OPTIMIST: OPTIMised video content delivery chains over joint multI-accesS edge computing and 5G radio network infrasTructures

Dionysis Xenakis[1], Carlo Centofanti[2], Claudia Rinaldi[3], Andrea Marotta[2], Christos Verikoukis[4], Nikos Passas[5], Stefano Tennina[6], and Dajana Cassioli[2]

[1]DISIM - University of L'Aquila
[2]CNIT - Consorzio Nazionale Interuniversitario per le Telecomunicazioni
[3]Iquadrat Informatica, Barcelona, Spain
[4]Department of Informatics and Telecommunications of the University of Athens
[5]Fogus Innovations Services
[6]WEST Aquila s.r.l.

***Abstract*—The OPTIMIST project is positioned into one of the most challenging and societal impactful innovation paths, by contributing to the design and implementation of a Multi-access Edge Computing-empowered service platform enabling the optimized delivery of the most popular type of traffic in the forthcoming 5G networks: mobile video. Advanced prediction tools (e.g. data analytics), MEC-enabled service provisioning, 5G networking, QoE-driven and model-based service optimization using stochastic modeling and algorithmic optimization, are major components toward a holistic system that combines analytical tools and close-to-market technologies. In addition, despite the considerable amount of valuable academic research conducted in the area of MEC- enabled service provisioning, the vast majority of obtained results remains hardly compatible (in terms of system models and implementation platforms) and are often limited to the scope of academic research with no envisaged market transfer plans. OPTIMIST fosters fruitful collaboration of academia and industry targeting at developing an innovative platform for fully personalized delivery of 5G mobile video content.**

***Index Terms*—Multi-access edge computing, 5G networks, Quality of Experience, mobile video, service provisioning**

I. Introduction

THE 5th generation of wireless communication technology (5G) has enabled innovative services going from civil protection applications [1] through blockchain [2] up to virtual and augmented reality [3][4] or high quality video streaming to rely on the opportunity of transferring large amount of data with unprecedented speed, reliability, and connectivity guarantees [5]. The process has seen an essential step toward the commerciability with the delivery of the 3rd generation partnership project (3GPP) New Radio (NR) [6], which describes a new radio interface and includes considerations on architectural options toward the evolution of LTE-compliant networks to fully- fledged 5G systems.

Although NR incorporates a plethora of technological innovations, the current version of the NR architecture is not yet able to fully meet the ambitious goals set by the International Telecommunication Union (ITU) for the IMT-2020 5G system [7]. More specifically, although performance targets regarding the i) peak data rate (10Gbps), ii) network capacity (absorption of 1Tbps of data in a smart office), and iii) end-to-end (e2e) latency ($< 10ms$), are close to the capabilities of the current version of the Rel. 15 (Phase-1) NR, performance targets regarding i) 5G service availability close to 99.9%, ii) user- perceived latency lower than 1ms and iii) user-perceived rate of at least 1Gbps, are currently out of reach [8]. The main reason is that apart from attaining high data-rate communications using multiple antennas, ultra- dense networks (UDNs) and mmWave spectrum, fulfilling the IMT-2020 objectives is linked to the capability of 5G to fully harness the abundant processing, radio network and storage resources that already exist at the network edge (e.g. mobile terminals, base stations, third-party equipment). To this end, smooth integration of Multi-access Edge Computing (MEC) in 5G is a critical component for optimizing network performance, also opening new business opportunities for mobile network operators (MNOs), over-the-top (OTT) service providers and third-party software/infrastructure vendors.

However, the integration of MEC to the 5G network ecosystem is in an early stage of development, with the ETSI MEC group only recently releasing the first white paper [8] on how the ETSI MEC reference architecture [9] could fit into 5G. MEC capabilities have been long-viewed as the cornerstone for seamless delivery of personalized video content where, for example, MEC nodes can i) predict content popularity to locally store appropriate video chunks in the near area of mobile users and offload the radio access network (RAN) during on-peak periods [10] (reducing thus the user-perceived latency), ii) employ local transcoding on high-resolution videos to match the screen resolution of mobile terminals (enhancing thus the user-perceived rate), and iii) move relevant content and context close to the end user (increasing thus the user-perceived 5G service availability). Besides, recent studies report that users spend increasing amounts of time both streaming and sharing video, making video traffic the critical mass (forecasted to reach 74% by 2024 [11]) of all mobile data traffic. Spatial audio also offer a wide area of research in the low latency domain [12] and may be integrated into video streaming technologies thanks to MEC and 5G architectures. Current literature includes loosely-coupled studies on how specific MEC features can be used to optimize video content delivery to smart phones. On the other hand, current market lacks MEC-empowered products that are compatible with 5G NR and ETSI MEC.

The remaining of the paper is organized as follows: in section II the ambition of the project is described, the methodological approach that has been forseen is instead presented in section IV; section V reports about current advancements, while conclusions are drawn in section VI.

II. The OPTIMIST goal

The OPTIMIST program sets the ambitious aim to develop a modular end-to-end service platform tailored to the optimized delivery of personalized video content in 5G mobile networks, providing one of the first world-wide implementations of MEC-enabled service provisioning in 5th generation (5G) network that is fully compatible with the emerging ETSI/3GPP reference architectures. OPTIMIST acronym stands for *"OPTIMised video content delivery chains leveraging data analysis over joint multI-accesS edge computing and 5G radio network infrasTructures"*. To achieve this, the OPTIMIST service platform will design and implement different MEC services, which are currently studied in an isolated fashion in current literature, (e.g. edge network caching exploiting edge storage resources, video trans-coding and data-driven content popularity prediction exploiting edge processing resources, optimized video content placement and delivery exploiting the new 5G radio capabilities), in the form of virtual network functions (VNFs) that are instantiated and optimized on-the-fly to construct a video service chain that is designed to meet the personalized requirements of 5G mobile video consumers. To formalize the integration of MEC capabilities into the operation of 5G mobile networks, the OPTIMIST service platform will be fully aligned with the existing and forthcoming standardization activities in the areas of MEC and 5G networks (ETSI MEC and 3GPP); thus, maximizing the impact of the project in the long-term both in terms of academic results (new methodological tools and algorithmic innovations) and market products (deliver specific products / services that will enhance the portfolio of industrial partners). To this end, OPTIMIST will leverage state-of-the-art (SotA) technologies in MEC-empowered service provisioning, data-driven service control and automation, QoE-driven dynamic adaptive video streaming over HTTP (DASH), GPS-free localization and machine learning (ML) for wireless communications.

III. The OPTIMIST solution

The OPTIMIST project addresses the challenging problem of delivering 5G mobile video content at scale exploiting MEC/RAN integration with the 5G architecture. The MEC-empowered service placement will exploit forecasts issued by prediction-driven service automation (data analytics, model-based decision support). One goal is to adhere to the ETSI MEC reference architecture and the 3GPP NR standards. The platform developed by the OPTIMIST project will be based on optimized service modules based on the most recent State of the Art (SotA). The focus will be to optimize different parts of the End to End (E2E) video content delivery chain. To reach such objectives, many domains need to be exploited but they are currently studied independently in literature and are not yet integrated altogether [13]. An example is the concept of network caching, which is a well known topic in literature and studied in various forms (i.e.: proactive placement of video content close to end users during off-peak periods to reduce congestion and delays during on-peak periods). Those approaches propose few or none integration with 5G network architecture and with MEC architecture. This gap need to be exploited to provide improved Quality of Experience (QoE) at the video consumers' side (e.g. by incorporating information on the 5G radio status, or encompassing MEC-enabled proximity estimation) and low latency [14]. Similar arguments can be made for the existence of protocols that can readily incorporate up-to-date knowledge on the availability of different bitrates of the same cached video (near the end users) during the deployment of DASH, an emerging technology that enables mobile terminals to dynamically adapt the bitrate of the consumed video in line with the network status [15]. Besides, support of stateful services over MEC-enabled infrastructures dictates more sophisticated mobility management across loosely-coupled systems to guarantee service continuity, through the seamless transfer of specific context and content from one MEC server to another (across the route followed by the mobile user).

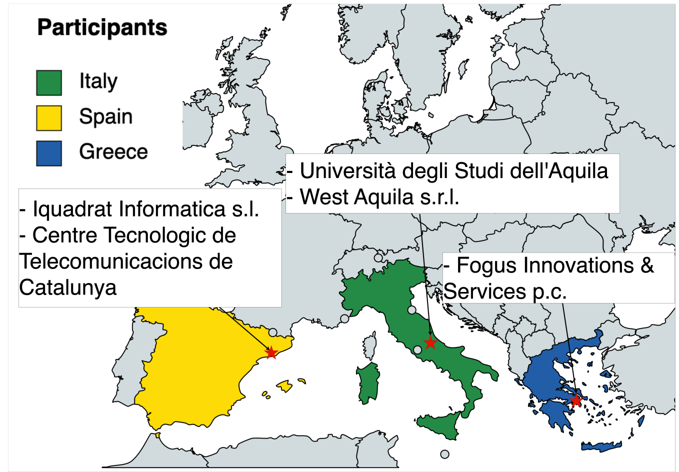

Fig. 1. OPTIMIST consortium.

A. Objectives

In view of that, the realization of the OPTIMIST video service platform is based on achieving a specific set of Research and Innovation Objectives (RIOs):

- RIO1. Conceptualize and develop a modular end-to-end video service delivery architecture integrating MEC-empowered service provisioning into the 5G network,
- RIO2. Design and implement a comprehensive MEC service orchestrator for the MEC-empowered support

of stateful video services across different MEC service platforms and 5G network coverage areas,
- RIO3. Design and implement a suite of enriched MEC services for the optimized delivery of video content in 3GPP and ETSI-compliant ICT infrastructures,
- RIO4. Design and implement an innovative protocol for dynamic adaptive video streaming over HTTP (DASH) that can incorporate up-to-date recommendations/knowledge from the MEC service orchestrator.

To complement the work towards the RIOs, OPTIMIST is pursuing the Technical Objectives (TOs) below:

- TO1. Design the OPTIMIST service modules and validate their performance using SotA evaluation tools,
- TO2. Integration of service modules into the OPTIMIST service platform, software verification and testing,
- TO3. Prototyping of the OPTIMIST service platform and testing in real-life scenarios.

B. Performance metrics

Through the entire project lifetime, the OPTIMIST RIO1-RIO4 as well as the complementary TO1-TO3 is targeted at fulfilling the following ambitious Measurable Performance Objectives (MPOs), all of which are in full accordance with the ITU requirements set for the 5th generation IMT-2020 [16] and 5GPPP[5]:

- MPO1. Provisioning of new video content delivery services in sub-minute scale,
- MPO2. Attain 5G video service availability close to 99.9% in the presence of MEC servers,
- Sub-decimetre (dm) accuracy in 99.999% of the cases in the presence of MEC servers,
- MPO4. Attain user-perceived latency lower than 1ms in the presence of MEC servers,
- MPO5. Attain user-perceived rate of at least 1Gbps in the presence of MEC servers.

IV. Methodological Approach

As previoulsy said, OPTIMIST aims to bridge the fundamental gap between academic (i.e. more theoretical and fundamental) and industrial research (i.e. more system-specific and devoted to solutions that can be implemented in real-life scenarios), endorsing the collaboration among experts in: i) designing advanced methodologies for data analysis tailored to MEC-enabled service creation, QoE-driven service optimization, cross- and intra-domain MEC platform management, and ii) implementing advanced modular NFV software encompassing advanced decision support on the E2E video delivery chain, fully harnessing the potential of MEC-enabled service provisioning and 5G networks. To this end, it is vital that the industrial partners transfer their deep know-how on development of software products and MEC-empowered services, tailored to real use cases and scenarios. Academic partners contribute in conveying their vast experience in optimization methodologies [17][18][19], algorithmic design and data analytics [20][21], and apply them in the context of video service provisioning over complex ICT infrastructures. Knowledge sharing is being attained through the implementation of research and innovation activities based on staff exchange between industry and academia. OPTIMIST Transfer of Knowledge (ToK) activities include:

- **Secondments** - The joint research work combines traditional academic research (e.g. SotA assessment, analytical modelling, computer simulations) with more hands-on development, such as software development (e.g. DASH mobile app, VNF/MEC service modules) and market products (OPTIMIST prototype). The secondments of 28 researchers have been planned based on the project requirements.
- **Advanced Teaching Modules** - OPTIMIST is engaging industrial fellows in the Master's programmes on Emerging ICT technologies and Networked embedded systems, to create advanced teaching modules where the industry market view complements academic background in emerging ICT technologies.
- **Co-Supervision of Students** - During their visits at academic institutions, researchers from industry are involved in co-supervision of MSc and PhD students. Each seconded researcher is or has already co-supervised at least one student during the secondment period.
- **Real-Life Experimental Testbeds** - OPTIMIST has a product-oriented methodology approach, planning the development of advanced software services by each project partner, including MEC service VNFs, DASH mobile application, a SotA simulator, and targeting to the implementation of a real-life experimental testbed realizing the e2e OPTIMIST service platform (WP6). The involvement of fellows in the design, analysis, implementation and e2e integration of the OPTIMIST simulator, service modules and service platform, is boosting knowledge sharing across beneficiaries and foster fruitful interactions outside the consortium as well (e.g. involvement of students in the assessment phase of the platform by using the OPTIMIST video delivery services).
- **Participation in Plenary Meetings** - All researchers are attending plenary project meetings (at least three per year), to present research achievements, compare results and methods, and understand how the project is organized and decisions are made. Video conferences are also periodically organized to coordinate the work towards the RIO, TOs, MPOs.
- **Interaction with Well-Structured Research Teams** - Academic partners organize internal meetings twice per month, discussing the achievements of the group (funded projects/proposals, technology transfer, etc.). Visiting researchers from industrial partners are attending these meetings and follow all research activities of the group. Likewise, industrial partners are committed to organize monthly meetings, allowing scientists from academia to get an overall view of the structure, organization, and operation of the company, becoming also aware of the project's implementation process and related products. Industrial beneficiaries will benefit from the feedback and advice of academic researchers to improve their products,

by encompassing relevant SotA tools and methodologies.

- **Participation in the Activities of Funded Projects** - The participation of beneficiaries in EU research projects is an additional asset for knowledge sharing. Each seconded researcher benefits from the interaction with people directly involved in these projects (e.g. 5GENESIS at Fogus, 5GSOLUTIONS at CTTC, AQUASENSE at West Aquila).
- **Organization of International Workshops** - As a part of the project the organization of two workshops and one conference is planned. In these public events, the results of the project will be presented, enabling exchange of opinions on ongoing research, enabling interaction with attendees outside the consortium to receive valuable feedback. Researchers from other MSCA projects will be invited (e.g. 5GSTEPFWD by IQU, SPOTLIGHT by UOA) enabling additional ToK.
- **Publications and "Conferencing"** - Complementary knowledge sharing is under achievement by the participation to scientific seminars, workshops, conferences. This provides valuable opportunities for networking with colleagues from all over the world, sharing views and ideas. The project plan assumes that each fellow will attend at least three of these activities during the secondment. OPTIMIST also fosters joint publications among beneficiaries in scientific magazines and journals.
- **Complementary skills for innovation training** - OPTIMIST places strong emphasis on transferable complementary skills, aiming to provide the OPTIMIST fellows with necessary skills to become team leaders in academia or industry. Therefore, a training programme of complementary skills is identified per fellow. Based on the expertise of each fellow, this program includes individual graduate courses available at the OPTIMIST academic partners and two specialized training courses.
- **Personal Development and Fulfillment** - During the project, the researchers are also enhancing or will enhance the knowledge of Spanish, Italian and Greek language and culture. This is instrumental asset to consolidate a common EU feeling across fellows.

A. The OPTIMIST timeline

OPTIMIST project started on the 1^{ST} of May, 2020 and will last for 48 months. It is articulated in 5 research Work Packages (WPs) (WP2 - WP6) and two management and dissemination/exploitation WPs (**WP1** and **WP7**). **WP2** is targeted to achieve RIO1, **WP3** targets to RIO2, **WP4** targets to RIO3 and TO1, **WP5** targets to RIO4 also playing a key role towards achieving MPO1-MPO5, whereas WP6 is targeted to the implementation of TO2 and TO3 towards the validation of MPO1-MPO5. The OPTIMIST WPs and their relation flows are shown in Fig. 2. In addition to the 324 PMs of research staff, the beneficiaries of the consortium will commit 81 PMs from their own resources without any additional funding requested from the European Commission. The OPTIMIST methodology is goint to be realized in three distinct phases.

1) : Phase 1: System requirements, platform design and development of OPTIMIST tools (WP2, activities in WP3 and WP4; M1-M18) This phase has seen academic and industrial beneficiaries working in synergy to: i) conduct thorough SotA reviews in the OPTIMIST fields according to the assignment of service modules made in Fig. 3, ii) specify technical requirements of the OPTIMIST service modules and define the E2E OPTIMIST service architecture in light of recent ETSI/3GPP standards, iii) identify necessary context, mobile big datasets and features, use cases and scenarios framework for 5G mobile video delivery, iv) establish a common view on the OPTIMIST service platform and create all necessary methodologies/tools towards the OPTIMIST RIOs, TOs, and MPOs. This phase has also asked to industrial beneficiaries to define methodological limitations and scalability issues to be considered during the OPTIMIST service platform design. They also had to release an initial business plan (including a potential market plan) for the designed modules and platform. Academic beneficiaries have to bring their experience in stochastic modelling (UOA/CTTC), algorithmic optimisation (UAQ), data analysis (CTTC/UAQ) and QoE-driven service provisioning (UOA), crystalizing SotA tools to be used. CTTC, a distinguished member of ETSI, will lead the design and specification of the ETSI-compliant OPTIMIST architecture.

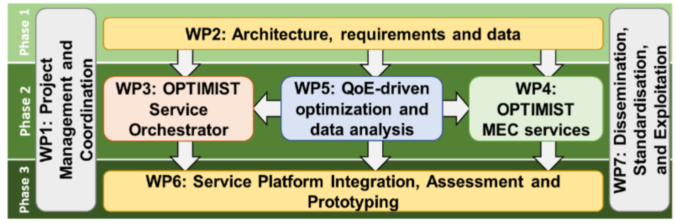

Fig. 2. OPTIMIST Work Packages.

2) Phase 2: Design, implementation and assessment of the OPTIMIST service components (activities WP3, WP4 and WP5; M19-M34): This phase was planned to conduct basic research towards the design and implementation of the OPTIMIST service components. Following the assignment of service modules in Fig. 3, UOA was required to deliver SotA designs and implementations for the orchestrator modules supporting E2E QoE control of the OPTIMIST video delivery chain (WP5), further covering aspects of stateful service support (WP3). Working closely with UOA and aiming to ensure seamless system-wide and E2E OPTIMIST service orchestration, IQU was required to harness its vast experience in SDN/NFV platform prototyping for 5G services (e.g. SEMIoTICS project) to provide appropriate E2E designs and implementations of the i) cross-platform management (WP3), ii) inter-host management (WP4) and iii) radio information/connectivity (WP4) service modules. Through the implementation of secondments to CTTC and UAQ, industrial fellows from FOG and WST had to leverage CTTC/UAQ experience in model- based and data-driven decision support towards the integration of advanced methodologies into the logic of the key MEC service modules (e.g. content caching in WP4 by FOG and mobility management by WST in WP3). Through the same process, CTTC and UAQ fellows had to identify practical limitations and scalability issues

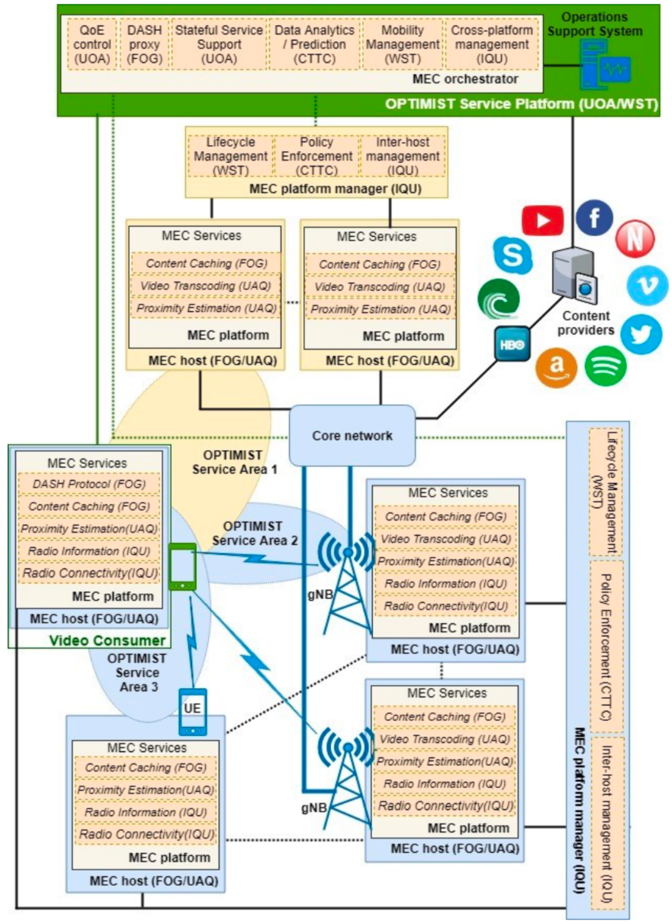

Fig. 3. OPTIMIST Architecture.

related to the design and implementation of the data- driven optimization mechanisms implemented by the Data Analytics/Prediction service module (CTTC in WP3) as well as to the deployment of the proposed proximity estimation/video transcoding mechanisms (UAQ in WP3). During this phase, WST was required to extend its OMNET++ simulation tool to accommodate the logic of the OPTIMIST service modules (orchestrator, platform manager, host) under a common system level simulator that is fully compatible with joint 5G/MEC infrastructures, providing valuable ground and insights towards the joint assessment of individual solutions (pre-integration phase).

3) Phase 3: End-to-end integration, joint optimization, proof-of-concept study and real-life experiments (WP6, activities in WP3, WP4 and WP5; M35 – M48): In this phase, OPTIMIST will aim to i) the rollout of individual service modules as market products (e.g. mobile application implementing the DASH protocol developed by FOG, VNFs for mobility and cross- platform management by WST and IQU, respectively) as well as to ii) the integration of individual service modules developed by all partners under the e2e OPTIMIST service architecture. To this end, WST will lead the joint performance assessment of the OPTIMIST service modules using the updated version of the OMNET++ SLS and together with UOA will lead the integration of service modules developed under WP3 and WP5 into the OPTIMIST service platform. In parallel, FOG and UAQ will join forces towards the implementation of MEC hosts integrating the OPTIMIST MEC services developed by UAQ, FOG, IQU under WP4. IQU will lead the integration of relevant service modules in the MEC platform manager, implementing two different setups: one for third-party MEC services and one for in-network 5G MEC services. CTTC will supervise the overall e2e integration with secondments implemented to FOG (responsible for the e2e integration of all service modules into the OPTIMIST service platform), contributing with its vast experience in e2e platform integration and large-scale performance evaluation. The outcome of this process will be jointly evaluated under the scenarios defined in Phase 1, providing new feedback to the final fine-tuning of individual service modules in view of the targeted objectives.

4) Technical workpackages content:

a) WP1: this WP carries out activities related to monitoring of project tasks and milestones, organization of project tasks and training events, management of the available funding and sources, organize plenary meetings, supervision of secondments and deliverable submission.

b) WP2: this WP lead activities on architecture, requirements and data. Task 2.1 on business cases and acquisition of methodogical tools has been completed together with technical requirements specification definition. An ongoing task started on Y2 and is related to the definition of the OPTIMIST service platform architecture.

c) WP3: is responsible to define the OPTIMIST service orchestrator in terms of design, integration and performance assessment. Task 3.1 succeeded to assest the SotA on service orchestrator design and interfacing. Task 3.2 is on design and implementation of the OPTIMIST service orchestrator modules and started on the second year of the project. Task 3.3 also started in year 2 and is related to service platform integration.

d) WP4: is based on MEC services. Task 4.1 worked on SotA assessment, MEC service design and interfacing producing the deliverable 4.1. Task 4.2 on the development of the MEC platform manager started during year 2 of the project and is ongoing. Tasks 4.3 and 4.4 will start during the 3^{rd} and the 4^th years.

e) WP5: is focussed on QoE-driven optimization and data analysis. Task 5.1 is about to end and is related to SotA assessment on 5G MEC service automation and QoE optimization. Tasks 5.2 and 5.3 started in year 2 and are about Data-driven and model-based service automation and QoE-driven service automation. Task 5.4 will start during year 3 and will manage the integration and performance assessment of QoE control and Data Analysis/Prediction service modules.

f) WP6: will start at the end of year 3 and will define service platform integration, assessment and prototyping of the OPTIMIST project.

g) WP7: this WP is related to the dissemination, the standardisation and the exploitation. Main contribution has been spent on D7.1 and D7.2 where publication of the obtained results in scientific journals and conferences, the participation to standardization bodies and the dissemination of information to special interest groups related with project outcomes, such as telecommunication operators and over the top service providers have been defined.

h) WP8: this WP on Ethics requirements is where the OPTIMIST consortium was asked to comply with ethics requirements, namely POPD.

V. Where we are

Basing on the project schedule Phases 1 and 2 should be concluded. Due to the COVID pandemic some of the milestones of the project have experimented some delay, but almost all the deadlines have been achieved in time or are close to be achieved. For the related technical WPs (WP2-WP6) it holds that: WP2 started on M1; WP3 started on M11; WP5 started on M10.

a) Phase 1: The consortium has collected, selected and assembled detailed information on user definition, usage scenarios and business requirements of the ETSI MEC architecture, with the emphasis given on mobile video content delivery which is the focus of the OPTIMIST service platform. Industrial partners have reviewed state-of-the-art tools towards implementation and real-life experimentation with the OPTIMIST service platform, while academic partners have specified potential algorithmic innovations, identified potential datasets and summarized existing modelling tools for developing and analyzing the OPTIMIST techniques [22]. Among the methodological tools that have been carefully reviewed and examined in light of their applicability within the OPTIMIST context, the OPTIMIST research team has reviewed recent work from the Open Container Initiative, comparing containers and VMs, on the Kubernetes Container orchestration engine, summarizing the potential of the Operator SDK (Ansible, Helm, Go) and the Operator Framework (Kopf, Java Operator SDK, Charmed Operator, etc.). Additional work has been conducted by reviewing the Kubernetes Cluster Networking CNI (Multus, OVS-CNI, Callico and Flannel), while emphasis has also been given in identifying Kubernetes production-ready distributions (kubeAdm, Kubespray, microK8s, Rancher, Openshigt, Airhship and k3s). Online optimization tools using federated learning and dynamic programming tools have also been overviewed.

Also, the consortium has conducted a meticulous study on existing documentation about the Multi-Access Edge Computing (MEC) architecture, with emphasis given in 5G/MEC integration. The MEC system consists of components which communicate one with another via communication links which are called “reference points”. MEC applications run on top of the virtualization infrastructure provided by the “MEC host” component, which can be described as an edge data center. The MEC applications create an environment for the MEC services which are produced and offered to the devices. The MEC Orchestrator component focuses on virtualization (or containerization) management tasks. It is a very important component which must maintain an overall view of the MEC system based on deployed MEC Hosts, available resources and available MEC Services. The consortium has put a lot of effort in identifying the key architectural and functional differences between the ETSI MEC and the ETSI NFV components, going very deep into the technical specifications of the OPTIMIST service platform in an ETSI MEC compliant fashion. A key characteristic in ETSI MEC architecture is that the applications and services must be deployed in multiple types of deployment, providing scalability. Accordingly, one requirement is that we must develop simple and controllable APIs that can be reused and sometimes controlled by the operator. At this point we had to understand and distinguish between the operator’s and the user’s needs. We can recall that ETSI group has standardized RESTful APIs with the help of OpenAPI 3 Specification. In extension to the APIs’ specification, we investigated the existing WEB Frameworks for python, in order to develop the REST services. Flask and Django 3 frameworks were two options. We investigated both of them in order to choose the most efficient and maintainable framework.

The consortium has detailed the OPTIMIST service platform architecture, taking into account standards and recent studies on the ETSI MEC, ETSI NFV and 3GPP NR architectures. The architecture was largely based on the DoA OPTIMIST reference architecture but has also been extended to account for additional features, including role’s specification per architecture component, APIs, open interface and information models definition, granting, lifecycle management, packaging and many more. The results of Tasks 2.1-2.3 were amalgamated in the project deliverable D2.1 that has been successfully delivered on time (M24) – April 2022.

b) Phase 2: The consortium has successfully conducted advanced research towards the design and implementation of the OPTIMIST service components. A deep state of the art has been conducted on Quality of Experience (QoE) for next generation mobile data networks incorporating Multi-access Edge Computing (MEC) capabilities. In particular, the interplay between DASH and edge network caching has been studied in slice-enabled mobile data networks [23] that can guarantee low latency [24] and some minimum rate performance [25] between i) the end user and the MEC-empowered cellular base station (BS) as well as ii) the MEC-empowered cellular BS and the content delivery network (CDN) hosting the full set of video bitrates and segments. Experimental results have demonstrated that network-agnostic DASH is incompatible with MEC-empowered edge network caching, while it further leads to severe under-utilization of reserved resources in MEC and slice-enabled mobile data networks. Accordingly, a novel mobile video streaming paradigm has been proposed where video bitrate selection and edge network caching are jointly optimized through coded video caching in line with the rate performance guarantees and the buffer reserved along the end-to-end content delivery path [26]. Formulating the aforementioned problem as a dynamic program (DP), a recursive algorithm has been developed to explore the full state space of the DP and an exact (optimal) algorithm of polynomial time has been derived to solve the joint network caching/video [27] bitrate selection problem independent of the optimization criterion under scope. A detailed complexity analysis provides valuable insights on the structure of the problem and draws useful guidelines for MEC-enabled video streaming in slice-enabled 5G/B5G networks.

VI. Conclusion

The OPTIMIST project sets ambitious goals with respect to the current state of the art on end-to-end video delivery service platforms. Initial results are demonstrating that the plan is working properly. Indeed, some of the targeted scientific outcomes have already been obtained in terms of advancements w.r.t. current SotA on MEC/RAN integration, NFV in 5G mobile data networks and MEC-empowered service provisioning for stateful video services, MEC host service modules. Moreover, even if there have been important problems in secondments organizations due to the COVID pandemic, those that have been carried out have demonstrated the fruitful outcomes of a proper collaboration between industry and academic. Future works are focused toward the complete fulfillment of OPTIMIST goals.

Acknowledgment

A special thanks to all the OPTIMIST consortium people that have worked on the OPTIMIST proposal on which this paper is based on. The OPTIMIST project is funded from the EXCELLENT SCIENCE - Marie Skłodowska-Curie Actions under grant agreement n° 872866.

References

[1] F. Franchi, A. Marotta, C. Rinaldi, F. Graziosi, and L. D'Errico, "Iot-based disaster management system on 5g urllc network," in *2019 International Conference on Information and Communication Technologies for Disaster Management (ICT-DM)*, 2019, pp. 1–4.

[2] D. Xenakis, A. Tsiota, C.-T. Koulis, C. Xenakis, and N. Passas, "Contract-less mobile data access beyond 5g: Fully-decentralized, high-throughput and anonymous asset trading over the blockchain," *IEEE Access*, vol. 9, pp. 73 963–74 016, 2021.

[3] C. Rinaldi, F. Franchi, A. Marotta, F. Graziosi, and C. Centofanti, "On the exploitation of 5g multi-access edge computing for spatial audio in cultural heritage applications," *IEEE Access*, vol. 9, pp. 155 197–155 206, 2021.

[4] T. Di Mascio, L. Tarantino, G. De Gasperis, and C. Pino, "Immersive virtual environments: A comparison of mixed reality and virtual reality headsets for asd treatment," in *Methodologies and Intelligent Systems for Technology Enhanced Learning, 9th International Conference*, R. Gennari, P. Vittorini, F. De la Prieta, T. Di Mascio, M. Temperini, R. Azambuja Silveira, and D. A. Ovalle Carranza, Eds. Cham: Springer International Publishing, 2020, pp. 153–163.

[5] H. E.-G. action, "Final report on programme progress and kpis," December 2017, accessed: 3-3-2023. [Online]. Available: https://5g-ppp.eu/wp-content/uploads/2017/10/Euro-5G-D2.6_Final-report-on-programme-progress-and-KPIs.pdf

[6] E. T. . . V15.3.1, "5g; nr; overall description; stage-2," October 2018, accessed: 3-3-2023. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/138300_138399/138300/15.03.01_60/ts_138300v150301p.pdf

[7] R. I.-R. M.2410-0, "Minimum requirements related to technical performance for imt-2020 radio interface(s)," November 2017, accessed: 10-5-2023. [Online]. Available: https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2410-2017-PDF-E.pdf

[8] E. W. P. N. 28, "Mec in 5g networks," June 2018, accessed: 10-5-2023. [Online]. Available: https://www.etsi.org/images/files/ETSIWhitePapers/etsi_wp28_mec_in_5G_FINAL.pdf

[9] M. access Edge Computing (MEC); Framework and R. Architecture, "Multi-access edge computing (mec); framework and reference architecture," January 2019, accessed: 12-5-2023. [Online]. Available: https://docplayer.net/133399022-Etsi-gs-mec-003-v2-1-1.html

[10] C. Centofanti, A. Marotta, C. Rinaldi, F. Franchi, D. Cassioli, and F. Graziosi, "Improved dash video streaming performance by mec-enabled optical access," in *2021 Asia Communications and Photonics Conference (ACP)*. IEEE, 2021, pp. 1–3.

[11] Ericsson, "Ericsson mobility report," November 2018.

[12] C. Rinaldi, F. Franchi, A. Marotta, F. Graziosi, and C. Centofanti, "On the exploitation of 5g multi-access edge computing for spatial audio in cultural heritage applications," *IEEE Access*, vol. 9, pp. 155 197–155 206, 2021.

[13] T. Taleb, K. Samdanis, B. Mada, H. Flinck, S. Dutta, and D. Sabella, "On multi-access edge computing: A survey of the emerging 5g network edge cloud architecture and orchestration," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 3, pp. 1657–1681, 2017.

[14] C. Centofanti, A. Marotta, D. Cassioli, F. Graziosi, V. Gudepu, and K. Kondepu, "End-to-end slicing via o-ran and software defined optical access," in *Optical Fiber Communication Conference*. Optica Publishing Group, 2023, pp. W3F–4.

[15] E. Liotou, K. Samdanis, E. Pateromichelakis, N. Passas, and L. Merakos, "Qoe-sdn app: A rate-guided qoe-aware sdn-app for http adaptive video streaming," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 3, pp. 598–615, 2018.

[16] M. Series, "Minimum requirements related to technical performance for imt-2020 radio interface (s)," *Report*, pp. 2410–0, 2017.

[17] L. Pomante, "Hw/sw co-design of dedicated heterogeneous parallel systems: An extended design space exploration approach," *IET Computers and Digital Techniques*, vol. 7, no. 6, pp. 246–254, 2013, cited By :15. [Online]. Available: www.scopus.com

[18] V. Muttillo, L. Pomante, M. Santic, and G. Valente, "System c-based co-simulation/analysis for system-level hardware/software co-design," *Computers and Electrical Engineering*, vol. 110, 2023. [Online]. Available: www.scopus.com

[19] L. Pomante, V. Muttillo, M. Santic, and P. Serri, "Systemc-based electronic system-level design space exploration environment for dedicated heterogeneous multi-processor systems," *Microprocessors and Microsystems*, vol. 72, 2020, cited By :13. [Online]. Available: www.scopus.com

[20] G. Valente, T. Fanni, C. Sau, T. D. Mascio, L. Pomante, and F. Palumbo, "A composable monitoring system for heterogeneous embedded platforms," *ACM Transactions on Embedded Computing Systems*, vol. 20, no. 5, 2021, cited By :6. [Online]. Available: www.scopus.com

[21] G. D'Andrea, T. Di Mascio, and G. Valente, "Self-adaptive loop for cpss: Is the dynamic partial reconfiguration profitable?" in *2019 8th Mediterranean Conference on Embedded Computing, MECO 2019 - Proceedings*, 2019, cited By :8. [Online]. Available: www.scopus.com

[22] V. Muttillo, G. Valente, and L. Pomante, "Design space exploration for mixed-criticality embedded systems considering hypervisor-based sw partitions," in *Proceedings - 21st Euromicro Conference on Digital System Design, DSD 2018*, 2018, pp. 740–744, cited By :8. [Online]. Available: www.scopus.com

[23] D. Xenakis, A. Tsiota, and N. Passas, "Admission control and end-to-end slicing for video streaming in mec-empowered cellular networks," in *GLOBECOM 2022-2022 IEEE Global Communications Conference*. IEEE, 2022, pp. 3423–3428.

[24] C. Centofanti, W. Tiberti, A. Marotta, F. Graziosi, and D. Cassioli, "Latency-aware kubernetes scheduling for microservices orchestration at the edge," in *2023 IEEE International Conference on Network Softwarization (NetSoft)*, 2022.

[25] C. Centofanti, A. Marotta, G. V., D. Cassioli, F. Graziosi, R. H., B. C., and K. Kondepu, "End-to-end slicing of ran based on next generation optical access network," in *2022 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)*, 2022.

[26] T. M. Ayenew, D. Xenakis, N. Passas, and L. Merakos, "Cooperative content caching in mec-enabled heterogeneous cellular networks," *IEEE Access*, vol. 9, pp. 98 883–98 903, 2021.

[27] E. Liotou, D. Xenakis, V. Georgara, G. Kourouniotis, and L. Merakos, "Cache-enabled adaptive video streaming: A qoe-based evaluation study," *Future Internet*, vol. 15, no. 7, p. 221, 2023.