5G-MoNArch project summary

The focus of the 5G-MoNArch project ("5G Mobile Network Architecture for diverse services, use cases, and applications in 5G and beyond") has been on developing a flexible, adaptable, and programmable mobile network architecture for 5G. Inter-slice control and cross-domain management, experiment-driven modelling and optimisation, native cloud-enabled protocol stack are innovative enablers for the sliced network. The concepts and enablers have been brought into practice through prototype implementations in two testbeds (the Smart Sea Port in Hamburg and the Touristic City in Turin) instantiating slices that include the vertical use case-driven functional innovations of network reliability, resilience and security, and resource elasticity, respectively.

5G-MoNArch has been conducted within Phase 2 of the 5th Generation Public Private Partnership (5G-PPP) and has been funded by the European Commission under contract number 761445 within the Horizon 2020 Framework Programme.

The project started on July 1st, 2017 and has finished on June 30th, 2019.

This document provides a brief summary of the scientific project results and achievements, an overview about the two project testbeds, the outcome of the verification and validation framework of the project, and the activities on dissemination, standardisation and exploitation. Finally, the conclusions on the project outcome are provided together with a summary of the impact created.

Summary of the results 2
Conceptual and research results 5
  Flexible and Adaptive Architecture Design (WP2) 5
  Resilience and Security (WP3) 6
  Resource Elasticity (WP4) 8
Implementation of the project testbeds 10
  Hamburg Smart Sea Port testbed 10
  Turin Touristic City testbed 12
Verification and validation of project results 14
Dissemination, Standardisation and Exploitation results 18
Conclusions and impact 19
References and Abbreviations 20

Summary of the results

5G-MoNArch brought the 5G mobile network architecture to the next step of evolution by developing a comprehensive network slicing framework and leveraging this framework's flexibility to fully integrate functions required for industrial, media & entertainment, and smart city use cases. Such integration of network functions renders the mobile network architecture to become usable for real 5G network deployments and applications. In order to achieve this goal, numerous detailed technical concepts and features have been introduced. The overall approach of the project is depicted in Figure 1.

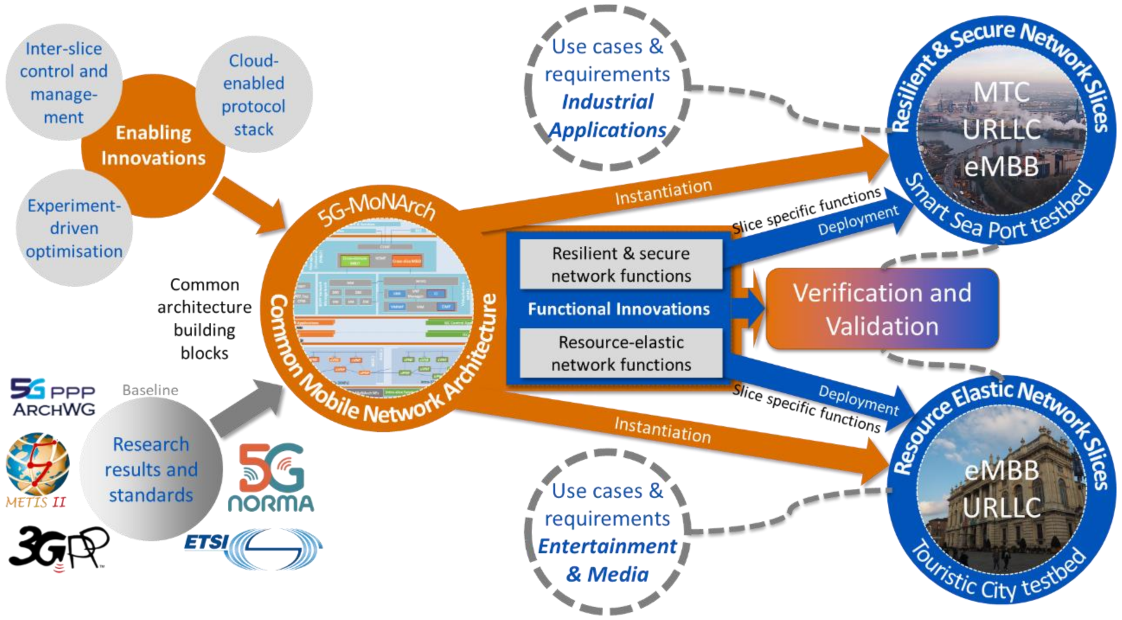

Figure 1: 5G-MoNArch approach

New overall architecture (WP2): The 5G-MoNArch common mobile network architecture provides full End-to-End (E2E) network slicing support by integrating the following features: (i) slice-specific and slice-common functions, (ii) multi-tenancy capable management & orchestration, (iii) inter-slice resource management, and (iv) optional integration of Radio Access Network (RAN) control applications. Furthermore, the architecture introduces the following novel features: (i) service-based characteristics spanning all layers with unified service-based interfaces, (ii) specific network slices blueprints, and (iii) an analytics framework covering network, management and RAN analytics functions as a main driver towards full network automation. The overall architecture incorporates requirements, functions and interfaces for the resilience & security as well as resource elasticity functions.

Resilience & security (WP3): To target industrial use cases with strong requirements on reliable, resilient and secure network services, 5G-MoNArch developed concepts and functions pertaining to the following areas: (i) RAN reliability, including data duplication solutions over multi-connectivity; (ii) telco cloud resilience 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 developed concepts were integrated with the overall architecture, thereby enabling solutions that instantiate a network slice dedicated to resilient and secure services.

Resource elasticity (WP4): To target media & entertainment use cases with strong requirements on the network to handle spatial and temporal traffic fluctuations such as peak demands without incurring in severe Service Level Agreement (SLA) violations, 5G-MoNArch enhanced the flexibility of the virtualised and cloudified network through distribution- and orchestration-based solutions. A key tool for this accomplishment has been the introduction of Artificial Intelligence (AI) and Analytics / Machine Learning (ML)-based functions in different functionalities of the network, including the design of elastic virtual network functions, to allow graceful resource scaling for cloud resources. The derived solutions have shown an increase of the network resource efficiency, while allowing also for network self-dimensioning as well as smart resource management.

To verify and validate the architecture and to show the feasibility and applicability of the developed concepts in real environments, 5G-MoNArch built on the two project testbeds as well as the verification and validation framework:

Testbeds (WP5): two testbeds were implemented: the Smart Sea Port testbed in Hamburg and the Touristic City testbed in Turin. Both testbeds contributed to the verification of performance targets and served as a baseline for the techno-economic validation.

- Smart Sea Port testbed: This testbed addressed a set of industrial use cases and showcased the applicability and functioning of E2E network slicing to this end, relying on the following features: (i) control and user plane separation, (ii) slice isolation, (iii) service creation within minutes, and (iv) high reliability, resilience and security services implemented in a large-scale environment. The use cases comprised in this testbed were (i) mobile sensor connectivity (barges in the port), (ii) high reliable traffic management (connected traffic light) and (iii) mobile broadband augmented reality applications, each of them having its own slice on top of a common infrastructure.
- Touristic City testbed: This testbed addressed a media & entertainment use case in a touristic environment. It showed the applicability and functioning of E2E network slicing focusing on the following features: (i) 5G new radio interface, (ii) control and user plane separation and orchestration, and (iii) resource elastic services implemented in a live environment with real end users, through the introduction of AI solutions. The use case covers a virtual reality (VR)-based and interactive museum visit for visitors with a virtual remote tour guide, involving applications very sensitive to latency and performance.

Verification and validation framework (WP6): to quantify the technical and socio-economic benefits of the technologies developed in 5G-MoNArch, a framework has been defined comprising the evaluation process as well as the set of targeted technical and economic Key Performance Indicators (KPIs). The evaluation was performed along three representative evaluation cases defined by the project.

- Technical verification: three means of technical verification were leveraged by the project: (i) simulation results from the technical work packages, (ii) measurements from the testbeds, and (iii) a large-scale simulation-based approach which integrated a selection of algorithms from the technical work packages into a common large-scale scenario. As a result, it could be shown that all performance targets defined by 5G-MoNArch or standards can be achieved by the developed concepts and architecture with only minor constraints regarding simultaneous achievement at all locations.
- Techno-economic validation: the benefits of the implemented services together with trade-offs between investments and return on investment were studied along the three evaluation cases. This study by relied on dedicated business analysis toolsets and comprised results from the testbeds, interviews with various stakeholders from within

and beyond the scope of the use cases implemented in the testbeds. The outcome (provided in deliverable 6.3) represents an important output of the project with respect to the goals of 5G-PPP Phase II projects.

The project has fully achieved or even exceeded its objectives both in terms of technical results as well as with respect to the testbed implementation. The new flexible and adaptive 5G mobile network architecture makes network slicing actually usable in real-world implementations and can easily integrate additional use case- and scenario-specific functions even beyond reliability, resilience, security and resource elasticity. With the latter the requirements of industrial and media & entertainment verticals could be fulfilled such that their requested services can be implemented with the intended quality. This could be proven through the realistic testbeds as well as the outcome of the verification and validation framework, which has furthermore shown the economic feasibility and relevance of the proposed solutions. This outcome and results are substantiated with the project's successful impact by bringing its results to the relevant research communities and verticals through dissemination and standardisation activities. With more than 80 publications from partners at international conferences and workshops as well as magazine and journals, the project had a high impact on the overall research community. With more than 100 contributions to 3rd Generation Partnership Project (3GPP) and European Telecommunication Standards Institute (ETSI) standards submitted from the project work, 5G-MoNArch left a footprint on standards which will become part of future products. The project also had excellent visibility within the industrial community, attained through (i) the testbeds and several very well attended dedicated events organised at their premises, (ii) intense interaction with verticals stakeholders at these events and through dedicated presentations and interviews, (iii) the presence at Mobile World Congress (MWC) 2018 and 2019, and (iv) the participation to EuCNC and other events with own booths. Finally, it is worth highlighting that 5G-MoNArch has been awarded with the GSM Association's (GSMA) 2019 GLOMO for "5G Industry Partnership" for the Smart Sea Port testbed at MWC 2019.

Project Consortium

- Nokia Bell Labs, Munich, Germany (Coordinator, WP3 lead)
- Universidad Carlos III de Madrid, Spain (Technical Manager)
- Deutsche Telekom AG, Berlin / Bonn / Darmstadt, Germany (Innovation Manager, WP6 lead)

- ATOS SE, Madrid, Spain (WP5 lead)
- Commissariat à l'énergie atomique et aux énergies alternatives (CEA LETI), Grenoble, France
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- Hamburg Port Authority (HPA), Hamburg, Germany
- Huawei Technologies Duesseldorf GmbH, Munich, Germany (WP2 lead)
- Mobics Ltd, Athens, Greece
- Nokia Bell Labs, Nozay, France
- Nomor Research GmbH, Munich, Germany
- Real Wireless Ltd, London, United Kingdom
- Samsung Electronics Ltd, Chertsey, United Kingdom (WP4 lead)
- Telecom Italia, Torino, Italy (WP7 lead)
- University of Kaiserslautern, Germany

Conceptual and research results

Flexible and Adaptive Architecture Design (WP2)

A key contribution of the project has been the complete specification of the overall 5G architecture which has been provided with [5GM-D23]. This overall 5G architecture provides E2E slicing support building on the following novel functionalities: (i) specification of slice-specific and slice-common functions, (ii) multi-tenancy capable Management and Orchestration (M&O), (iii) inter-slice resource management, and (iv) optional integration of RAN control applications (see Figure 2). In addition to these design aspects, the overall architecture comprises further novel features: (i) Service-based characteristics spanning all layers with unified service-based interface design; and (ii) the ability to collect and analyse per-slice aggregated data, and to aid network optimisation via the novel E2E integrated data analytics framework. The proposed integrated data analytics framework comprises domain-specific data analytics functions, i.e., network data analytics function, management data analytics function, and RAN data analytics function, as well as the interworking between the aforementioned functions. It is envisioned that this framework will become an important milestone for network automation. The data analytics capability has been further introduced to RAN, where optional exposure to the controller layer is presented. In addition to the conventional reference point architecture description, the notion of inter-domain and intra-domain interfaces capitalising on the service-based architecture (SBA) principles has been introduced. This unified interface description enables the interactions between functions on the M&O layer and functions on the network layer, in order to achieve enhanced flexibility and orchestration capabilities. The unified SBA design is expected to be of particular relevance for future 5G releases beyond 3GPP Release 16.

The proposed novel architectural concepts have been contributed to the target standards with a particular focus on 3GPP SA2, SA5, and RAN3 working groups. Further collaboration took place with the GSMA to define the concept of 5G-MoNArch slice blueprint and to provide an efficient tool for designing and deploying network slices. The 5G-MoNArch Network Slice Blueprint concept is the universal means for such service-specific design and operations of network slices. Moreover, a use case and a proof-of-concept of 5G-MoNArch have been accepted at the ETSI industry specification group on Experiential Networked Intelligence (ENI), related to cross-slice elastic resource management and orchestration based on the 5G-MoNArch innovations. Finally, the 5G-MoNArch novel components have been integrated into the 5G-PPP Architecture working group white paper v3.0, which reflects the European view on the 5G architecture.

To realise the individual 5G-MoNArch features, a set of novel enablers and innovation elements have been developed that map onto three enabling innovations: (i) telco cloud-enabled protocol stack, which includes a telco cloud-aware protocol and interface design as well as a terminal-aware protocol design; (ii) inter-slice control and management, which includes inter-slice context-aware optimisation, resource management and a management & orchestration framework; and (iii) experiment-driven optimisation, which includes machine learning-based optimisation and measurement campaigns on the higher layers of the protocol stack. The final qualitative and quantitative analyses of all enablers were provided along with their impact on the 5G-MoNArch overall architecture and protocol stack [5GM-D23]. The definition of the 5G-MoNArch overall architecture includes the novel components along with the functional architecture descriptions of different domains. The specific protocols have been described via message sequence charts that are needed for the 5G system realisation. Furthermore, the specific instantiations of the 5G-MoNArch architecture with respect to the functional innovations developed have been provided, coupled with the associated testbed use cases, in order to demonstrate network slicing elasticity [5GM-D42] and resilience and security [5GM-D32] as shown in Figure 2.

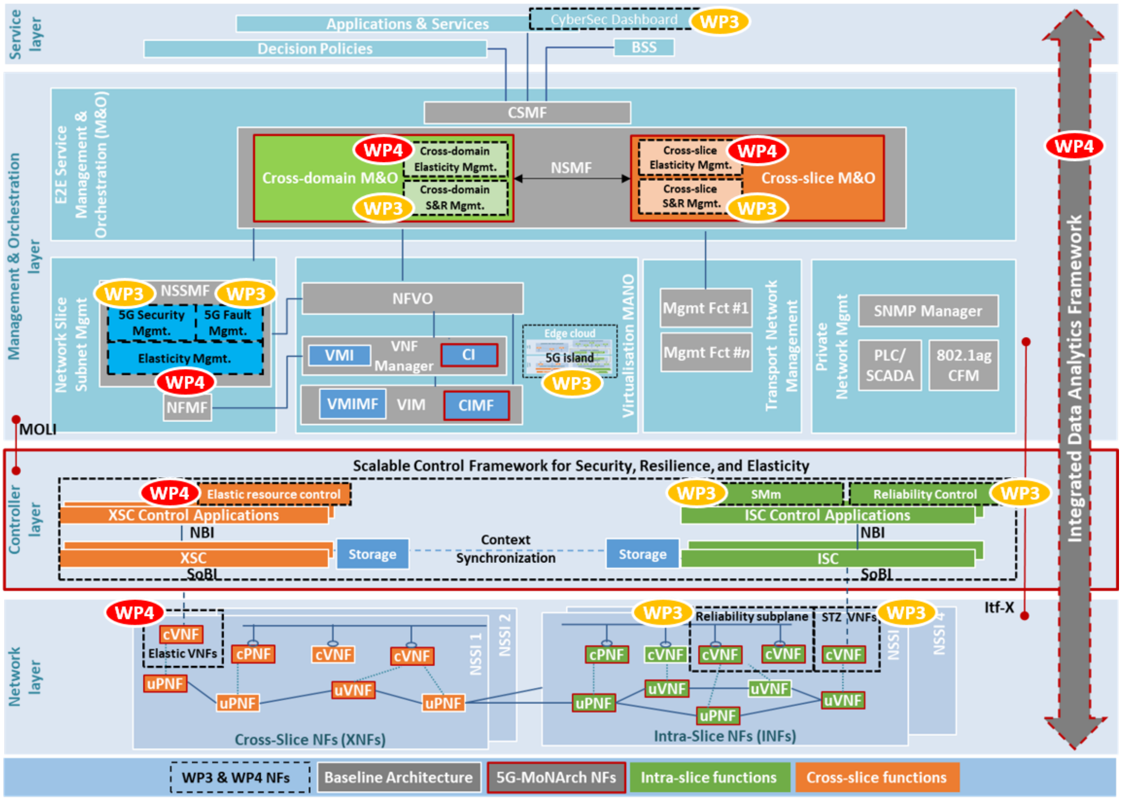

Figure 2: 5G-MoNArch final overall architecture; reference point representation where 5G-MoNArch introduced functions and WP3 and WP4 novel components are explicitly marked

Resilience and Security (WP3)

One key objective of 5G-MoNArch has been to leverage the 5G architecture to realise reliable, resilient and secure network slices reflecting particularly industrial requirements. For this purpose, a resilience and security framework together with a set of functional modules has been developed within WP3 [5GM-D32], consisting of three major working areas: (i) Link reliability at the radio access level (referred to as RAN reliability); (ii) Robust operation of Network Functions (NFs) at the telco cloud (referred to as telco cloud resilience); (iii) Secure operation of NFs across the entire network setup (referred to as Security). The framework includes the role definition of the developed modules and their interaction with the other modules of the overall architecture. Some of the WP3 solutions have been deployed in the Hamburg Smart Sea Port testbed.

For RAN reliability new concepts on the data duplication technique have been developed, which allows mobile terminals to receive multiple replicas of the transmitted data packet through separate distributed network units (see Figure 3), thereby increasing the probability of correct packet reception even in case of terminal mobility (handover) or adverse radio conditions. The concept assessment by means of system level simulations has shown a significantly improved RAN reliability (percentage of lost packets and latency for packet delivery), at the cost of overhead in throughput. As an alternative solution advances on network coding have been investigated which offer even higher levels of reliability provided that relatively long latency can be tolerated. Finally, a hybrid approach combining the advantages data duplication and network coding towards an optimal compromise between reliability and latency has been developed.

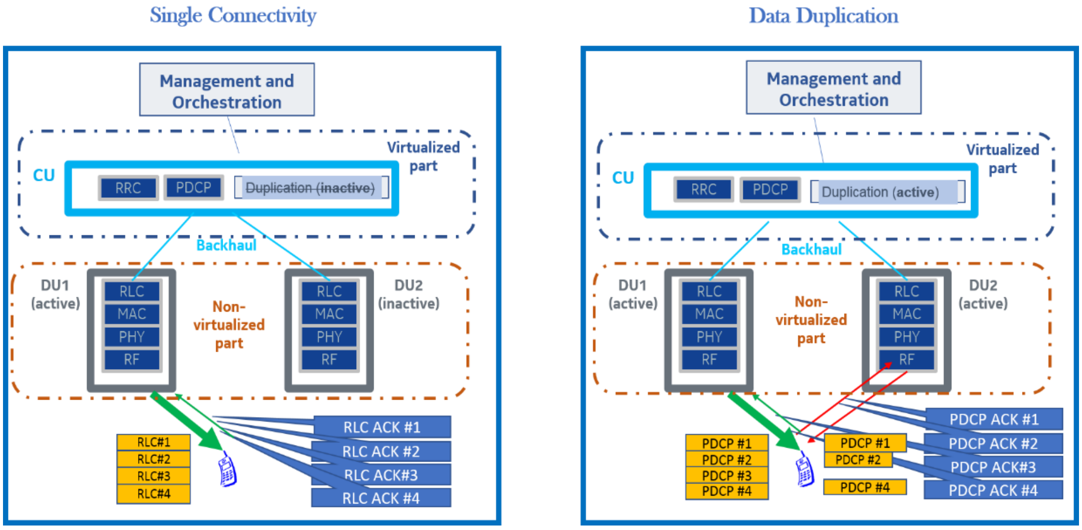

Figure 3: The concept of data duplication, where multiple replicas of packets are coordinated at a central network unit and transmitted to the terminal via distributed network units

Telco cloud resilience offers robustness of NFs at the telco cloud towards high levels of E2E network availability. The WP3 work has included the development of techniques for deploying cognitive NFs to identify and correlate the root cause of faults for effective fault mitigation. The concept of resource redundancy at the telco cloud has been investigated and assessed with respect to its ability to provide high levels of NF availability. Emphasis has been put on providing robust network controllers through a network controller scalability technique which minimises controller faults. Finally, the concept of “5G islands” allowing NFs to autonomously migrate from the central to the edge clouds without a central steering has been investigated.

Security aspects of 5G network deployments have been studied by WP3 with particular emphasis on industrial setups similar to the Hamburg Smart Sea Port testbed. In this regard a holistic threat analysis on the main components of a 5G network has been provided, including devices, network elements, and network slicing-specific security aspects. A study on the concept of security trust zones has been conducted including an investigation of their suitability in realistic 5G setups. Finally, an anomaly detection method has been developed, applicable for identifying potential abnormal network traffic behaviours thereby triggering security alerts.

Together with the individual studies on resilience and security, WP3 has conducted a joint study on resilience and security when deployed over common virtualised infrastructures. This involved synergies as well as common resource allocation considerations which assess the impact of fault management (FM) approaches to security management and vice versa. Results have shown an increasing efficiency of the telco cloud resource usage if resilience and security solutions interact with one another in common slice setups. Relevant use cases and results are shown in Figure 4.

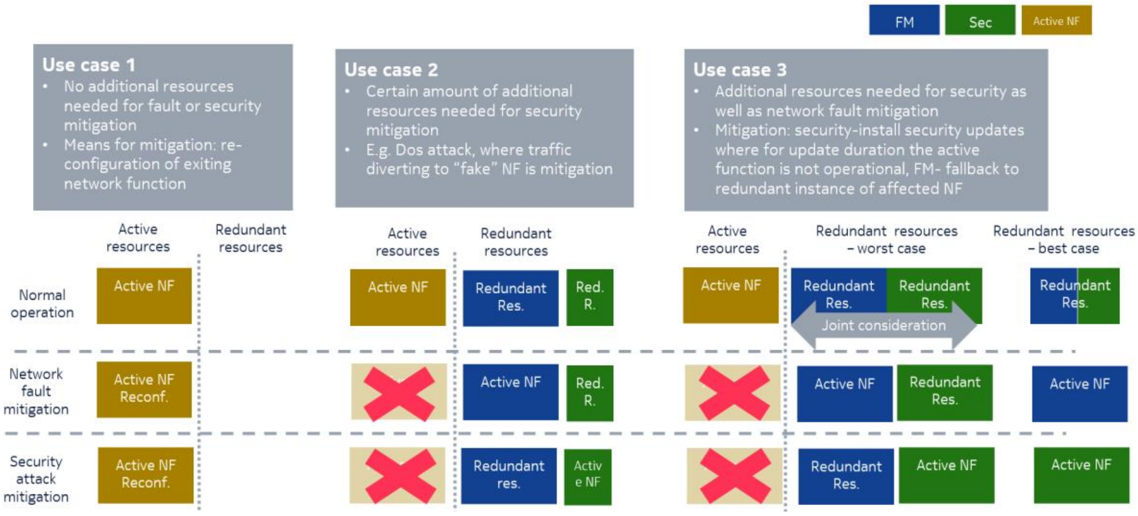

Figure 4: Synergies between fault and security management and relevant use cases

Resource Elasticity (WP4)

Resource elasticity addresses the challenge on the virtualised and cloudified 5G systems to provide a high level of flexibility, in order to host a great variety of verticals with very heterogeneous requirements. Resource elasticity represents a novel concept worked out in WP4 that aims at dramatically increasing computational resource efficiency in edge and central clouds, by reducing over-provisioning, while allowing for network self-dimensioning and smart resource distribution and orchestration, all of this assisted by AI and ML techniques. Some of the WP4 solutions have been deployed in the Turin Touristic City testbed.

The bulk of the WP4 work included the following areas: i) a comprehensive set of mechanisms and algorithms (14 in total) to provide elasticity to the network along the three dimensions of elasticity (computational, orchestration-driven, and slice-aware) as shown in Table 1; ii) the implications of resource elasticity on 5G network architecture, and iii) practical implementation aspects of elasticity including an experimental lab demonstration based on Open Air Interface (OAI) on elasticity at Virtualised NF (VNF) level.

AI/ML has been envisioned as the tool to enhance the performance of elasticity algorithms. To achieve an optimised utilisation of cloud resources in the complex 5G network, while providing desired SLA under 5G network slicing, fast and fine-grained AI/ML-based algorithms for M&O have been designed and fully integrated into the overall 5G architecture. This increases cost efficiency by avoiding both, resource under- and overprovisioning, which are the main causes of service outages and excessive expenditure.

Table 1: Challenges and solutions summary for the three elasticity dimensions

Elasticity dimension	Challenges	Solutions summary
Computational elasticity	Graceful scaling of computational resources based on load	VNF design accounting for computational resources
Orchestration-driven elasticity	NF interdependencies	VNF scaling and placing mechanisms accounting for central and edge clouds
Slice-aware elasticity	E2E cross-slice optimisation	Resource allocation mechanisms exploiting multiplexing across slices

Three examples of new elastic AI/ML-based algorithms along the three dimensions of elasticity (see Figure 5) that improve the elastic network lifecycle management performance are:

- A computationally elastic scheduler applying deep learning to signal-to-noise ratio prediction and the reinforcement learning technique of contextual bandits for making scheduling decisions. Thus, by exploiting this short-term prediction of the context, the algorithm can optimise the usage of the computing resources, by selecting the best amount of resources at any time.
- Slice-aware resource management based on traffic prediction using deep artificial neural networks (i.e., supervised learning). The usage of deep learning techniques can greatly benefit resource orchestration: specifically, the proposed algorithm finds the best trade-off between resource overprovisioning and the penalty incurred by unserved demand.
- Efficient slice setup using the unsupervised learning technique of spectral clustering. While instantiating a slice (composed, in turn, by several VNFs), the slices that are already being served may undergo re-orchestration to optimise the resource allocation, and our proposed algorithm computes it through unsupervised learning.

WP4 has developed the building blocks of an intelligent and elastic architecture, introducing AI/ML as built-in feature, including the specification of all relevant interfaces and high-level procedures for the elastic operation of the network and their components [5GM-D42]. This included detailed message sequence charts among the relevant interfaces for elasticity. The elastic architecture has been provided as an extension to ETSI ENI.

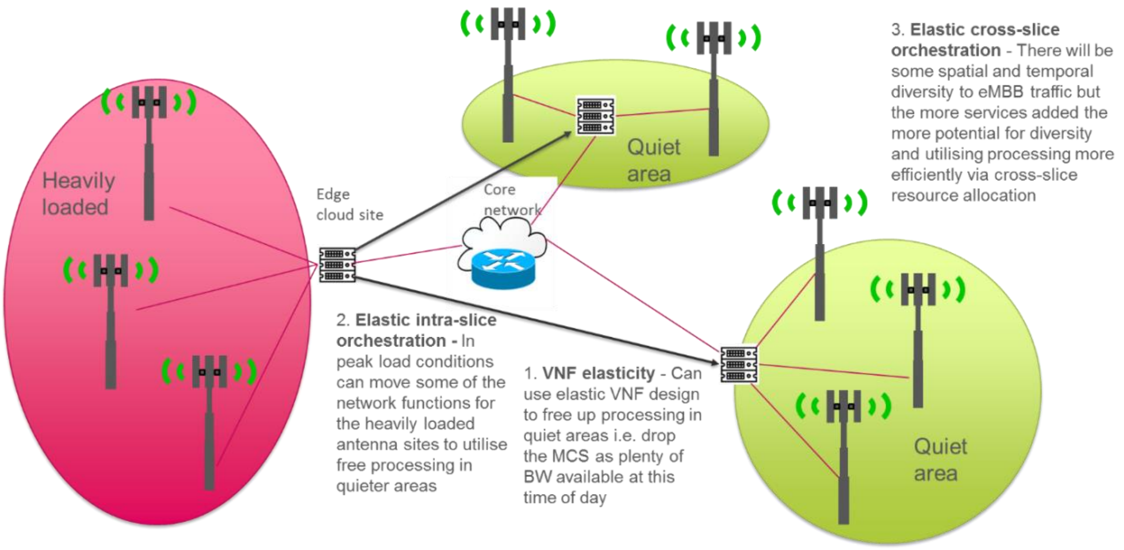

Figure 5: Illustration of where the three dimensions of elasticity impact equipment in the network

Some of the elasticity innovations have been implemented in the Touristic City Testbed, providing a view on how elasticity can improve the network operation with a real-world service. Furthermore, the demonstrator for computational elasticity based on OAI has allowed to test and proof the operability and effectiveness of the computational elasticity algorithms in the context of network slicing within typical mobile radio network deployments. The VNFs within the protocol stack have been extended with new functionality that facilitates self-inspection of the VNFs in terms of computational resource utilisation and interaction with a computational elasticity controller within the network architecture.

Implementation of the project testbeds

A central part of the work conducted within 5G-MoNArch was the implementation of the two testbeds within WP5 of the project that have showcased, proven and verified the applicability of network slicing, the 5G network architecture, and the 5G-MoNArch features and innovations with verticals-defined use cases and real-world network environments [5GM-D52].

Hamburg Smart Sea Port testbed

The Smart Sea Port testbed has evaluated the reliability, resilience and security concepts and the overall network architecture developed in 5G-MoNArch, and has deployed three network slices to address different industrial use cases and requirements within the Hamburg port area:

- An Ultra-Reliable Low Latency Communication (URLLC) slice for connecting a traffic light to the port's traffic control centre, to enable the improvement of the traffic flow for trucks within the port area.
- An enhanced Mobile Broadband (eMBB) slice serving interactive Augmented Reality (AR) for engineering teams to improve certain port operations such as asset maintenance and repair.
- A Massive Machine Type Communication (mMTC) slice to connect environmental sensors installed on mobile barges to the application cloud of Hamburg Port Authority (HPA) for measuring air quality in the port.

The testbed has deployed two base stations operating at a frequency of 700 MHz that cover the port area almost completely. The base stations have been built on commercial hardware with prototypic firmware / software and protocol stack providing full network slicing capabilities. Two terminal types using commercial router boards (multi-slice terminals for all use cases) and software defined radio with small-form-factor PCs (multi-connectivity terminals only for the mMTC use case) were deployed, both working reliably up to a distance of about 10km over the air. For the data centres hosting the slicing-enabled 5G core network, commercial servers have been deployed to a local (edge cloud) and a remote (central cloud) data centre of Deutsche Telekom. A specific slice design and lifecycle management tool has been developed. The setup and use cases of the testbed are depicted in Figure 6.

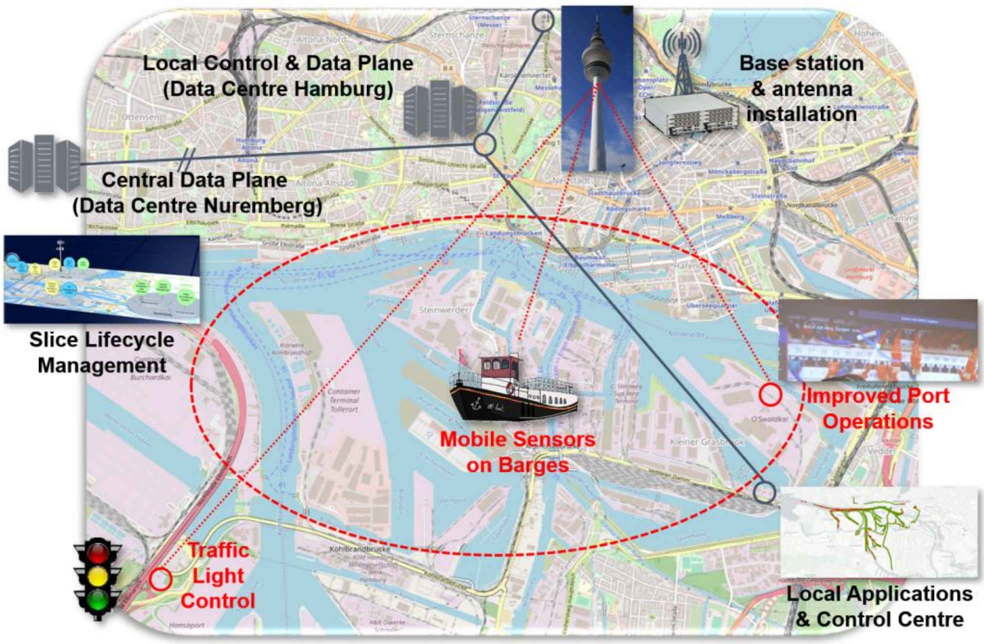

Figure 6: Hamburg Smart Sea Port testbed schematic setup and use cases

The testbed has demonstrated how network slicing can be applied in a real-live outdoor macro industrial deployment with high reliability, resilience and security requirements. In particular, the testbed has deployed multi-slice capable devices which connect to more than one network slice (logical network) providing different and isolated services that can be provided either from the edge cloud or the central cloud.

The deployment of the testbed in a real-world macro deployment using commercial data centres and transport network, and the full integration of the use cases with the operational environment of HPA (traffic control centre, applications control centre) as the testbed's vertical have already shown its high economic relevance. This has been clearly supported by a considerable interest and positive feedback during public presentations of the testbed to verticals and stakeholders of the port environment and beyond (e.g., smart cities, airports, transportation) which require reliable and secure mobile connectivity for their use cases. Moreover, the GSMA awarded the testbed with the Global Mobile (GLOMO) award on 5G Industry Partnership at MWC 2019. The socio-economic analysis conducted in 5G-MoNArch WP6 which has used the testbed as baseline for one of the evaluation cases further substantiated this relevance [5GM-D63], and these analysis results have started to be used for several business case descriptions of consortium external analyst companies. Finally, HPA stated that with the verification of the advantages and performance of 5G network slicing through the testbed, a commercial deployment of such technologies should start right away as they are crucial for the future of ports.

Figure 7 shows some pictures and screenshots of the testbed deployment and installation.

Figure 7: Hamburg Smart Sea Port testbed: base station at Hamburg TV tower (upper left), device installation for traffic light (upper middle), multi-connectivity device as installed on barges (upper right), slice lifecycle mgmt. tool (bottom left), KPI panel (bottom right)

Turin Touristic City testbed

The Touristic City testbed has evaluated the network elasticity concept and the orchestration techniques developed in 5G-MoNArch, and has deployed two network slices in order to provide visitors with an interactive Virtual Reality (VR) visit to the Palazzo Madama museum in Turin:

- An eMBB network slice that serves 360° videos to a 5G wireless connected VR headset.
- An URLLC network slice to handle all the other client-server communications (voice-over-IP, real-time multi-user interaction or the 3D models movement control).

The testbed has used a 5G radio interface implementing physical and medium access control layers as well as higher layers in compliance with the 3GPP standard including various functionalities aligned with Release 15. The physical layer has used software defined radio with reconfigurable parameters with the baseband unit implemented on a x86 platform. The eMBB and URLLC slices have used different bandwidth parts aiming at satisfying the different requirements for each slice in terms of latency and reliability. The testbed has implemented a full orchestrator for the VNFs based on an open source protocol stack (MANO) using OpenStack as virtual infrastructure manager. A specific graphical user interface has been developed to access relevant service metrics and KPIs. A schematic setup of the testbed is depicted in Figure 8.

The testbed has shown how AI can be used to smoothly adapt the resource utilisation in the network to the actual demand, namely, graceful degradation in case of overload situations which are typical for eMBB touristic or multimedia scenarios. The testbed has contributed to demonstrate the ETSI ENI approach as a viable technology for the improvement of the telecommunication networks, with the testbed being an official proof-of-concept of the group.

Generally speaking, VR is one application with a high potential and 5G is a fundamental enabling technology. The Touristic City testbed use case provides an interactive VR environment to visit the Madama Reale chamber at Palazzo Madama, where the end-user (located at the museum bookshop) can interact with a real tourist guide (located at a small wardrobe room) through their avatars and get involved in specific activities such as thematic tutorials or instructional games. The testbed showcased this feature through the implementation of a restauration tutorial, in which the tourist was involved.

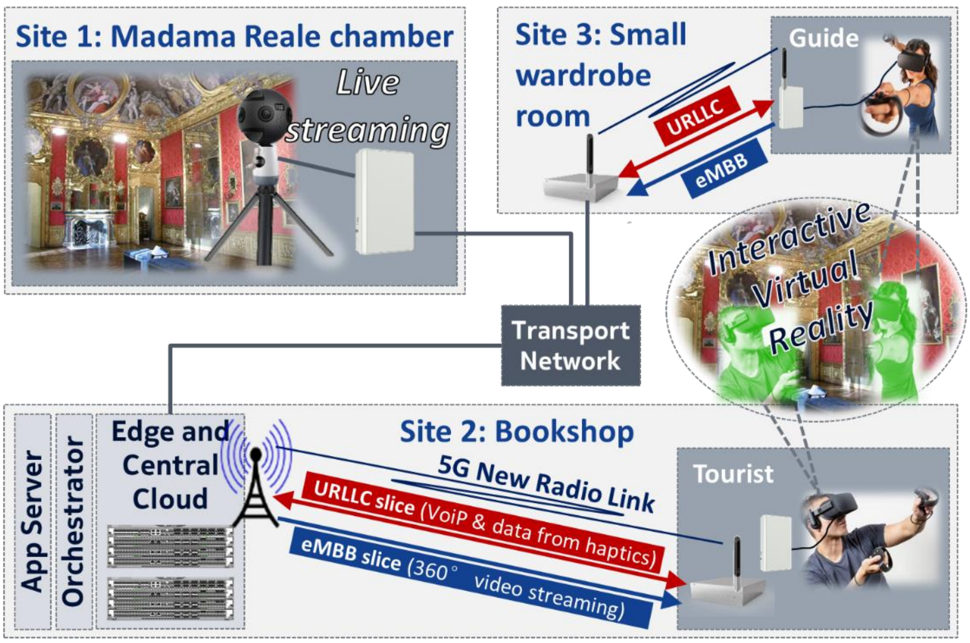

Figure 8: Turin Touristic City testbed schematic setup and use cases

According to the Fondazione Torino Musei, the museum operator representing the vertical involved in the testbed, enabling a solution such as the one provided by 5G-MoNArch can clearly improve the experience of a visitor at a museum and allows elderly people or people with reduced mobility in general to visit the museum remotely. The monetisation of this service would be linked to its exploitation by the museum operator who was already actively involved in the requirements definition and the development of this testbed and has shown interest in continuing its use after the end of the project. These considerations have been corroborated during the tests with real users (museum visitors), expressed through direct feedback and through a questionnaire asking about their willingness to pay a higher museum entrance in exchange of this improved experiences. The answer was positive in most of the cases.

Figure 9 shows the testbed live operation and deployment at Palazzo Madama.

Figure 9: Turin Touristic City testbed life demonstration with interactive Virtual Reality application running (upper); full setup at bookshop in Palazzo Madama with radio base station and monitoring GUI (lower)

Verification and validation of project results

5G-MoNArch established a verification and validation framework (WP6) across the whole project to quantify the technical and economic benefits of the developed architecture, functional innovations and enablers. The verification used technical, commercial and economic KPIs, including area traffic capacity, cost efficiency, E2E latency and reliability, re-orchestration delay, service creation time, and slice isolation. To assess KPI improvements, three evaluation cases have been defined and analysed within the Hamburg study area:

- Evaluation case 1 (EC1) – delivery of industrial services, requiring high reliability, in the Hamburg port area, by extending the existing wide area mobile network.
- Evaluation case 2 (EC2) – serving the temporary demand hotspots created by large cruise ships arriving in the Port of Hamburg more cost efficiently using elasticity.
- Evaluation case 3 (EC3) – delivery of smart city and vehicular services to the wider city area using the same extension of the existing wide area mobile network as in EC1.

Technical verification results have been gathered from (i) enabler specific simulation results provided by WP2-4, (ii) measurements from the two testbeds, and (iii) system-level simulations of the Hamburg study area (see Figure 10), leveraging a simulation tool that brings together a number of 5G-MoNArch selected enablers. These results demonstrate that all KPI targets set for the project are met with the 5G-MoNArch approach (see Table 2 and [5GM-D63] for details). For example, E2E latencies below 5 milliseconds are achievable by orchestrating the relevant network and application functions to be placed at data centres near to the antenna sites. Measurements of slice creation time have shown that new services/slices can be deployed within 6 minutes or less across a 5G-MoNArch-based network infrastructure (as demonstrated in both testbeds).

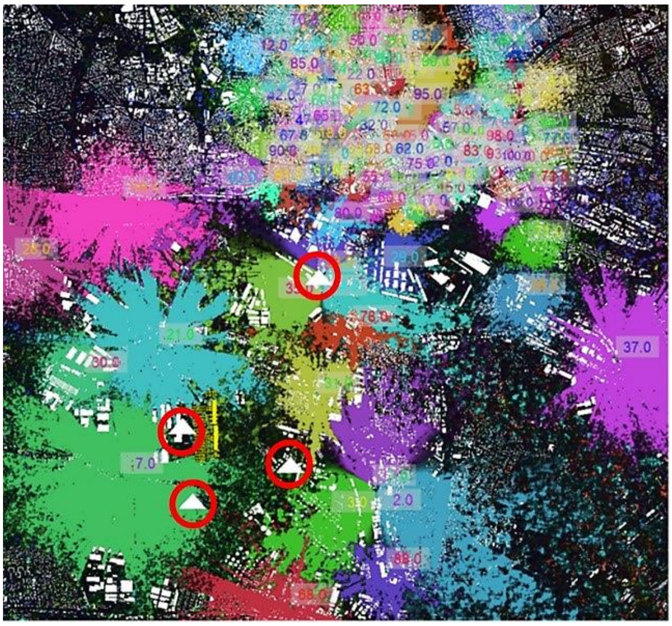

Figure 10: Network-level simulator screenshot for Hamburg study area with high-density city centre (upper part) and macro coverage port area (lower part) [5GM-D63]

Beyond the analysis of individual KPIs, trade-offs between the different KPIs have been studied in 5G-MoNArch. Results show that not all KPI targets can be met simultaneously for all services and at every location within a wide area radio network. Indeed, supporting all KPIs ubiquitously and simultaneously was never the intention of the project, as many services will only be required in particular locations. For example, improvements in area traffic capacity to serve eMBB demand hotspots will not be required or practical at all locations in the network. The provisioning of highly reliable services in areas overlapping with demand hotspots would reduce the availability of network resources for eMBB traffic, impacting its area traffic capacity.

Table 2: Performance objectives based on defined KPIs and achievements by 5G-MoNArch

KPI	KPI objective	Demonstrated by	5G-MoNArch results
Area traffic capacity	Improvement by factor ~10 (compared to non-5G systems)	Simulations / emulations	Reduction of used PRBs by a factor of 18.75 in low demand case across slices evaluated in EC2 slice-aware elasticity assessment. Capacity gains by dynamic reallocation of network resources across slices in the order of a factor of 10 for RAN and a factor of 2 for the Core Network. Techno-economic evaluations of EC2 show elasticity making hotspot deployments more cost effective and feasible (see "Cost efficiency")
Cost efficiency	(1) 5G-PPP Phase 1 economic analysis: TCO reduction of 14% (2) At least a factor of 2	(1) Economic analysis and measurements in both testbeds (2) Economic analysis and measurements in Touristic City testbed	(1) Total Cost of Ownership (TCO) reduction of 44% due to multi-service support via network slicing for industrial services, and (2) TCO reduction by between 38% and 68% for demand hotspot techno-economic analysis of EC2
E2E latency	5 milliseconds (for scenarios / slices / services where such latency is required)	Technical analysis Measurements in both testbeds	≤ 5 milliseconds E2E latency using elastic VNF orchestration
E2E reliability	Four or five 9's (dependent on scenarios / slices / services considered)	Simulations / emulations Measurements in Smart Sea Port testbed	99.999% with 1 millisecond latency using a URLLC air interface and a bursty traffic model EC1 commercial analysis shows feasibility of dimensioning for highly reliable industrial service of port automation
Relocation delay	No service disruption	Measurements in Touristic City testbed	No service interruption observed. The time required for relocation is a few milliseconds compared to ~74 minutes using a legacy solution
Security	Comparable to proprietary solutions	Simulations for Smart Sea Port testbed environment	Security Trust Zones can efficiently isolate and handle various types of threats. An average response time of 280 milliseconds was achieved against batches of threats occurring at different paces.
Service creation time	Minutes	Measurements in both testbeds	6 minutes or less to deploy a fully functional service after request
Slice Isolation	Changes in one slice without negative impact on other slices running on the same infrastructure	Measurements in both testbeds	Quality of Service in terms of throughput in a slice is ensured despite of high traffic load in another slice.

In addition to the trade-offs between technical KPIs, there is also very often a trade-off between the infrastructure investment required and the achievable KPI levels. This was investigated in the techno-economic analysis of the evaluation cases. This analysis focused on quantifying the (i) benefits of the services considered, and hence opportunities for new revenue streams or wider socio-economic benefits, and (ii) implications for network costs, which involved modelling the existing network in the Hamburg study area and dimensioning this to allow for new services using the 5G-MoNArch innovations.

Within EC1, the provisioning of wireless services to both HPA and other industrial users of the port area on top of a commercial eMBB network of a Mobile Service Provider (MSP) was considered. This included services such as Intelligent Transport Systems (ITS), automation of port machinery, environmental monitoring, and AR to support maintenance and construction. Figure 11 shows exemplarily the estimated annual revenues from industrial business applications in the port area for the MSP on top of eMBB over time, and the Total Cost of Ownership (TCO) required for service implementation. Combining revenues with additional network costs gave a positive business case for all EC1 services. The results show significant Return on Investment (ROI) gains of up to 20% (which was achieved when all industrial services were provided simultaneously from the same shared infrastructure set in our EC1 case study).

For EC2, the results achieved quantify the benefits of flexible on-demand resource allocation using the resource elasticity techniques in virtualised 5G networks. They emphasise the network cost reduction potential to cover temporary traffic demand hot spot deployments. Cost savings of more than 60% were found for the case study of a cruise ship terminal. These savings apply to the cost of a small cell network deployed in addition to the existing wide area mobile network to serve such a hotspot implementing suitable infrastructure sharing and elasticity mechanisms.

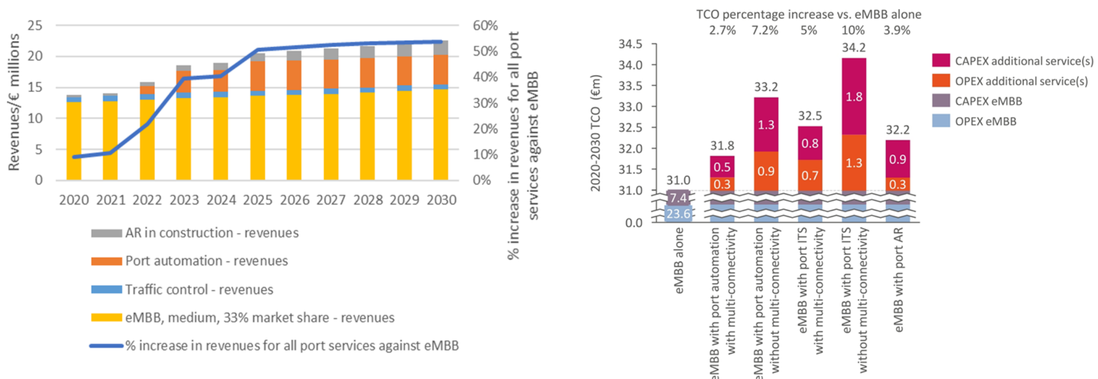

Figure 11: Estimated MSP revenues for additional sea port services on top of eMBB and TCO required for network implementation

Further techno-economic results considering the extension of the eMBB network in the Hamburg study area to not only accommodate industrial port services but also to deliver smart city and vehicular services to the wider city area, show that the commercial drivers are not sufficient for all 5G services. For example, the analysis of smart city services, such as city ITS, has shown a negative impact on the baseline eMBB ROI under current commercial models. However, these smart city services also have significant social and wider economic benefits. This implies that public private partnerships and/or new deployment models may be needed to ensure that the wider value of these services is not lost due to commercial pressures. The results also demonstrate that multi-service networks enabled by network slicing allow economies of scale, so that multiple tenants can be addressed more efficiently from a shared network infrastructure than being addressed individually.

Within the validation process, the claimed improvements in technical performance and economic and social value delivered by 5G-MoNArch's architectural approach were discussed with different stakeholder groups from the telecommunications industry, vertical industries, city councils as well as regulatory and governmental bodies (cf. stakeholder map shown in Figure 12). Especially, in the development and showcasing of the project testbeds, real verticals and end-users were involved. The feedback received, both from the sea port and tourism sectors, has confirmed that the services and use cases envisaged by 5G-MoNArch's testbeds are of clear importance. Furthermore, these use cases have the potential to generate both operational and wider socio-economic benefits. However, with the technology still seen as relatively immature and the business cases yet to be articulated more precisely, there is clearly some way to go in order to convince stakeholders that 5G is the right solution to deliver these applications. From this perspective, the verification activities undertaken in 5G-MoNArch have been welcomed to help demonstrate the technical ability of 5G and capture benefits against the levels of investment required.

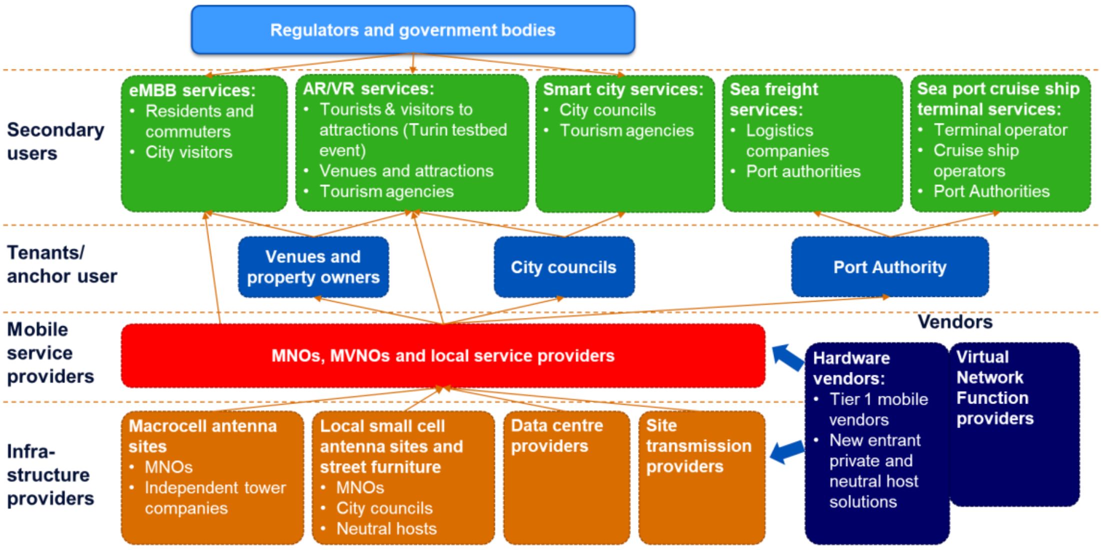

Figure 12: Stakeholder map used for the validation of socio-economic results

Dissemination, Standardisation and Exploitation results

5G-MoNArch has taken considerable efforts with respect to dissemination, standardisation and exploitation in order to maximise the technical and commercial impact of the project results. These activities have been coordinated within WP7 of the project

Regarding dissemination to the scientific community, a total of 39 papers at conferences and workshops (including ACM MobiCom, IEEE INFOCOM and ICC), 23 journal articles (including IEEE Transactions on Wireless Communications, IEEE Wireless Communications and IEEE/ACM Transactions on Networking) and 20 invited talks, presentations and keynotes have been produced by project members on the various technical results regarding network architecture, resilience and security, and resource elasticity. In total six workshops have been organised at international conferences. 5G-MoNArch has been present with own booths at the EuCNC conferences in 2018 and 2019, presenting intermediate and final research results as well as demonstrators, and the Touristic City testbed with full user experience in Valencia 2019.

On a broader front, the project achieved a strong impact through the Internet Website https://5g-monarch.eu (with more than 100000 visits) as well as the social channels (Twitter, YouTube, LinkedIn). A major role played the two dissemination events organised by the project with the focus to present the project results and in particular the operational testbeds to verticals and stakeholders: (i) in Turin in May 2019 for the Touristic City testbed and (ii) in Hamburg in June 2019 for the Smart Sea Port testbed and the overall project results. The presence and feedback by verticals and stakeholders were excellent in both cases, thereby underlining the timeliness of the project work as well as the technical and economic relevance of the technologies and results. To be mentioned here again is that the two testbeds were real-world implementations of verticals-defined use cases, involving these verticals directly in the deployment as well as real end users. This contributed considerably to the strong footprint of the project.

This timeliness and relevance of the project was underpinned through the presence at MWC in Barcelona in 2018 as well as 2019, with 5G-MoNArch being the only Phase 2 project selected twice by the 5G-PPP. While in 2018 the overall concept of the project was presented, the 2019 focus was on a live remote demonstration of the Smart Sea Port testbed, which attracted many visitors from vertical industries, mobile operators and regulators as well as media. The Smart Sea Port testbed was finally awarded with the 2019 GSMA GLOMO on 5G industry partnership. The presence at the European ICT event in December 2018, with a 5G-MoNArch organised networking session, further contributed to the interaction with stakeholders.

Contributing to standardisation has been a central focus in the project to promote the industrial impact of the results. Of highest relevance has thereby been 3GPP, especially SA2 (with more than 50 contributions) and SA5 (10 contributions), in addition to RAN (in particular, RAN 2 and RAN3). In ETSI, the project established an important liaison with the ENI group, where one elasticity use case from WP4 has been adopted as an official proof-of-concept. Further collaboration took place with GSMA on the network slice blueprint, cf. WP2 description.

Beyond the various dissemination and standardisation activities, the project has paid particular attention to exploitation of the results as well as the insights from the testbed deployment and operation within the partner organisations. Based on the scientific and research results several patent applications were filed to protect the partners' commercial interests. Many partners successfully used the results to impact their own business and improve their commercial solutions.

Conclusions and impact

The overall objective of 5G-MoNArch to make the 5G mobile network architecture actually usable in practice, by bringing it to the next step of evolution, has been fully achieved. Based on the requirements of real-world verticals' use cases, a flexible and adaptive network architecture framework that allows to fully integrate functions for industrial, media & entertainment, and smart city use cases has been developed. The applicability of this framework and the developed features for reliability, resilience, security and resource elasticity in real-world environments has been showcased and proven with the testbeds and the simulation-based verification. The techno-economic verification has gone beyond this technical feasibility and highlighted the economic advances of the developed solutions, which has been finally validated through stakeholders. This success of the project has led to substantial impact at different levels:

Impact from a European perspective: The technology developed by the project improves end-user access to high speed and better performing Internet services, which is one of the key pillars of the European Digital Agenda for 2020. Furthermore, by bringing innovative solutions to the market, 5G-MoNArch has contributed to the inclusive societies target by "closing the research and innovation divide in Europe" and "strengthening the evidence base and support for the Innovation Union and European Research Area." In terms of industrial strength, 5G-MoNArch has contributed to put Europe in the forefront of the development of 5G technology, which is a segment where Europe has traditionally been strong and seeks to preserve its leadership.

Impact on society: There are concrete social benefits resulting from the project use-cases:

- The Smart Sea Port use cases: There is an increasing request by citizens and authorities on solutions to optimise road traffic flows and avoid traffic jams. In parallel, cities and citizens are increasingly concerned by pollution issues in urban areas. These concerns apply to smart city, smart port, but also other scenarios. Corresponding applications have been implemented and proven within the Smart Sea Port testbed.
- The Touristic City use cases: One of the fundamental objectives of museums is to educate. With solutions as those developed by 5G-MoNArch, culture and education can be combined with entertainment, encouraging museums visits and promoting a better understanding of cultural heritage in society. This kind of solutions also contribute to make venues such as museums more sustainable.

Economic and commercial impact: 5G-MoNArch has clearly contributed to creating a more sustainable business model for the telecommunications sector, e.g., by proposing features and technologies that result in lower cost services and improve user experience. The project has developed a set of innovations and technical solutions with the potential to become commercial opportunities in terms of new products or service propositions. Some of the project partners who have developed them have filed for patents to facilitate the future exploitation of these innovations and have also developed 5G-MoNArch innovations on top of commercial products.

Impact on vertical players: With the two testbeds, the project could demonstrate the potential of 5G technology in real environments and engage with vertical players and end-users. The feedback received, both from the sea port and tourism sectors, has confirmed that the services and applications proposed under 5G-MoNArch's testbeds and verified in the evaluation cases are most relevant for them. The feedback received confirms that there are promising business opportunities based on 5G Network Slicing and new roles arising in the ecosystem.

Impact on standards: A substantial number of project contributions were made to 3GPP and ETSI out of which more than 70 were accepted or approved. These are essential for the adoption of the project innovations by the market.

References and Abbreviations

[5GM-D23]	5G-MoNArch Deliverable D2.3, "Final overall architecture", May 2019
[5GM-D32]	5G-MoNArch Deliverable D3.2, "Final resilience and security report", April 2019
[5GM-D42]	5G-MoNArch Deliverable D4.2, "Final design and evaluation of resource elastic functions", April 2019
[5GM-D52]	5G-MoNArch Deliverable D5.2, "Final report on testbed activities and experimental evaluation", June 2019
[5GM-D63]	5G-MoNArch Deliverable D6.3, "Final report on architectural verification and validation", July 2019

Deliverables download online: https://5g-monarch.eu/deliverables/

3GPP	3rd Generation Partnership Project
5G	5th Generation mobile wireless communication system
5G-PPP	5G Public Private Partnership
AI	Artificial Intelligence
AR	Augmented Reality
E2E	End-to-End
EC	Evaluation Case
eMBB	enhanced Mobile Broadband
ENI	Experimental Network Intelligence
ETSI	European Telecommunications Standardisation Institute
FM	Fault Management
GSM	Global System for Mobile communication
GSMA	GSM Association
HPA	Hamburg Port Authority
ITS	Intelligent Transport Systems
KPI	Key Performance Indicator
M&O	Management and Orchestration
ML	Machine Learning
MSP	Mobile Service Provider
MWC	Mobile World Congress
NF	Network Function
OAI	Open Air Interface
RAN	Radio Access Network
ROI	Return on Invest
ROI	Return On Invest
SA	System Architecture (3GPP WGs)
SBA	Service-Based Architecture
SLA	Service Level Agreement
TCO	Total Cost of Ownership
URLLC	Ultra-Reliable Low Latency Communication
VNF	Virtualised Network Function
VR	Virtual Reality
WG	Working Group
WP	Work Package