS position)
- Preferred throttle percentage -> Throttle control
- Preferred brake percentage -> Brake control
- Preferred wheel angle -> Steering wheel control

The table below presents the computed Key Performance Indicators (KPIs) per individual data stream for a specific trial iteration of TC01.

<table>
<thead>
<tr>
<th>Data Stream</th>
<th>Mean Lat. (µs)</th>
<th>Mean Throughput (µs)</th>
<th>Jitter (bps)</th>
<th>Loss Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNSS Pos.</td>
<td>30159.16</td>
<td>4651.69</td>
<td>9149.09</td>
<td>0</td>
</tr>
<tr>
<td>Front Cam.</td>
<td>42378.31</td>
<td>2165787.34</td>
<td>7730.31</td>
<td>0.053820</td>
</tr>
<tr>
<td>Back Cam.</td>
<td>40180.17</td>
<td>1490055.50</td>
<td>6375.40</td>
<td>0</td>
</tr>
<tr>
<td>Right Cam.</td>
<td>38176.08</td>
<td>1436088.75</td>
<td>8467.67</td>
<td>0.043837</td>
</tr>
<tr>
<td>Left Cam.</td>
<td>44091.86</td>
<td>1643104.52</td>
<td>8520.49</td>
<td>0.041779</td>
</tr>
<tr>
<td>Throttle Ctrl.</td>
<td>24432.25</td>
<td>220.72</td>
<td>3915.70</td>
<td>0</td>
</tr>
<tr>
<td>Brake Ctrl.</td>
<td>24633.00</td>
<td>22.30</td>
<td>5245.50</td>
<td>0</td>
</tr>
<tr>
<td>Wheel Ctrl.</td>
<td>25190.55</td>
<td>7088.25</td>
<td>5144.67</td>
<td>0</td>
</tr>
<tr>
<td>Vehicle State</td>
<td>30791.02</td>
<td>4257.11</td>
<td>8893.27</td>
<td>0</td>
</tr>
<tr>
<td>Autom. State</td>
<td>30882.94</td>
<td>4180.73</td>
<td>9533.60</td>
<td>0.103627</td>
</tr>
</tbody>
</table>
The overall performance of the TeSo service is summarized by considering the following representative KPIs:

- **UL Throughput**: sum of the mean throughput of the four camera streams
- **DL One-Way Latency**: mean one-way latency of the wheel control data stream as an archetypal remote-control signal

The achieved UL throughput and DL One-Way Latency are depicted in the figures below:
T4S1 – VEHICLE PROGNOSTICS
Involved partners: VTT (Lead partner)

Introduction
An application running at the network edge and having the capability to access the Internet, enables any vehicle passing the coverage area of a 5G-enabled Roadside Unit (RSU) to report its current functional state to a local or remote diagnosis service and receive a just-in-time repair notification. A vehicle service application linked to repair centres needs to obtain and analyse data from the vehicle periodically and an RSU application can provide this data by collecting it from the passing cars on the road. Based on the analysis outcome, the repair centre will notify the vehicle owner with any identified issues.

Objectives
The vehicle prognostics use case trials focus on the validation of the 5G uplink performance with test traffic based on typical On-Board Diagnostics – Second Generation (OBD-II) message sizes. By emulating the vehicle prognostics service data with software and hardware-based traffic generators, the validation trials are flexibly configured to focus on the uplink data throughput, end-to-end latency of the data path from the user device to the network edge. Based on the achieved 5G uplink performance, specific focus of the trials is to assess the scalability of the trialled service when the amount of service users increases inside a single cell.

Key results
The vehicle prognostics trials examined the service on top of a 5G network focusing on the performance of the 5G uplink data transfer using typical OBD-II message format and data patterns in terms of the total message length and payload size. The size of the message payload varied between 12-1400 B during the trials. The most important KPIs measured from the data traffic during the trials are the user experienced uplink throughput and end-to-end latency. In the case of the vehicle prognostics use case scenario, the end-to-end path was between the user equipment and local network server and contained only the 5G uplink. The target value for the user experienced uplink throughput was set to 1-10 Mbps. For the end-to-end latency and reliability, a target values of 100 ms and 99.999% were used, respectively.

The following table summarises the measured user experienced throughput values when a typical 255 B payload size is used. The table also shows the maximum achievable user experienced throughput with Maximum Transmission Unit (MTU) sized packets in the utilised trial configuration. From the table we can see that the throughput for a single user remains quite low in a typical vehicle prog-
nostics usage scenario and the maximum achievable user experienced uplink throughput is enough to fulfil the service target with both 4G and 5G.

<table>
<thead>
<tr>
<th>Network configuration</th>
<th>User experienced throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>4G with 255 B payload size</td>
<td>112 kbps</td>
</tr>
<tr>
<td>5G with 255 B payload size</td>
<td>394 kbps</td>
</tr>
<tr>
<td>4G with MTU payload size and full buffer traffic</td>
<td>28 Mbps</td>
</tr>
<tr>
<td>5G with MTU payload size and full buffer traffic</td>
<td>62 Mbps</td>
</tr>
</tbody>
</table>

When it comes to the scalability of the vehicle prognostics service, the following graph shows the measured end-to-end latencies as a function of the number of individual users in a 5G cell. We can see that even though the average measured latencies in the 5G uplink stay below 80 ms even for 20 individual users, the latency variance, i.e., jitter, begins to increase significantly when the number of individual users is more than 8. This means that the target latency of 100 ms can only be achieved with the associated 99.999 % reliability when the number of simultaneous vehicle prognostics service users is 8 or less in a single 5G cell. This clearly shows that the packet data scheduling algorithms in the current 5G equipment are not optimised for uplink traffic, which can create performance problems even for services with low and moderate KPI requirements when the number of simultaneous users begins to increase.
**T4S2 – OVER-THE-AIR (OTA) UPDATES**

Involved partners: VTT (Lead partner)

**Introduction**

Engine control unit is a generic term for a hardware module with corresponding software in a vehicle that controls some electronic functions within the on-board systems. It can control anything from the steering wheel to the brakes, and is in key role in automated driving. The engine control unit is a critical part of the vehicle and, as the vehicles become more and more automated, needs regular software updates. Over-the-air updates provide significant cost-savings, as the vehicles are not required to be recalled and updated in a dedicated physical location by a manufacturer or service centre.

**Objectives**

The over-the-air update use case trials focus on the baseline performance of the 5G downlink for generic data transfer as well as the assessment of the applicability of 4G-based cellular broadcasting functionality as a backup method for the distribution of the engine control unit software updates. Based on the achieved 5G downlink and 4G broadcast/multicast performance, specific focus of the trials is to assess the scalability of the trialled service when the amount of service users increases inside a single cell.

**Key results**

The over-the-air updates trials examined the service on top of a 5G network focusing on the performance of the 5G downlink data transfer when different size engine control unit update packages are being downloaded from the application server to the user equipment. The sizes of the update packages varied between 1-100 MB during the trials. The most important KPI measured from the data traffic during the trials was the user experienced downlink throughput and the overall file download time. The target value for the user experienced downlink throughput was set to 10-100 Mbps.

The following table summarises the measured user experienced throughput values when 10 MB update package size is used. When focusing only on the unicast throughput values, the minimum requirement can be reached already with 4G, even though 5G provides clearly better throughput performance. From the perspective of service scalability, more interesting is to assess when it would be beneficial to utilise 4G broadcast/multicast instead of 5G unicast. In other words, how many users can there be in one 5G cell before the user experienced throughput for one over-the-air service user fall below the target value.
The service scalability assessment was performed using an user equipment emu-
lator, which generates the users into the 5G link so that the gNB sees both the
control and user plane load as with real physical devices. The user amount in the
5G cell was increased gradually and the achieved user experienced throughput
performance was recorded and compared to that achieved with 4G broadcast/
multicast.

The measured user experienced throughput results as a function of the number
of individual users in a 5G cell are shown in the graph below. When the meas-
ured performance shown with a blue line is compared to that achieved with 4G
broadcast/multicast (Evolved Multimedia Broadcast and Multicast Services, eM-
BMS) shown with yellow, we can see that the performance of the broadcast/
multicast is better when the number of individual users in the cell is 48 or more.
In order to have a fair comparison, the comparison threshold for the 10 Mbps
throughput has been converted to goodput (8.2 Mbps) so that the difference in
the protocol overheads is removed from the results (File Transfer Protocol (FTP)
had to be used at the application layer for the 4G broadcast multicast trials).

<table>
<thead>
<tr>
<th>Network configuration</th>
<th>User experienced throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>4G unicast</td>
<td>79 Mbps</td>
</tr>
<tr>
<td>4G broadcast/multicast</td>
<td>9.6 Mbps</td>
</tr>
<tr>
<td>5G unicast</td>
<td>128 Mbps</td>
</tr>
</tbody>
</table>
When looking at the measured engine control unit update package download times as a function of the number of individual users in a 5G cell shown in the graph below, we see the same limit of 48 or more users when it is better to use 4G broadcast/multicast instead of 5G unicast. With the throughput of 9.6 Mbps and protocol overheads related to the download of a 10 MB data file, the comparison threshold between 4G broadcast/multicast and 5G unicast performance is set to 9.8 s. It should be noted that in a non-congested cell, the typical download time for a 10 MB file over 5G downlink is approximately 1s.
T4S3 – SMART TRAFFIC CORRIDORS
Involved partners: WINGS (Lead partner), EPI, OCC, TUC, UOS

Introduction
Vehicles can utilise selected routes in order to reduce pollution or congestion, especially in areas that suffer the most. Data gathered from air quality sensors and information related to vehicle-emissions can be intelligently utilised and combined to control the routes that a vehicle is recommended or mandated to follow in any given journey. The gain resulting from implementing an optimal routing service based on air pollution, is reduction of the pollution levels especially in urban areas, as well as a more effective routing for the drivers resulting in saving time and fuel costs.

Objectives
The smart traffic corridors use case trials focus on providing a routing/navigation service, which minimises the impact of pollution for most of the Air Quality Management Areas (AQMAs) due to the vehicle’s emissions, while simultaneously minimizing the travel time and respective travel costs for the driver. Optimal vehicle routing is achieved through monitoring of emissions and guiding single vehicles or groups of them to be routed based on locally implemented emissions corridors. Vehicles such as lorries or older ones with high emissions are guided through a high emissions corridor whilst low emissions or electric vehicles are given more flexibility on the routes they take to their destination.

Key results
The smart traffic corridors trials examined the service on top of a 5G network. The most important KPI measured from the data traffic during the trials is the round-trip time (RTT), this includes the processing time of the service and internal RTT latencies regarding requests to external APIs.
Key results

The smart traffic corridors trials examined the service on top of a 5G network. The most important KPI measured from the data traffic during the trials is the round-trip time (RTT), this includes the processing time of the service and internal RTT latencies regarding requests to external APIs.
**T4S4 – LOCATION BASED ADVERTISING**

Involved partners: **EPI** (Lead partner), UOS

**Introduction**

With vehicle and passenger information readily available, location-based servers can be implemented to stream content (upon request, if required) as well as local advertising or traffic guidance to vehicles and road users. This becomes especially useful in car-sharing models where vehicles are not owned, and the origin and destination of each journey may vary depending on the passengers.

**Objectives**

The aim is to implement and demonstrate high quality multimedia delivery to vehicles over 5G and measure the network metrics like throughput and latency.

**Key results**

An On-Board Unit (OBU) based on Android OS, was used, using on a standard automotive grade system on a chip (SoC). The application was written portably in the Java language native to the platform. The server uses standard server HW based on Intel and runs HTTP Live Streaming (HLS) Application. A 5G CPE was used to provide 5G connectivity. The application screenshot is shown below.

The measurements were done by inserting logs into the code. The main data exchange is occurring during HD video download and the average payload size and throughput was measured.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (4G)</th>
<th>Value (5G-SA)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload Size</td>
<td>444 KB (Avg)</td>
<td>444 KB (Avg)</td>
<td>Size of video slice</td>
</tr>
<tr>
<td>Throughput</td>
<td>6.8 Mbps (Avg)</td>
<td>223 Mbps (Avg)</td>
<td>Average throughput for the transfer of one video slice</td>
</tr>
<tr>
<td>Messaging Rate</td>
<td>0.7 s (Avg)</td>
<td>0.3 s (Avg)</td>
<td>Time between receiving video slices</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value (4G)</td>
<td>Value (5G-SA)</td>
<td>Comment</td>
</tr>
<tr>
<td>-----------------</td>
<td>---------------------</td>
<td>---------------------</td>
<td>---------------------------------------------------</td>
</tr>
<tr>
<td>Payload</td>
<td>444 KB (Average)</td>
<td>444 KB (Average)</td>
<td>Size of video slice</td>
</tr>
<tr>
<td>Throughput</td>
<td>6.8 Mbps (Average)</td>
<td>223 Mbps (Average)</td>
<td>Average throughout for the transfer of one video slice</td>
</tr>
<tr>
<td>Messaging Rate</td>
<td>0.7 s (Average)</td>
<td>0.3 s (Average)</td>
<td>Time between receiving video slices</td>
</tr>
<tr>
<td>Latency</td>
<td>0.3 s</td>
<td>8.34 ms</td>
<td>Time for initial HTTP request-reply</td>
</tr>
</tbody>
</table>
T4S5 – END-TO-END (E2E) SLICING
Involved partners: UOS (Lead partner)

Introduction
A network slice is a logically separated, self-contained, independent, and secured part of the network, targeting different services with different requirements. With network slicing, CSPs can create multiple virtual networks, or network ‘slices,’ which can deliver application-specific network performance. The multiplicity of use case scenarios that may run simultaneously inside the same vehicle calls for a form of customisation to simultaneously support the diverse and often conflicting requirements of each of them. In this respect, different E2E slices can be used to simultaneously support the various V2X applications running inside the same vehicle. For instance, passengers can watch a HD movie, while a collision awareness application detects a road hazard and triggers an emergency message for the cars behind to slow down or stop to prevent a collision.

Objectives
The aim is to trial and demonstrate network slicing-as-a-service (NSaaS) capability via dynamic (automated) orchestration of resources and their deployment, over the Surrey 5GENESIS platform, based on 3GPP Rel.16 5G SA configuration. In particular, the NSaaS functionality is offered in support of the various use cases of the transport vertical. All applications interact with the 5GENESIS trial facility, via the experimenter portal.

Key results
The key metrics considered are:
- E2E slice deployment time (a.k.a. “service creation time“)
- DL/UL throughput
- Latency and jitter

The final trials setup consists of following:
- Core: Rel.16 5G Core SA, eMBB slice
- RAN: 5G RAN (Commercial), MU-MIMO capable
- UE: 5G commercial (P40 pro)

The measurement and testing tools of the facility are exploited during T4S5 trials. In particular, the following components are used i) Performance Monitoring tools, incl. PING and iPerf TAP plug-ins, ii) InfluxDB (storage), and iii) Grafana (visualisation). The setup considered is depicted in the following figure.
Service (slice) creation time

The test case aims to provide network connectivity to a specific location using a 5G Mobile Network deployed and configured inside a sliced infrastructure. Initial request to start the experiments is sent by the 5GENESIS Portal to the Experiment Life Cycle Manager (ELCM) that is responsible for applying the 5GENESIS Experimentation Methodology followed by results collection. The experiments provide metrics regarding the duration of the process, beginning from the moment a request is received by the Slice Manager, until the Mobile Network is fully operational and ready to accept UE’s connections. Time records are collected for each one of the Service Creation stages (i.e. NS placement time, NS provisioning time, NS deployment time, Transport network configuration time (via WIM) and Radio configuration time) individually, that together constitute the overall “E2E slice deployment time (aka. "service creation time")”. A selection of collected results are illustrated in the figure and table below.

The results show that the average time for service creation is 54 s, with detailed results provided in the following table. The deployed service corresponds to the deployment of
The results show that the average time for service creation is 54 s, with detailed results provided in the following table. The deployed service corresponds to the deployment of instance of 5G core NFs (as a single VNF), accompanied by the configuration of the network and radio elements.

<table>
<thead>
<tr>
<th></th>
<th>Service creation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (s)</td>
<td>53.6</td>
</tr>
<tr>
<td>Median (s)</td>
<td>53.8</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2.4</td>
</tr>
<tr>
<td>95th percentile (s)</td>
<td>57.1</td>
</tr>
<tr>
<td>5th percentile (s)</td>
<td>50.1</td>
</tr>
</tbody>
</table>

Round Trip Time (RTT)

The purpose of this test case is to assess the end-to-end RTT and jitter from a 5G UE client to a server over a 5GNR SA Rel.16 mobile network. The mean RTT measured is 12 ms.
Throughput

The purpose of this test case is to assess the results of the Throughput tests performed in the UL and DL directions in the Surrey Platform.

In the UL direction, the throughput of both UDP and TCP protocols was measured. For UDP, the 95th percentile throughput was 157 Mbps while for TCP the respective throughput value was 148 Mbps. In the DL direction, the 95th percentile throughput for UDP is 1108 Mbps and for TCP is 748 Mbps. Further detailed statistics are provided in the figures and table below.
<table>
<thead>
<tr>
<th></th>
<th>UDP DL</th>
<th>UDP UL</th>
<th>TCP DL</th>
<th>TCP UL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean (Mbps)</strong></td>
<td>1018.2</td>
<td>137.4</td>
<td>562.8</td>
<td>114.1</td>
</tr>
<tr>
<td><strong>Median (Mbps)</strong></td>
<td>1017.5</td>
<td>141.1</td>
<td>570.8</td>
<td>113.1</td>
</tr>
<tr>
<td><strong>Standard deviation</strong></td>
<td>60.2</td>
<td>15.6</td>
<td>109.6</td>
<td>20.8</td>
</tr>
<tr>
<td><strong>95th percentile (Mbps)</strong></td>
<td>1108.3</td>
<td>157.5</td>
<td>748.0</td>
<td>148.5</td>
</tr>
<tr>
<td><strong>5th percentile (Mbps)</strong></td>
<td>919.9</td>
<td>105.8</td>
<td>379.4</td>
<td>79.1</td>
</tr>
</tbody>
</table>
T4S6 – VEHICLE SOURCED HIGH DEFINITION MAPPING
Involved partners: EPI (Lead partner), UOS

Introduction
Autonomous vehicles do not only require on-board sensors to perceive the world around them, but also HD maps to aid their decision making. HD maps of roads and infrastructure will take years to capture and consolidate. There is the added issue of dynamic changes to these maps over time. An innovative means to collect and maintain up to date data would be to crowdsource this information through vehicle on-board sensors which would stream back to a central service, firstly to establish baseline maps and subsequently to manage change detection.

Objectives
The aim is to implement and demonstrate capture of sensor data like LiDAR, upload this over 5G and measure the network metrics.

Key results
The On-Board Unit based on Ubuntu Linux/ Robot Operating System uses a standard Intel SoC. Application is written portably in the C++ language native to the platform. The sensors like LiDAR are interfaced, and the sensors data is streamed to the backend using a 5G CPE. The server uses standard server HW based on Intel and runs an offline mapping application.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (5G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>Not Applicable</td>
</tr>
<tr>
<td></td>
<td>Using a TCP stream oriented reliable connection, data is uploaded continuously</td>
</tr>
</tbody>
</table>
The measurements were done by inserting logs into the code. The main data exchange is occurring during LiDAR data transfer and the network KPIs were measured.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (5G)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>Not Applicable</td>
<td>Using a TCP stream oriented reliable connection, data is uploaded continuously</td>
</tr>
<tr>
<td>Throughput</td>
<td>80.5 Mbps</td>
<td>The rate at which data is uploaded.</td>
</tr>
<tr>
<td>Messaging Rate</td>
<td>Not Applicable</td>
<td>Using a TCP stream oriented reliable connection, data is uploaded continuously</td>
</tr>
<tr>
<td>Latency</td>
<td>Not Applicable</td>
<td>No reply messaging from server</td>
</tr>
</tbody>
</table>
T4S7 – ENVIRONMENTAL SERVICES
Involved partners: EPI (Lead partner), UOS

Introduction
Vehicles may provide a rich and real time source of weather and environmental information through existing on-board sensors such as light sensors for external light conditions such as cloud cover and fog, wiper data for intensity of rain, Suspension data for monitoring road conditions such as potholes. These can be consolidated to create hyper local weather maps aiding drivers and AVs in day-to-day driving but also to assist local authorities to improve road maintenance.

Objectives
The aim is to implement and demonstrate capture of air quality data using IoT technologies and upload this over 5G and measure the network metrics.

Key results
An On-Board Unit (OBU) based on Android OS, was used, based on a standard automotive grade system on a chip (SoC). Air quality sensors measuring PM are interfaced, by which the sensor data is uploaded to backend. The server uses standard server HW based on Intel and runs an IoT oriented server Application, using the MQTT protocol. A 5G CPE was used to provide 5G connectivity. The application screenshot is shown below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>9~10 B</td>
<td>Protocol overhead of MQTT, TCP/IP not considered</td>
</tr>
<tr>
<td>Throughput</td>
<td>Not Applicable</td>
<td>Required data rates are very low</td>
</tr>
</tbody>
</table>
The measurements were done by inserting logs into the code. The main data exchange is occurring during sensor data transfer and the network KPIs was measured.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (4G &amp; 5G-SA)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>9~10 B</td>
<td>Protocol overhead of MQTT, TCP/IP not considered</td>
</tr>
<tr>
<td>Throughput</td>
<td>Not Applicable</td>
<td>Required data rates are very low</td>
</tr>
<tr>
<td>Messaging Rate</td>
<td>1 message each 5 s</td>
<td>Currently air quality samples are taken once in 5 s</td>
</tr>
<tr>
<td>Latency</td>
<td>Not Applicable</td>
<td>No reply messaging from server</td>
</tr>
</tbody>
</table>
AQUACULTURE VERTICAL TRIALS

This report provides an overview of the aquaculture vertical scenarios of the 5G-HEART project. Aquaculture is one of the fastest growing animal food producing sector in the world and is an increasingly important contributor to economic growth and global food supply. The major challenges to EU aquaculture growth can be summarised to adaptation to market changes and competition, as well as need for technical improvements (maintaining health / welfare of livestock, integration of activity with the environment, optimizing resource use and spatial planning.

As of the above, new/emerging technologies and innovations in monitoring and management systems in terms of controlling and improving the feeding means to fish species can enable economically, environmentally and socially sustainable aquaculture development throughout EU and generate enhanced public and investor confidence in EU aquaculture. Therefore there is an ongoing shift in the industry to adopt advanced technology that utilises artificial intelligence, machine learning and data analytics to predict and provide the best possible care for their fish stocks.

The data that are acquired from the IoT technology, is key to tackling some of the sector’s most pressing challenges, including global issues like improving fish health through better monitoring of stock and better monitoring of fish feeding. While these concerns affect some fish farms more than others, finding solutions is in the interest of everyone, whether that is to eliminate the risk of suffocation due to low oxygen levels, water pollution and unsuitable pen conditions, or parasites and disease. The farm environment can be monitored more efficiently and with greater coverage (more sensors across the site’s multiple cages), enabling near real-time corrective measures to be implemented. What is more, the impacts of the farm on the surrounding environment can be followed more closely, allowing for better environmental management. Machine learning is also an effective tool, in that data acquired are then used to create predictive models leading to more confident decision-making, timely alerts and automated systems. In addition, underwater cameras are used to observe fish behavior when feeding to help farmers determine feeding schedules and thus improve the feeding procedure. Video imaging is used also to optimise feeding, biomass estimation and disease detection.

IoT is used to collect real-time information on biomass – the weight and length of a fish – to monitor growth and alter feeding levels accordingly. Systems that enables analysis of disease spreading monitoring, without the need to handle fish, reduce the need for staff to visit sites – improving health and safety within the business and minimizing expenditure on travel.
The underlying report details the aquaculture vertical trials of the 5G-HEART project which are implemented in Greece and Norway. They are structured in five scenarios which are: the A1S1: “Sensory data monitoring” that uses sensors to monitor the quality of the sea water, A1S2: “Camera data monitoring” that uses underwater cameras to monitor the feeding and health of fish, A1S3: “Automation and Actuation Functionalities” that uses a drone to monitor the fish cage, A1S4: “Edge and cloud based computing”, that uses edge computing for the quick processing of the data and processes, and A1S5: “Cage to cage on site communication” that uses communication between cages.

The above first three scenarios are conducted in Greece in the aquaculture farm of Skironis by utilizing the 5G-EVE infrastructure and all the scenarios except the A1S3 are conducted in Norway in different fish farms by utilizing the 5G-VINNI infrastructure.
A1S1 – SENSORY DATA MONITORING
Involved partners: WINGS (Lead partner), ACTA, ERICSSON, ICOM, MI, NTUA, OTE, SEALAB, SKIRONIS, TELENOR

Introduction
Marine aquaculture in Europe has been evolved into a high-tech industry, with many modern aquaculture systems incorporating the collection of heterogeneous data from multiple sources into their daily routines. These procedures are primarily manual and labour intensive, relying on the efforts of the farm staff and regular site visits for monitoring and data collection. The workload on the operator is exacerbated when multiple parameters need to be monitored, such as water quality, fish behaviour and health, feeding, cage structural integrity, etc. Each parameter may require a series of different time consuming procedures, thus making data collection time consuming. Therefore, in recent years automatic data collection systems have become extremely popular. Different sensors have been developed to collect data on a variety of parameters on a continuous basis, enhancing the facility operator’s monitoring capabilities by decreasing the effort required for the collection of the data, while increasing the measurement rate and precision.

Objectives
This scenario, implemented on Greece and Norway, focuses on the continuous sensory data collection monitoring of the site. More and more fish farms use to gather big amounts of data to monitor and analyse the performance of the farm. Parameters like oxygen, temperature, salinity and meteorological data are frequently obtained to evaluate water quality and guarantee the life quality of the site in general. Platforms provide these kinds of functionalities, support data collection from multiple data sources and import the collected data into the management system.

Key results
Norwegian trials
Measuring application KPI’s for A1S1, a scoring table with relevant statements was made for the end-users of the Bluethink GO user interface. The table below presents average results from the feedback with a score of 1 to 10, where 1 is worst and 10 is best.

<table>
<thead>
<tr>
<th>Statement</th>
<th>Score 1-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensordata is realtime</td>
<td>9</td>
</tr>
<tr>
<td>Sensordata is stable</td>
<td>8</td>
</tr>
<tr>
<td>Sensordata is reliable</td>
<td>9</td>
</tr>
<tr>
<td>Overall experience</td>
<td>8</td>
</tr>
<tr>
<td>Average score:</td>
<td>8,5</td>
</tr>
</tbody>
</table>
Results from the live experience show little to no difference from using the application on 4G.

The following table shows the uptime metrics sensory data and the figure is a visual result for uptime over a 30 day period, with a 1 hour bin size. The downtime seen on the graph is due to configuration on the network.

<table>
<thead>
<tr>
<th>Timeframe</th>
<th>Bin size</th>
<th>Percentage uptime</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 h</td>
<td>10 s</td>
<td>98.495544497 %</td>
</tr>
<tr>
<td>2 days</td>
<td>10 s</td>
<td>99.247728719 %</td>
</tr>
<tr>
<td>7 days</td>
<td>10 s</td>
<td>99.758601875 %</td>
</tr>
<tr>
<td>30 days</td>
<td>10 s</td>
<td>74.812211373 %</td>
</tr>
</tbody>
</table>

The following figure shows the software that is used to display sensory data, both live stream and historically. This page can be accessed anytime, both from a laptop or a mobile.

Greek trials

The 5G-HEART network performance was monitored during the use of the specific sensors. Physical and virtual probes were deployed along the transport and radio parts of the network from Athens to Skironis site.

During the actual testing, the network performance was measured live and the results for the End-to-end path, demonstrated 0 % loss, 12 ms latency and 0.6 ms jitter.
The actual traffic generated by the monitored sensors was very low, around 200 kbps.
A1S2 – CAMERA DATA MONITORING

Involved partners: WINGS (Lead partner), ACTA, ERICSSON, ICOM, MI, NTUA, OTE, SEALAB, SKIRONIS, TELENOR

Introduction

Fish behaviour, disease and feeding as well as infrastructure monitoring are very important aspects of modern aquaculture. Efficient identification and management of the various incidents that may come up during production is crucial for the welfare of the fish as well as for the maintenance of the infrastructure. The availability of camera streams transmitting the current status of the site aims to face current practices that include frequent visits on site and thus, additional effort for the operator.

Objectives

In this scenario, the aquaculture solutions developed will take up to support video streaming directly to the operator. Furthermore, any issues regarding disease or behavioural irregularities can be identified using Computer Vision and Artificial Intelligence algorithms, while the feeding procedure is optimised by specifying suitable times to start and stop feeding according to behaviour observations as well as to feed waste observations at real-time. These features will become available over a specifically defined user interface. In order to support the concurrent operation of multiple camera streams for monitoring all available fish cages as well as the infrastructure for maintenance and security purposes, the optimisation of the network infrastructure is necessary. As described in detail later, the utilisation of multiple cameras will validate the applicability of 5G through the concurrent monitoring of all cages through a software platform, as well as the 360-degrees video coverage of the whole infrastructure, providing a variety of different loads that will stress the network.

Key results

Norwegian trials

Measuring application KPI’s for A1S2, a scoring table with relevant statements was made for the end-users of the camera system and Bluethink GO user interface. The table below presents average results from the feedback with a score of 1 to 10, where 1 is worst and 10 is best.
Results from the live experience show that using 5G will enable the end-user to stream high-quality video from 2 or 3 cameras at the same time without the video quality being impacted. A standard fish farm in Norway consists of 6-8 cages, and it proves the bandwidth is still too low to manage up to 8 streams of high-quality video at the same time.

Results in the following table show that we achieve less than 1 % frame loss in all four cases, regardless of 4G/5G. No conclusive results can be seen.

<table>
<thead>
<tr>
<th>Setup</th>
<th>Network</th>
<th>Frame loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>4G</td>
<td>0,10666667 %</td>
</tr>
<tr>
<td>Static</td>
<td>5G</td>
<td>0,30666667 %</td>
</tr>
<tr>
<td>Moving</td>
<td>4G</td>
<td>0,50666667 %</td>
</tr>
<tr>
<td>Moving</td>
<td>5G</td>
<td>0,07333333 %</td>
</tr>
</tbody>
</table>

The following figure shows uptime over a 30-day period with a 10 second bin size.

The two figures below show example under water images with good quality (left) and bad quality (right).
Greek trials

The 5G-HEART network performance was monitored during the use of the underwater as well as the surveillance cameras. Physical and virtual probes were deployed along the transport and radio parts of the network from Athens to Skironis site. Results were collected and provided for data analytics through Kafka to Prometheus.

For the underwater camera the actual traffic was measured around 5 Mbps as shown in the figure below.

In the 360 degree camera monitoring case, the camera stream is processed by a server to provide streams of low and high resolution for a requested field of view (360 degrees or smaller). The processed streams are transmitted via the 5G network to the application client (the operator). While the operator changes the FOV lower quality video is visualised for minimizing the delay and high resolution stream is presented when the FOV is stabilised to optimise the quality of the video shown.
The overall traffic for the surveillance cameras was around 10 Mbps, while the maximum TCP throughput capacity of the network was demonstrated to be 160-320 Mbps on the downlink (depending on radio conditions and location), but 62 Mbps on the uplink.

The E2E latency remained around 15 ms, while path loss demonstrated peaks of 0.8 % and jitter was around 4 ms.
Regarding the usage of computational resources, in the following figures we depict the CPU and memory usage for both the server (top row) and the gateway (middle row) that are managing the video streams at the application site and aquaculture sites, as well as the client (bottom row) that is receiving the video streams at the cloud part of the infrastructure.
In the figure below, the traffic sent by the server that is managing the video stream by the camera and the associated incoming traffic in the client are shown. In the following figure, a correlation analysis is provided based on the received network and application performance metrics. By examining all the metrics, high correlation is shown in the resource usage metrics of the client (that receives the video stream) and the delay in the network. Given that the increased delay is due to increase in the throughput of the network links, the workload posed on the client is also higher, leading to increased usage of resources. By examining in detail the trend in the consumption of CPU and memory resources by the client, optimal scalability policies can be designed. Through the correlations, it is also shown that the gateway is both CPU and memory intensive (high correlation with the bytes sent).
Moving one step further, in the two figures below we focus on the relationship among the latency and jitter values in the network and their impact on the performance of the application part in the client. It seems that the increase in the CPU usage of the client is associated with increased levels of the latency, while there is no severe impact on the jitter parameter.
A1S3 – AUTOMATION AND ACTUATION FUNCTIONALITIES

Involved partners: WINGS (Lead partner), ACTA, ERICSSON, ICOM, NTUA, OTE, SKIRONIS

Introduction

Current aquaculture techniques rely on the manual activities executed during daily/weekly maintenance and management of the site. Maintenance tasks such as fixing the mooring systems or identifying damages at an early stage require the presence of divers that inspect and maintain the infrastructure. Additionally, the operator’s daily presence is required for husbandry operations such as feeding, grading, or stocking. However, modern trends give value to the applicability of remote techniques that allow the operator to execute frequent operations without visiting the farm. Automatic feeder machines are widely available, while autonomous agents such as underwater drones that allow monitoring of the whole underwater infrastructure with actuation capabilities such as anchor or nets maintenance are also considered for such operations.

Objectives

This scenario involves the incorporation of a drone to be placed in the fish cage for continuously monitoring the quality of the cage (e.g. if the net is broken, if an intruder to the cage is approaching, etc). Currently most of the aquaculture systems are using human persons to inspect the nets at certain periods, not continuously which is something that requires extra staff effort. With the use of the drone the operational costs can be lowered and cage condition can be provided online continuously. Therefore the use of the drone in fish cages can automate the otherwise tedious human involvement tasks.

In this scenario, focus is given in the application details regarding fish and infrastructure monitoring which exploits underwater drones observing the site’s aquaculture underwater infrastructure.

The user application architecture consists of two parts. The aquaculture site equipment responsible for the collection, processing and transmission of the data, and the cloud platform responsible for the storage and visualisation of the collected data as well as the enhancement of monitoring and management capabilities via analytics and decision-making algorithms. These components are described in detail in the next sections. The data flow of the architecture that generates the network traffic can be described as follows. Data is collected from the available drones and is aggregated into gateways that take up to pre-process and transmit the data through the network to the cloud platform, while producing early alerts for infrastructure damages or warnings. At the cloud, data is stored, analysed and distributed to all applications that need to consume it.
As a result, a series of decision-making support functionalities are enabled, producing suggestions, warnings, alerts to the operators, enhancing their ability to manage the aquaculture system.

**Key results**

The 5G-HEART network performance was monitored during the use of the drone and its camera. Physical and virtual probes were deployed along the transport and radio parts of the network from Athens to Skironis site.

During the actual trial, the traffic generated by the monitored sensors was around 15 Mbps.

In the following figure, a correlation analysis is provided based on the received network and application performance metrics. By examining all the metrics, it seems that the data processing functionalities in the drone are highly memory intensive. On the other hand, no severe constraints are noticed in terms of CPU usage. Furthermore, the increase in the throughput served by the gateway seems to lead to increase in the measured network latency. The latter seems to be mainly present in the cases where we have both operation of the drone with parallel video streaming by the cameras in the aquaculture site (see the last figure where in the first half of the experiment only the drone is operational, while in the second half, all the application parts are operational).
During the actual trial, the traffic generated by the monitored sensors was around 15 Mbps. In the following figure, a correlation analysis is provided based on the received network and application performance metrics. By examining all the metrics, it seems that the data processing functionalities in the drone are highly memory intensive. On the other hand, no severe constraints are noticed in terms of CPU usage. Furthermore, the increase in the throughput served by the gateway seems to lead to increase in the measured network latency. The latter seems to be mainly present in the cases where we have both operation of the drone with parallel video streaming by the cameras in the aquaculture site (see the last figure where in the first half of the experiment only the drone is operational, while in the second half, all the application parts are operational).
Introduction

The Norwegian aquaculture industry is the second largest industry in Norway, only beaten by the oil industry. With 420 million salmon swimming in the sea at any time the need for better and constant surveillance is bigger than ever. The farming industry still has many processes that can be automated both for decision support and fully automated decisions made based on the input. Monitoring the production generates massive amounts of data streams to be processed, analysed and processed by the farmer. The lack of good network solutions can be a bottleneck for the production facility if the data that is transmitted from the site demands higher bandwidth than what is available. Therefore, both Edge- and Cloud-based processing is needed to get the right data, at the right time, for the right purpose.

With the Edge paradigm, computing and storage are brought closer to the customer. While this reduces latency and the bandwidth requirements towards the Cloud, additional costs in terms of deployment and operation are also incurred. Hence, a deeper assessment of the right trade-off between cost and benefits for the use case. For this scenario, a Device Edge is deployed on the customer premises to host the AI-based Pellet Detection application that uses high quality underwater videos as input.

Objectives

In this scenario the AI application Pellet Detection will be run on edge, providing decision support during feeding. Artificial intelligence with pellet detection will help lower the feed waste and pollution of the sea bed, and then contribute to a more sustainable production and lower environmental footprint. An optimal feeding regime will also be economically beneficial for the fish farming company. Every cage will represent a unique stream of raw data from sensors and cameras, and some of the data will be processed before entering the barge or the cloud.

Key results

In order to investigate how the pellet detector is influenced by the quality of the data stream, the accuracy of pellet detections were compared for the same images undergoing varying degrees of compression.
The benchmarking dataset is composed of 504 annotated underwater images of HD resolution. An example of the frame quality under different compression rates are shown in the figure below.

In the following figure, the relative detection precision versus compression rate is shown. It is observed that at even relatively small compression rates <10x, the drop in detection precision is significant (>20 %). In scenarios with very limited bandwidth, where dramatic compression rates are needed to maintain real-time execution, the precision is reduced by around 60-80 %.

If underwater videos are processed locally in the Edge and do not need to be sent to the cloud, the throughput requirements will be reduced by around 58 % in a typical installation with 8 cages.
A1S5 – CAGE TO CAGE – ON SITE COMMUNICATION
Involved partners: Telenor (lead partner), SEALAB

Introduction
Various service and maintenance operations at the aquaculture site such as boats for transport and delousing, handling mortalities, net inspections, etc. are greatly facilitated and improved by having access to sensor and video data from the cage, as well as data from management systems, while conducting their operations. Additionally, the operation and navigation of underwater cameras in real time require the network to support low latency.

5G provides high uplink throughputs needed for sending the high quality videos towards the Cloud. Deploying 5G gateways at each cage, in addition to the one on the feed barge will remove the high maintenance optical cables currently used between the cages and the barge. As regards latency, either a Private 5G Network or a Local Breakout (Mobile Edge with User Plane Function) is necessary to keep the traffic locally.

Objectives
By moving the 5G connection point from the centralised feed barge of the site to connection points at each cage, this test will also identify the benefits of 5G technologies in comparison with cabled networks (e.g. fibre optics, Ethernet) and wireless networks such as 4G, and Radio over Internet Protocol (RoIP) that are most frequently used today. Throughput, latency and coverage will be measured in this test. This scenario is implemented in the Norwegian pilot site.

Key results
Removing the optical fibres and going 100 % wireless will further reduce the throughput requirements on the 5G gateways. Figure below shows the required throughputs when sending all streams (i.e., 17 streams - from 8 subsea cameras and 9 surface cameras in a typical installation with 8 cages and a feed barge), 8 subsea camera streams, 9 surface camera streams, or 4 subsea and 4 surface camera streams, via 1 shared 5G gateway. In all cases, over 100Mbps uplink throughput is required to send the streams to the cloud. On the other hand, if 1 5G gateway is installed on each fish cage and 1 on the feed barge, the requirements drop to below 50 Mbps, which maximises the image quality of the streams.
With 1 shared gateway on fish farm and optical fibers between barge and cages.

With 1 gateway on feed barge and 1 on each cage.
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