Hamburg Smart Sea Port: Network Slicing Testbed for Industrial Use Cases

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***Abstract*—Network slicing is a key driver for the 4th industrial revolution as it enables the concurrent implementation and operation of a large variety of challenging requirements regarding network performance, reliability, resilience and security, involving Internet of Things (IoT) and other relevant use cases for industrial environments. The aim of the European project 5G-MoNArch was thereby to enhance the existing baseline 5G network architecture with dedicated functions and features supporting these use cases and requirements, and to bring these concepts to practice through real-world testbeds. The Hamburg Smart Sea Port testbed exemplary represented a real-world industrial environment and was in this context the first macro-scale E2E slicing testbed.**

Keywords—5G; network slicing; IoT; Smart Sea Port

INTRODUCTION

5th Generation (5G) mobile networks are characterised by a diversity of requirements and services. To support such diverse and extreme requirements in terms of latency, reliability and throughput, 5G introduces profound changes in architectural design. One of the key novel concepts is *network slicing*, which enables the infrastructure to be divided into several *logical slices* or, in other words, logically separate sub-networks. Each network slice can invoke (virtual) network functions running on the common infrastructure, and tailor them to meet the specific requirements of the use cases, services and applications running over these network slices.

The 5G-MoNArch project (“5G Mobile Network Architecture for diverse services, use cases, and applications in 5G and beyond”) [1] was a pioneering project with the aims to design a network slicing-enabled flexible, adaptable, and programmable mobile network architecture for 5G, and to bring this architecture to practice by deploying it in real-world testbeds. The ultimate goal was to provide a novel 5G network architecture that can reach out to new economic sectors and verticals with the corresponding societal and economic impact.

The 5G-MoNArch mobile network architecture [2] provides full End-to-End (E2E) network slicing support by integrating slice-specific and slice-common functions, multi-tenancy capable management & orchestration, inter-slice resource management, and optional integration of Radio Access Network (RAN) control applications. Further, the architecture introduced features for characteristics spanning all network layers with unified service-based interfaces, specific network slice blueprints, and an analytics framework covering network management and RAN functions as main driver towards full network automation.

The concepts and enablers of 5G-MoNArch were brought into practice through prototype implementations in two testbeds: the Smart Sea Port in Hamburg and the Touristic City in Turin, instantiating slices that included the vertical use case driven functional innovations. In particular, the Smart Sea Port testbed, representing an industrial environment, implemented network reliability, resilience and security to ensure a proper operation of the port, while the Touristic City, representing a media and entertainment environment, implemented resource elasticity to provide an efficient usage of the network resources.

Hamburg Smart Sea Port

Sea ports exemplary represent complex industrial environments and involve a large number of stakeholders with diverse economic goals, use cases, and technical requirements [7]. Global trade with increasing cargo volumes and competition between ports (cf. Fig. 1) puts pressure on port operators – such as the Hamburg Port Authority (HPA) – to improve operational efficiency and cost. These challenges, additionally tightened through fortified regulations on, for example, environmental monitoring and protection, work safety and security, require improved processes and tailored technical solutions.

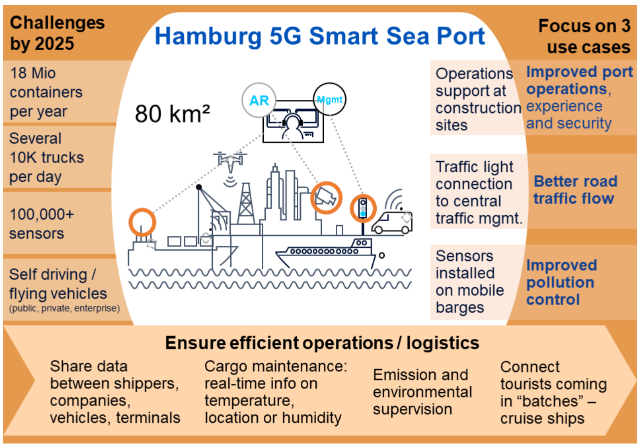

Fig. 1. Hamburg Smart Sea Port: Challenges and Use Cases

The deployment of industry-focused slices, leveraged through new communication technologies introduced with 5G, enables a large variety of new use cases and applications and plays a key role in improving operational efficiency. E2E network slicing as one key 5G technology thereby provides an excellent means to easily deploy industrial use cases through fully separated logical private networks, which can be tailored to the use cases’ individual requirements. The overall goal of the 5G-MoNArch Hamburg Smart Sea Port testbed was therefore to showcase the applicability and functioning of E2E network slicing for industrial use cases in a real-world large-scale environment [4].

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Smart Sea Port use cases

Exemplary for addressing the above challenges, the use cases comprised in the Smart Sea Port testbed were (i) better road traffic flow (traffic light connected to central port traffic management), (ii) improved port operations, experience and security (augmented reality applications for on-site water gate maintenance and construction sites) and (iii) improved pollution control (environmental sensors installed on mobile barges in the port), each of them having its own network slice on top of a common physical network infrastructure.

(i) Better road traffic flow: with tens of thousands of trucks per day, the Hamburg port needs to optimize the traffic flow through a central traffic management system. This requires live monitoring of the status of *traffic lights* and allow for their remote control and change of settings to adapt to changing traffic conditions and requirements. Furthermore, temporary traffic lights located, e.g., at roadwork sites, need to be included to the central traffic control as well. Currently, traffic lights are either connected using analogue technology and inflexible and expensive fixed line infrastructure, or they are not connected at all as the necessary infrastructure is not available everywhere in the 80 km² port area. The goal of this use case was therefore to showcase that a fast, simple and cost efficient connection of traffic lights to the central traffic management system can be achieved through the 5G network, while ensuring through a dedicated network slice that this connection is highly reliable and secure, and provides a guaranteed performance. Even under extreme conditions, for example, in case of radio channel degradations or network traffic peaks, the reliability of the network slice shall not be compromised. In that sense, *better road traffic flow* represents an exemplary use case for *Ultra-Reliable Low Latency Communication (URLLC)* in an industrial environment (intelligent transportation systems), even though low latency is not required for the traffic light control, but the focus is on the high reliability of the network slice.

(ii) Improved port operations: with the HPA being responsible for the maintenance and repair of a large variety of technical installations, buildings and other assets (e.g., bridges, water gates), conducted by mobile engineering teams, and the requirement to have specific documentation or expert knowledge available live on site whenever needed, the current approach to always drive the relevant experts themselves to the site is time-consuming and costly in an 80km² area. The foreseen solution is to improve operations efficiency by providing *Augmented / Virtual Reality (AR / VR) headsets* (for the Smart Sea Port testbed, Microsoft HoloLens was used) to the mobile engineering teams and enable a live remote connection to experts in the operations centre. For example, the remote expert sees the live video of a technical installation and can provide through the AR headset dedicated support to the technician on site by marking dedicated components, while providing voice instructions on the handling. A second application was to enable the mobile engineering teams to remotely access and visualise Computer-Aided Design (CAD) construction plans along with real-time or simulated data such as animated function descriptions. Such use cases require a fast and flexible implementation of AR / VR and video streaming applications within the complete port area. The testbed implemented a dedicated Mobile Broadband (MBB) network slice supporting the latency-critical AR applications with the required Quality of Service (QoS) and Quality of Experience (QoE). Key aspect was hereby to showcase that this network slice can be operated in parallel with the other use cases' slices of the testbed without impacting the respective reliability, resilience, security and performance requirements through a full slice isolation, this being a key challenge to be achieved for industrial applications.

(iii) Improved pollution control: with tightened environmental and safety regulations a continuous and live measurement of air quality, pollution, or the detection of hazardous substances is mandatory. Fixed measurement stations are expensive and not adaptive to changing settings of the port infrastructure, changing weather conditions, or changing lawful regulations. Offline measurements with mobile measurement stations may lead to detection delays. Therefore, *environmental sensors* (e.g., air temperature & pressure, carbon dioxide, nitrogen dioxide, fine dust) together with GPS sensors were installed on *mobile barges* roaming in the port. These barges were on regular operation in the port during daytime, for example, inspection rides, depth measurements in the port's different basins, or transportation of personnel to remote location. The installed environmental sensors were connected through a dedicated network slice to the IoT cloud of the HPA, to get a real-time view on the location-specific environmental status in the port and enable the visualisation of the measured data, data relationships, and leverage the identification of incidents and events. This approach did not only allow for a fast and simple deployment of many sensors at any location, but in particular has built the basis for equipping a large variety of moving vehicles (cars, trucks, or even drones) with sensors. Improved pollution control represents an exemplary use case of *massive Machine Type Communication (mMTC)*, requiring highly reliable and resilient connectivity for transmitting data from many sources at high frequency. Even in the case of high terminal mobility or with challenging radio conditions such as the (partial) connection loss due to shielding behind ships or large buildings the sensor data transmission shall be guaranteed.

Fig. 2 shows a map of the Hamburg Sea Port and the location of the three described use cases (in red text and paintings), together with the schematic setup of the testbed installation as described in detail in the next chapter.

Fig. 2. Hamburg Smart Sea Port: Use Cases (red) and Schematic Setup

Functional Requirements

The Hamburg Smart Sea port aimed at the proof of a set of key functional requirements and features of the 5G-MoNArch architecture and furthermore a set of Key Performance Indicators (KPIs) defined in [5].

Control plane (CP) and user plane (UP) separation: this is a key feature to guarantee data privacy and integrity to verticals as each UP instance is use case-specific, while the

CP instance is shared. This furthermore leverages a flexible implementation as – depending on the use case requirements – each UP can be instantiated at the most appropriate location (referred to as orchestration) regarding, e.g., latency or performance requirements.

Slice isolation: a major requirement for slices is the ability to separate traffic in terms of data privacy and integrity, but also with respect to performance. For example, the traffic light monitoring and control operation in the URLLC slice must not be impaired by other services such as MBB that can cause peak loads. Fig. 3 exemplary shows a screenshot from the testbed operation where at 22:40 minutes a peak traffic is induced for the MBB slice, with the latency going clearly up, while the latency for the URLLC (IoT) slice remains constant.

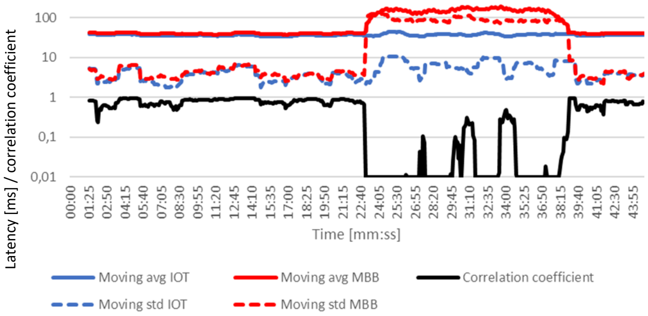

Fig. 3. Slice isolation: no impact to IoT slice latency in case of traffic peak induced for MBB slice

Service creation within minutes: when a customer requires to instantiate a new use case, service or application, in legacy networks the whole process typically took weeks or even months. A central goal of the testbed was therefore to proof that – with network slicing – this whole process can be conducted within minutes.

Highly reliable, resilient and secure services: being central requirements for industrial (and other) use cases, 5G-MoNArch developed a set of functions and features [3] pertaining: *(i) RAN reliability* through data duplication and network coding, *(ii) telco cloud resilience* to increase the robustness of the telco cloud deploying, cognitive network functions for fault identification and correlation as well as robust network controllers and "5G islands", and *(iii) security enhancements*, including threat analysis and anomaly detection. The Smart Sea Port testbed thereby focused on the implementation and proof-of-concept for *data duplication*, which uses a redundant transmission of data packets through duplicating the same message over two separate radio links (*multi-connectivity* via different radio base stations), thereby contributing to a clearly reduced packet error probability.

Testbed Setup

The Smart Sea Port testbed basically included the following components [3]: terminals, the network-side equipment, the network slicing functionality, and use case-specific applications. Fig. 2 shows schematically shows the deployment location of these components and their interconnection together with the location of the implemented and the use cases.

Terminals

Two different types of terminals were implemented to enable the network slicing functionality as well as the reliability and resilience features. The first terminal type was a *multi-connectivity mobile terminal* based on Software-Defined Radio (SDR) and small-form-factor personal computers. This setup was required to implement a protocol stack enabling the multi-connectivity feature, being essential for the use case on *improved pollution control* (mobile barges), where the terminal shall be connected to, and send and receive data from multiple base stations in parallel through Data Duplication. The second terminal type was a *multi-slice mobile terminal* building on a commercial device, where the multi-slice capability could be implemented at the application layer. Using a commercial device clearly increased the overall terminal reliability compared to the SDR-based one, key for the *better road traffic flow* use case where the connection of the traffic light required very high reliability. Furthermore, the form factor of the multi-slice mobile terminal was considerably lower which played an important role for the *improved port operations* use case.

The terminals were implemented use-case specific: three barges operated by the HPA were equipped each with one multi-connectivity terminal, one multi-slice terminal, and two different sensor boxes with environmental sensors to cover the *improved pollution control* use case. For the *better road traffic flow* use case, one traffic light in the port area, located at a busy intersection at the port area entrance (connecting motorway A7 to the Köhlbrand bridge) was equipped with a multi-slice terminal. Finally, for the *improved port operations* use case, an AR test environment was implemented at the HPA headquarter and could be connected to the testbed via a multi-slice terminal. Two additional multi-slice terminals were deployed at Nokia offices in Hamburg for test reasons, and to be used for trade shows and a live demonstration with a mobile traffic light at the final 5G-MoNArch workshop.

Network-side equipment

The network infrastructure was implemented on top of commercial Nokia products compliant to the 3rd Generation Partnership Project (3GPP) Release 14 Long Term Evolution – Advanced (LTE-A) standard with adaptations of the protocol stack that enabled the required 5G features for E2E network slicing, reliability and resilience. For the *radio*, single carrier Frequency Division Duplex (FDD) in the 700 MHz band was chosen, with a bandwidth of 10 MHz in each, uplink and downlink. Two partially overlapping *macro cells* were deployed, each served by a dedicated *base station*. The installation of the radio equipment took place at the Heinrich-Hertz TV tower in Hamburg, with the antennas mounted at an elevation of 182 metres. This setup allowed to cover a large area in the port, enabled to run multi-connectivity (in the cell overlap area), and furthermore ensured good connectivity even at the location of the traffic light with a distance of more than 6km line-of-sight. Several measurement campaigns were conducted during the installation phase of the testbed to proof and improve the configuration.

Accordingly, the *mobile core* and the *data centres* used modified commercial equipment supporting multiple slices and CP and UP separation. The edge cloud local CP and UP were implemented with two servers at a data centre of Deutsche Telekom (DT) in Hamburg, and the central cloud UP with four servers at a data centre in Nuremberg (approx. 460 km distance). This setup enabled the assessment of latency benefits of edge cloud deployments, such that the UP for latency-critical use cases (e.g., URLLC) was implemented locally (edge) while the UP for performance-critical general MBB use cases was implemented centrally. All sites were interconnected using the optical fibre infrastructure of DT.

Network slicing functionality

Besides the adaptation of the protocol stack at terminal and network side, the Smart Sea Port testbed implemented the full tool chain to enable E2E network slicing. In particular, this included a proprietary web-based *network slice lifecycle management (Slice LCM) tool* with a graphical user interface. Through this tool the complete live workflow for designing (creation of slice blueprints), creating, instantiating, activating, modifying (during runtime), and decommissioning slices was executed. The tool furthermore controlled the pre-provisioning of the necessary software for a (new) slice on the network infrastructure as well as the network environment preparation (i.e., preparing and selecting the appropriate Virtual Machines). Due to the direct connection of the tool to the live network, the key goal of the testbed to enable service and slice creation within minutes could be provided – in a way representative for a real-world deployment.

Applications

Several applications were implemented for the testbed. Firstly, this included the AR application for the improved port operations use case. Secondly, a performance monitoring tool (KPI panel) with GUI, to continuously monitor and visualise, e.g., round-trip latency (through PING) and a set of radio KPIs and parameters such as Reference Signal Received Power / Quality or connected cell. This included information on the live status of the traffic light but also a tracking of the mobile barges (cf. Fig. 4) and some of the measurements taken by the sensors. Finally, the HPA used their environmental monitoring tools to evaluate the collected sensor data.

Fig. 4. Screenshot of KPI panel showing different measurements tracking from one of the mobile barges: PING round trip delay for both terminal types (multi-slice upper left, multi-connectivity upper right), signal strenght (bottom left), signal quality (bottom centre), air temperature (bottom right)

Key Insights and Results

The overall goal of the 5G-MoNArch Hamburg Smart Sea Port testbed – to showcase the applicability and functioning of E2E network slicing for industrial use cases in a real-world large-scale environment – could be fully achieved. With the facts that the testbed implemented three real-world vertical use cases (defined by the Hamburg Port Authority), was implemented based on (modified and adapted) slicing-enabled commercial equipment, used a commercial infrastructure, and had at least parts of the use cases and applications integrated with the live port operations shows the full success towards achieving the overall goal.

Regarding the specific key goals of the Smart Sea Port on control and user plane separation and slice isolation, the implementation of the testbed as such and its successful operation and functioning could prove these goals. The implemented solution for slice LCM, enabling the creation, deployment and activation of a new slice (service) for the customer in less than 10 minutes clearly overachieved the initially defined target of <90 minutes. Finally, the concepts and solutions developed for network reliability could be implemented and proven to be fully effective.

On the other side, several insights were gained during the phases of the testbed planning and implementation. Firstly, it turned out that slice design is a challenging task, since the mapping between required service quality and required network functions typically is out of scope for the vertical. Collaboration with, and support through a mobile network operator, or future (AI/ML-based) tools for this mapping are necessary. Secondly, it turned out that the network infrastructure setup was not too complex, but the provisioning of slicing-capable terminals was a major challenge

Beyond the concepts, functions and features developed into the Smart Sea Port testbed, some 5G-MoNArch concepts were developed in other contexts: network elasticity algorithms and a fully automated orchestration were implemented in the Touristic City testbed [4], and the security concepts, in particular Security Trust Zones [3], were evaluated through simulations.

The Smart Sea Port environment played a key role in the techno-economic evaluation of the 5G-MoNArch architecture and concepts, as the investigated evaluation cases represent an enhancement of the Smart Sea Port use cases. This included an enhanced MBB network to deliver industrial services (e.g., for terminal operators), temporary hotspots to handle high peak traffic loads generated by cruise ships arriving in the Hamburg port, and another enhanced MBB scenario going beyond the port scenario and targeting smart city and vehicular services. A large number of KPIs have been investigated therefore together with an evaluation of economic benefits based on detailed collaboration with stakeholders of the evaluation cases. The results of the analysis work are compiled in [6].

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