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MASTER THESIS

A review study of European R&D projects for satellite communications in 5G/6G era

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Supervisor: **Dr. Panagiotis Mathiopoulos,** Professor

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ΕΘΝΙΚΟ ΚΑΙ ΚΑΠΟΔΙΣΤΡΙΑΚΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΘΗΝΩΝ

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ABSTRACT

Over the last decades satellite telecommunication systems offer many types of multimedia services like Satellite TV, telephony and broadband internet access. The long-term technological evolutions occurred into state-of-the-art satellite systems altogether with the addition of new high throughput geostatic and non-geostatic systems, individual satellites can now achieve a peak bandwidth of up to Gbps, and with possible extension into satellite constellation systems the total capacity can reach up to Tbps. Supplementary, with systems latency being comparable to terrestrial infrastructures and with integration of several computer science technologies, satellite systems can achieve new & more advanced roles inside a heterogeneous 5G network's ecosystem.

In this thesis, we have studied European Space Agency (ESA's) and European Union's (EU) Horizon 2020 Research and Development (R&D) funded projects in order to describe the satellite capabilities within a 5G heterogeneous network, mentioning the impact of the evolution of digital satellite communications and furthermore the integration with the state-of the art & future terrain telecommunication systems by new technologies occurred through the evolution of electronic & free space optical communications alongside with the integration of computer science's technologies like Software Defined Networking (SDN) and Network Function Virtualization (NFV).

In order to describe this evolution we have studied the concepts of each individual project, categorized chronically and individual by its scientific field of research. Our main scientific trends for this thesis are:

- Satellite Integration studies & strategies into the 5G terrestrial networks
- Integration of SDN and NFV technologies on 5G satellite component
- Satellite's role in the Internet of Things applications over 5G terrestrial networks
- Satellite's role in Content Distribution Networks & internet protocols impact over user's Quality of Experience (QoE) over a satellite link
- The future proposals upon the evolution of Satellite systems by upcoming improvements and corresponding standards

Finally, we have created an Annex for technical details upon the evolution of physical layer of the satellite systems with the corresponding bibliography of this thesis for future study.

SUBJECT AREA: Telecommunications, Digital Satellite Communications

KEYWORDS: DVB-S2X, 5G, SDN, NFV, IoT, CDN, OISL, 5G Satellite Component

ΠΕΡΙΛΗΨΗ

Κατά τις τελευταίες δεκαετίες τα δορυφορικά συστήματα τηλεπικοινωνιών έχουν προσφέρει μια γκάμα από πολυμεσικές υπηρεσίες όπως δορυφορική τηλεόραση, δορυφορική τηλεφωνία και ευρυζωνική πρόσβαση στο διαδίκτυο. Οι μακροπρόθεσμες τεχνολογικές αναβαθμίσεις σε συνδυασμό με την προσθήκη νέων δορυφορικών συστημάτων γεωστατικής και ελλειπτικής τροχιάς και με την ενσωμάτωση τεχνολογιών πληροφορικής έχουν ωθήσει την αύξηση του μέγιστου εύρους των δορυφόρων στο 1Gbps σε μεμονωμένους δορυφόρους ενώ σε διάταξη αστερισμού μπορούν να ξεπεράσουν το 1 Tbps. Σε συνδυασμό με την μείωση του χρόνου απόκρισης σε ρυθμούς ανταγωνιστικούς με τις χερσαίες υποδομές ανοίγουν νέες ευκαιρίες και νέους ρόλους εντός ενός οικοσυστήματος ετερογενούς δικτύων 5ης γενιάς.

Σε αυτήν την διατριβή, αξιολογούμε επιδοτούμενα επιστημονικά προγράμματα έρευνας και ανάπτυξης της Ευρωπαϊκής Επιτροπής Διαστήματος (ESA) και του προγράμματος επιδότησης Horizon 2020 της Ευρωπαϊκής Ένωσης, προκειμένου να εξηγήσουμε τις δυνατότητες των δορυφόρων εντός ενός ετερογενούς δικτύου 5ης γενιάς, αναφέρουμε συγκεκριμένα αυτά που αφορούν την εξέλιξη των δορυφορικών ψηφιακών συστημάτων και την ικανότητα ενσωμάτωσης τους σε τωρινές αλλά και μελλοντικές υποδομές χερσαίων τηλεπικοινωνιακών δικτύων μέσω της εμφάνισης νέων τεχνολογιών στις ηλεκτρονικές και οπτικές επικοινωνίες αέρος μαζί με την εμφάνιση τεχνολογιών πληροφορικής όπως της δικτύωσης βασισμένης στο λογισμικό και της εικονικοποίησης λειτουργιών δικτύου.

Αναφερόμαστε στους στόχους του κάθε project ξεχωριστά και κατηγοριοποιημένα στους ακόλουθους τομείς έρευνας:

- Συσσωμάτωση των δορυφόρων με τα επίγεια δίκτυα 5ης γενιάς με οργανωμένες μελέτες και στρατηγικές
- Ενσωμάτωση των τεχνολογιών δικτύωσης βασισμένης στο λογισμικό και εικονικοποίησης λειτουργιών δικτύου στο δορυφορικών τμήμα των δικτύων 5ης γενιάς
- Ο ρόλος των δορυφόρων σε εφαρμογές του διαδικτύου των πραγμάτων σε συνάφεια με τα χερσαία δίκτυα 5ης γενιάς
- Ο ρόλος των δορυφόρων στην δίκτυα διανομής πολυμεσικού περιεχομένου & η επιρροή των πρωτοκόλλων διαδικτύου στην ποιότητα υπηρεσίας χρήστη κατά την διάρκεια μιας δορυφορικής σύνδεσης.
- Μελλοντικές βελτιώσεις και εφαρμογές στα δορυφορικά συστήματα με έμφαση στα μελλοντικά πρότυπα του φυσικό επιπέδου

Στο τέλος διαθέτουμε ένα παράρτημα που αφορά τεχνικές αναλύσεις στην εξέλιξη του φυσικού επιπέδου των δορυφορικών συστημάτων, συνοδευόμενο με την συσχετιζόμενη βιβλιογραφία για περαιτέρω μελέτη.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ: Τηλεπικοινωνίες, Ψηφιακές Δορυφορικές Επικοινωνίες

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: DVB-S2X, 5G, SDN, NFV, IoT, CDN, OISL, Συνθετικό δορυφορικό κομμάτι των 5G

To my parents.

To Nick, Panagiotis, Christos, Giorgos & Christos.

To Eirini, Nikos & Dionysis.

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PREFACE

This overview has been conducted within the timeline of July 2019 to August 2021 using data from final reports of ESA's projects cross-referenced with technical reports from E.U. funded projects around the globe, some of them still under progress as a consequence they might not serve yet deliverable reports nor scientific papers therefore the author has conducted research based on general and technical information from each individual project's website. It is possible for academics, scientists and students to request further details of each project by ESA's ARTES 4 program Website via registration and EU CORDIS database's website.

1. INTRODUCTION

We are living today in the world of digital communications. Through the new era of 5G telecommunications, the people of this world will be able to experience several types of entertainment simultaneously, like high quality video streaming, broadband internet access, and the up-coming Virtual Reality applications altogether with critical response applications like health robotics operations, autonomous vehicles and IoT-based applications like drone farming.

Over the last decade the satellite industry through funded projects has tried to solve the question of global network coverage, mostly based on geo-static orbit satellite (GEO-satellites & constellations) but it doesn't produced solutions to meet 5G specifications because of several reasons, the most significant the excessive time for round trip (RTT) of satellite RF signals that can be translated as excessive big latency, especially for quick-responsive data-exchange scenarios like VoIP calls. Lower orbit systems must also become applied so satellite industry can offer complement solutions for 5G and quick responsive applications with corresponding stability (e.g. M2M communications & online gaming). Over the past decade, several studies have been conducted in order to answer the question if the satellite systems can act as a valuable asset for 5G services.

The satellite systems of the future are planned to operate into a hybrid state of using electrical and optoelectronic interfaces for data transmission, several standards for transmission with more extended spectrum which concludes millimeter wavebands, supplementary the current and future Low-Orbit (LEO) constellations with Medium-Orbit (MEO's) and GEO's will be combined as part of the future Hardware Abstraction Layer of software-defined 5G networks for network automation, reduced latency over critical applications and improved configuration of their resources through techniques like network slicing and considering improvements for better and faster handshake on web service access with much better values of Quality Of Experience (QoE) than state-of-the-art implementations.

During our bibliographical research we have found many R&D reports related directly and indirectly with the research developed for producing high throughput satellites to complement the needs of 5G terrestrial networks. The most related projects we found offers a set of solutions to the modern industry for innovations, designs and releasing new technologies for creating hybrid terrestrial-satellite 5G networks combined into one ecosystem with the following capabilities:

- Full coverage of future Hybrid Satellite-Terrestrial 5G networks at the globe through backhauling operations
- Improved efficiency of Hybrid 5G networks on resources management through the integration of SDN / NFV technologies
- Operating cloud services through satellite links
- Improved response for the IoT dedicated networks e.g. Narrowband-IoT
- Uninterrupted and secure Video Broadcasting across the globe
- Improved web surfing and online gaming with close to zero-latency
- Improved inter-satellite connectivity through expansion techniques of the available spectrum including optoelectronic inter-satellite links (O-ISL) and security through new mechanisms like public-key style Quantum-key distribution.

Our research has found several projects implicating to the creation of broadband satellite services and their usage on applications like 5G backhauling. The European Space Agency through ARTES 4 Program which consists a big part of ESA's "SPACE FOR 5G" campaign (located in [1]), has executed many projects over the last years in order to guide the current industry to invest in the integration of satellite systems with 5G terrestrial communication systems, supplementary, European Union through the HORIZON2020 funding program has funded many scientific projects [2] producing testing platforms on many countries including Cyprus, Germany and North Korea. Within the following chapters we present them upon their scientific area and its individual time schedule as follows:

- Chapter 2 presents the projects that are focused on proposing industry solutions for satellite systems integration to 5G, some of them with physical or simulated testing platforms (Testbeds) in order to provide to the public audience a Proof of Concept for satellite services (PoC).

- Chapter 3 presents the projects that studied the impact of SDN & NFV technologies that will help in the integration of satellite systems to 5G terrestrial networks and their impact on cloud services.

- Chapter 4 focuses on the projects that studied the usage of satellite systems for drones & IoT communication.

- Chapter 5 presents the projects that focus on the satellite impact over cloud services. More specifically, studies for Content Distribution Networks (CDN) support & the impact of advanced internet protocols over satellite networks and overall Quality of Experience (QoE).

- Chapter 6 focuses on ongoing projects that will present in the near future improvements over satellite systems by term of physical layer, security & future applications towards 6G.

Concluding, into the main body of this research thesis we present the evolution of satellite digital communications and their possible roles into a 5G ecosystem, influenced by the material we gather from a big number of Research and Development (R&D) ESA projects and similar funded by the EU's Horizon 2020 program, producing a brief description of each project's goals and its proposals than have been applied into the 5G cellular networks state-of-art.

Finally, in Chapter 7 reports our conclusions and our considered scenarios for the future use of satellite systems over 5G and beyond. Supplementary, there is an Annex with technical reports upon the evolution of the satellite systems physical layer followed by the corresponding bibliography for further study.

2. SATELLITE COMMUNICATION SYSTEMS FOR 5G

Satellite industry until a few years ago was operating for special use cases, supplementary due to the lack of knowledge and technology available at the time the satellite telecommunication systems were only suitable for services like television signal broadcasting and internet broadband connections. Over the last decades many communication technologies have evolved opening new use cases for satellite systems and further involvement of satellite industry in assisting traditionally terrestrial services like backhauling. ESA & EU through HORIZON 2020 program have funded many R&D projects for the implementation of state-of-the-art and future satellite systems into a 5G/6G ecosystem.

In this chapter we are notifying the projects than provided public or academic, information about the required specifications of satellite systems under 5G network co-operation and procedures performed for standardization by the industry in order to identify the possible roles of satellites as a component of a 5G network. In summary, we report the projects historically in order to determine the timeline of standardization procedures and we mention in overall the standardization reports, the technologies required for the realization of a 5G satellite component & the tests that have been completed until nowadays for the feasibility of satellite systems operation for 5G traffic offloading & backhauling.

Concluding, we mention by the ongoing projects & the corresponding research and tests, the possible future trends that will impact the evolution of satellite systems in terms of standardization and performance under evaluation & commercial use.

2.1 ESA-FUNDED PROJECTS TIMELINE

The ESA has performed within the last decade, scientific research about the procedures that must take place in order to satellite systems become a part of 5G terrestrial networks in a new form of hybrid telecommunications ecosystem. We have listed them below by their chronologically order of their initiation:

- **OCEAN** (**O**bjective **C**ost-**E**ffectiveness **A**nalysis of broadband **N**etwork deployments) (2014-2017)

OCEAN was a project funded by the ESA to fulfill the need of creating a cost effectiveness report for implementing Geostatic Orbit High Throughput Satellites (GEO HTS) for direct internet connections to end users (home satellite internet) & perform backhauling operations in cellular terrestrial LTE networks wherever they exist in North Africa, Australia and alpine regions across the world. The cost effectiveness report, mentions a number of intermediate technological advancements some of them have been already occupied today.

The report has some very good Key Point Indicators (KPI) more specifically in the usable bandwidth by the satellite systems which is one of the first reports at its time for implementing satellite backhauling networks that use not only the old bandwidth spectrum of L & S bands but also Ka and Q/V bands for future deployment and integration, supplementary the mathematic formulas presented here seems to be very accurate for calculating CAPEX and OPEX values for future satellite systems deployment.

Considering its timeline of operations it achieved a very feasible study for creating a possible and industrial efficient timeline schedule to serve needs and services like broadband internet and multimedia content broadcasting, however it does not fulfilling the current state of the art needs of 5G networks. The project doesn’t report anything about MEO-LEO satellite constellations & their corresponding impact in its calculations, resulting in more expensive solutions than current state-of-the-art implementations and scenarios like Tesla’s SpaceX or ESA’s EDRS, it doesn’t also take into account technologies like the implication of SDN into the network, at the lifespan of the project because of lack of interest from terrestrial network providers in the above areas to adapt more backhaul solutions at its time, the project wasn’t completely accurate in its results and the corresponding areas about the efficiency of satellite integration such as end users throughput. In other words the project sustains a more 3G towards 4G research perspective instead of aiming directly to 5G solutions and its corresponding technologies and specifications.

The project has proved that under careful and accurate calculations that is possible for network providers to release sufficient solutions empowering distant alpine & rural areas to acquire broadband internet connections with the assistance of GEO HTS satellites but not with the currently required skills for 5G networks due to lack of interest and experimentation of the assisted industry at its timeline. [3]

- **SATINET** [**Sat**ellite communications (**Sat**com) **I**ntegration with LTE-based core **Net**work emulator] (2015-2018)

The objective of this project was to study and demonstrate the integration of mobile satellite networks in the 3GPP LTE core network, focusing on networking, management, control and system operational issues, through the specification and design of the necessary mechanisms (protocols, interfaces) and the development of a testbed emulator. The course of this project has been broken in two parts, to plan & design the integration architecture of satellites for the 5G terrestrial networks & to demonstrate the integration through a testbed platform under different use cases of territories for broadband connections to prove its efficiency.

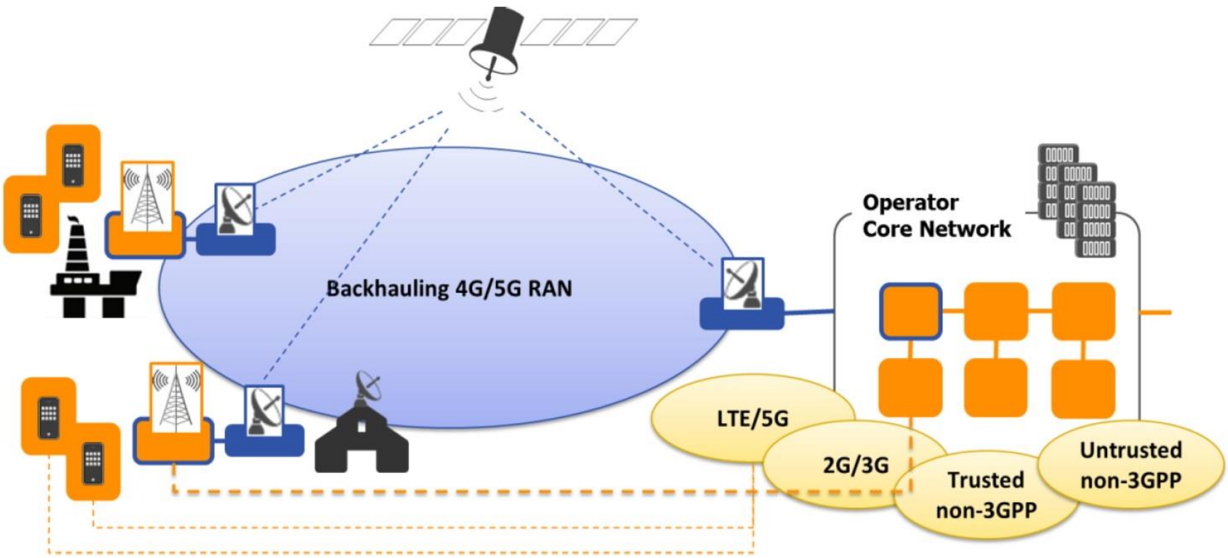

Figure 1: Illustration of a 5G ecosystem using a satellite as backhaul to connect remote areas and provide an alternative backhauling option to the terrestrial network [4]

The project offers a detailed analysis of the possible scenarios for satellite systems role in their integration with the terrestrial LTE systems as LTE network component and a corresponding high level technical analysis of their convergence layer, importing SDN technology as a medium for software convergence for all types of usages by using Open5Gcore protocol for network management within its simulations. Supplementary, it is one of the first performed analyses of a feasible 4G to 5G technological transition with the assistance of satellite systems, combined with a realistic 5G ecosystem simulation.

Under better management this project could offer better results by performing real-time tests with a satellite system instead of using a simulated GEO satellite system for its scenarios, supplementary it could take advantage of more advanced standards like DVB-S2X & DVB-RCS2. Also, it could add LEO satellites in simulations to collect data about the differentials in the responsiveness of the end users equipment when using internet-based services. It also doesn’t take into account more advanced techniques about Network functions in the convergence layer, like using SDN & NFV techniques for better interconnection between the terrestrial and the space segment for a unified future LTE network implementation.

The project in total, presents a feasible plan of the evolution of LTE networks with the assistance of satellite technology although its considerations aren't the optimal about the kind of satellites or standards compared to the current state of the art. However its significance is important do to the fact it is one of the first and certainly not least significant research projects form ESA that mention the satellites as a transparent 5G network component. [4]

- **SPECSI** (**S**trategic **P**ositioning of the **E**uropean and **C**anadian **S**atcom **I**ndustry) (2015-2018)

The SPECSI project was an ESA project for developing a roadmap for the satellite industry (satcom) examining the role of satellites in future communication networks and applications within the years 2020-2025. It studied emerging Information Communication Technology (ICT) trends to identify future opportunities for satcom and their associated system propositions.

It is the first reported study of ESA to determine how the European and Canadian satellite industry can be best supported through the ARTES 4 program. The scope of the study included geostationary and non-geostationary (MEO, LEO, HEO) systems, High Altitude PlatformS (HAPS) like ion/stratosphere drones, user and ground segments and any possible combination of them. More specifically, the project presented solutions over the challenges of 5G networks deployment taking into account the possibilities of all kinds of satellite & HAPS for internet backhauling. Supplementary, not only it takes into account various RF bands including Q/V bands and possible use of optoelectronic interconnections in satellite constellations for advanced efficiency, it also proposes possible deployment plans for all categories of satellites. The project serves many recommendations for solving issues like mapping of the available spectrum for satellite usage, coverage models & future satellite design for launch & deployment. The project presented simulated conditions of satellite operation over Arctic pole and also in North Africa in order to declare the satellite's capability for complete territory coverage.

One of the interesting aspects of this project is that it presents a theoretical background for taking advantage of the virtualization of network functions (NFV technology), however it doesn't perform deep analysis for computer science technologies such as SDN & NFV and it doesn't offer a specific guideline on how computer science industry's companies can effort to develop software and technologies that will promote an existence of a 5G unified & heterogeneous network via software implementations.

In conclusion, this project because of its recommendations in spectrum analysis and technological advancements plays a key role until today in the production steps of standardizations in groups like 3GPP in order to define satellite as a LTE network component within #15, #16 and #17 LTE releases, although in LTE release 16 and above exists an actual definition of a 5G satellite component. Moreover, the mentioning of optoelectronics opens new windows of opportunities for technologies that can be set as the future base for the operating of future 6G networks such as Quantum-Key distribution algorithms for advanced security which is explained in following chapters. [5]

- **METAMORPHOSIS** (TOPOLOGIES, ARCHITECTURES, BUSINESS MODELS, AND OPERATIONAL CONCEPTS FOR FUTURE VIRTUAL NETWORK OPERATIONS) (2017 - 2020)

METAMORPHOSIS was a technoeconomical research project to provide to satellite & terrestrial network industry a roadmap for establishing an integrated satellite terrestrial reference architecture enabling service integration across different forms of end user's services,

The project in order to establish that created a report defining reference scenarios, use cases, business models, value chain configuration evolutions, and associated requirements for 5G services for targeted types of network operation, supplementary defining an integrated satellite-terrestrial reference functional architecture, with the associated interfaces (APIs) and feasible overall management and orchestration (MANO) recommendations.

The project presents essentially a technoeconomical research with possible use for standardization purposes, it isn't a technical research. In other words it reports very few technical details upon the applicable satellite formations or standards in order to fulfill the specifications of presented use cases. [6]

- **ALIX** (Support to Standardization of Satellite 5G Component) (2017-2020)

ALIX was a EU funded project, established in order to develop a future guideline between ESA & 3GPP organizations for performing studies of standardization for satellite systems operation as a standardized 5G network component, studying its role over 5G Radio Access Network infestations (RAN) and its corresponding service and system aspects.

This project has one of the rarest reported roadmaps aiming to supporting active participation in the 3GPP standardization process to define the 5G satellite component and its interfaces with other networks as well as the creation of a critical mass of research to influence this standardization process. It identified for the modern industry possible roles for satellites in 5G as well as possible integration scenarios which are being characterized in 3GPP state-of-the-art Technical Reports (TR), supplementary it reports the regional industry associations on 5G that will implicate the satellites as a 5G network component, presenting a full list of industry standardization groups across the globe that will be present in 5G standardizations on ITU's IMT-2020 standardization with the timeline of operations from 2018 to January 2020.

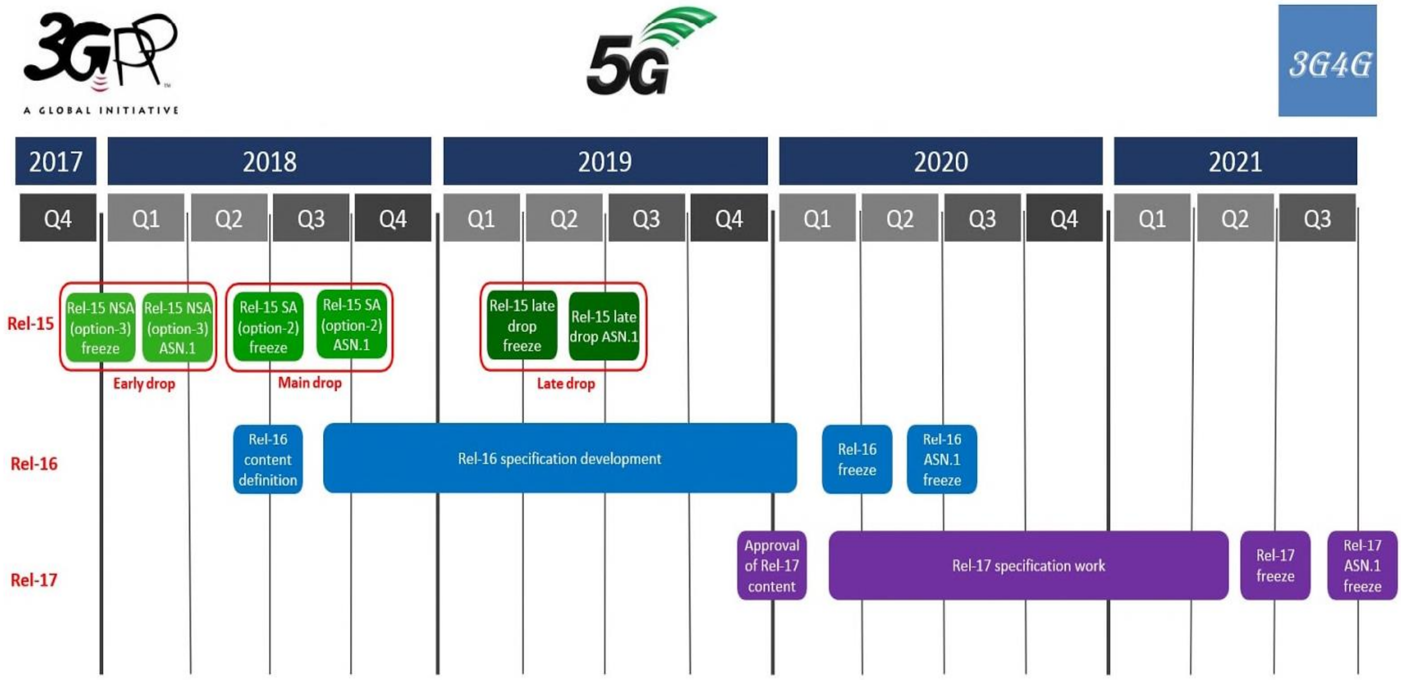

Figure 2: Originally 3GPP work plan on 5G created by 3G4G based on 3GPP roadmap until July 2019 – Timeline expanded due to COVID-19 pandemic [7]

It must be mentioned that the project's report hasn't determine the consequences of COVID-19 pandemic report on the research procedures of 5G satellite component standardization, supplementary the project it isn't a physical layer technical report instead it promotes several recommendations and 3GPP's TR's so future R&D projects may continue furthermore studies.

In conclusion, the project presents a timeline report about the establishment of a Standardization Special Interest Group, with the assistance of 3GPP in order to gather a number of satellite communication industry stakeholders, performing contributions to on-going studies for a standardized 5G satellite component existence as well as the relevant preparation of future study and work items which can be used as a base for future 6G services over the upcoming LTE releases above #19. [7]

2.2 HORIZON 2020-FUNDED PROJECTS TIMELINE

In many countries European Union has funded research programs by the Horizon 2020 funding program for the standardization of a 5G satellite component and technical research upon its physical layer. The projects in historical order can be described as follows:

- **RIFE** (architectu**R**e for an **I**nternet **F**or **E**verybody) (2015-2018)

RIFE was a European-funded research project which presented recommendations and some theoretical solutions about the question of coverage and offering broadband internet connections to countries and areas not capable of physical connection with their outer world or capable of perform more cost-effective broadband networks with the assistance of satellite over terrestrials.

The project is one of the first who provided recommendations for many broadband and multimedia use cases scenarios, supplementary it offers suggestions & strategies about creating possible network architectures and services and feasible guidelines for future manufacturers in order to create more efficient community internet networks than its current state-of-the-art solutions in distant territories like African rural areas combining all the existing technologies that GEO-HTS satellites could offer at that time period combined with an real-time experiment of implementation of its corresponding proposals via actual satellite network tests. [8]

The project although it solves the question of coverage in distant areas it doesn't fulfill the lack of knowledge in some research areas such as:

1. The project was focused on how in countries with no terrestrial network or very weak or in areas with urgent need for internet connection will be provided broadband internet connections everywhere, every time, to everybody. However it mentions generically the potential use of satcoms for backhauling and traffic offloading on the cellular networks in the mentioned areas which at the time mostly where 3G+ and in some cases 4G with their corresponding specifications & needs, in other words it doesn't take into account the specifications of a heterogeneous 5G network (i.e. latency & throughput).
2. The project mentions generically the potential of SDN/NFV technologies implementation whenever reported the best possible scenarios for packet routing/switching with the proposed network topologies, it doesn't analyze or describes a feasible roadmap or its consequence in the reduction of CAPEX and OPEX in a network.
3. The project mentions in RF transmissions the DVB-S & DVB-RCS for downlink and uplink channels with simple TDMA for user access with potential use of DVB-S2/DVB-RCS2, it doesn't mentioned more advanced standards nor user access methods like Multi-Frequency TDMA and DVB-S2X.
4. The project's opinion is that the satellites were very expensive, especially for backhauling. That was partially true at its time, because in the project's lifetime it was taken into account only the GEO satellites combined with the mentioned standards above. The project doesn't take into account, the potential capabilities of GEO/MEO/LEO combined satellite systems that could reduce its calculated OPEX values.

In conclusion, the project's goals were focused more on offering solutions for more efficient satellite internet connections for distant communities instead of assisting the existed cellular networks. However RIFE's significance it is not minor and is mentioned in this assortment due to the fact that was one of the first projects with similar goals to the ESA's SPECSI projects determining possible future internet services needs of its time and presenting actual solutions for deployment to the global satellite industry. [8]

- **SANSA** (**S**hared **A**ccess Terrestrial-Satellite Backhaul **N**etwork enabled by **S**mart **A**ntennas) (2015-2018)

The SANSA was a technical research project developed to offer several recommendations for software implementations & spectrum analysis studies to the industry in order to expand the current useful spectrum for the future LTE heterogeneous networks & both in terrestrial & space segment of the physical layer and offered solutions to reduce the effects of possible bottleneck in both.

The SANSA's project innovation was the proposal of a spectrum efficient self-organizing hybrid terrestrial-satellite backhaul, in order to perform a physical layer theoretical analysis for both terrestrial and space segment of future 5G networks, from the state-of-the-art to the future trends, focusing on satellite systems. Supplementary it indicates possible use cases for satellites in LTE backhauling technologies and digital video broadcasting though the internet (i.e. IPTV). Its spectrum analysis declares that it is possible to expand the current RF spectrum into L, S, C, X, Ku, Ka, Q/V & W bands combining future involvement of optoelectronic communications, focusing in the future benefits for intra-satellite communications.

The project after several simulations and experimentations declared that the most efficient spectrum for optoelectronic emissions for intra-space communications is at the bands with central frequency of 0,8 μm wavelength between LEO satellites & 1,06 μm between LEO & GEO because of their corresponding distances. Supplementary, the project by acquiring data of the EU-funded VITAL project (described within the next chapters) mentions the benefits of the future usage of SDN & NFV technologies in order to create a unified control plane which will allow the operators to efficiently manage and optimize the operation of hybrid satellite-terrestrial networks, providing the operators with appropriate tools and interfaces in order to establish end-to-end fully operable virtualized satellite networks to be offered to third-party operators/service providers. [9], [10]

The project in order to support its considerations it takes into account the technological agreements between EU and other non-EU countries for future satellite infestations, however the most of them are based only in technologically advanced GEO-based satellite solutions which it doesn't match to the current state-of-the-art, supplementary it doesn't take into account actual or upcoming LEO satellites implementations projects such as TESLA's SpaceX which there weren't existed as actual infestation at its lifespan period.

To conclude, SANSA can be considered as one of the most analytical projects reported in this thesis about the creation, operation & improvement of the 5G heterogeneous networks, the produced information can be used by future R&D projects as a base for further studies for the 6G physical layer and its upcoming services & innovations with the involvement of state-of-the art computer science technologies. [9], [10], [11]

- **5G-CHAMPION** (**5G C**ommunication with a **H**eterogeneous, **A**gile **M**obile network in the Pyeongchang Winter Olympic competit**ion**) (2016-2018)

The 5GCHAMPION was a EU-funded project to provoke the co-operation between European and North Korean companies in order to develop key enabling technologies for a hybrid proof-of-concept environment of a 5G prototype network to be showcased at the 2018 Winter Olympics in Pyeongchang city. The project's plan was to allow maximum visibility and optimized usage of the available technology offering information for future studies in order to be applicable in 2020 with the official global launch of 5G networks.

This project was the first reported to present a study for deployment of 5G heterogeneous networks in South Korea, it presents a physical layer study for using satellite systems for narrowband IoT applications and basic voice services. The study shows that 5G UE can operate at low bitrate through satellites with minimum configuration updates providing a continuity of service and backhauling to the terrestrial infrastructure for narrowband IoT services. With its state-of-the-art technologies the capacity that could be provided through satellite or HAPS components such as high-amplitude drones, would allow to reach high density of user served per square kilometer in order to significantly increase the number of served IoT devices. Supplementary, the project performed a Proof-of-concept experiment by the operation of a testbed platform for a demonstrative 5G hybrid backhaul network. The demonstration has proved that future satellite systems as a 5G transparent network component, with the involvement of GNSS system for cooperative high precision outdoor positioning can operate coherently with the terrestrial LTE systems using all types of physical satellite infrastructures under 6GHz band space transmissions.

The project's planning may seem very feasible, but it doesn't mention the potential for complete backhaul solution over LTE networks, perhaps from the beginning of the transcendence of terrestrial copper-based networks to passive optical networks in rural area, also it doesn't perform an analyses of the potential of improvements that will occur by future LEO constellations both in IoT & backhaul applications.

In the end, the scientific conclusions of this project promoted to the South Korea authorities and into the global industry a feasible solution of a 5G heterogeneous network with satellites as a specific purpose 5G component. Its theories and conclusions put the base for future evolution of 5G networks like 5G ALL-STAR project to bring new technologies into reality. [12], [13]

- **FUTURE-MOBILE** (2016-2018)

FUTURE-MOBILE was a specific purpose's project to attempt to solve theoretical and practical questions of beamforming for an evolved form of co-existence of aerial terrestrial and satellite communications RF signals within a future 5G heterogeneous network.

The project's stuff manage to publish a several amount of scientific reports which offered proposals to develop a unified theoretical framework in order to investigate characteristics of transmit signals, and design spectral/energy efficient beamforming algorithms, design of distributed Remote Radio Heads (RRHs-based) caching techniques for reducing downloading delay with optimization and consideration of capacity constraints on the network equipment. Investigate the precoding design and interference mitigation for distributed massive MIMO systems, coexisting with satellite networks in order to solve beamforming optimization problems.

The project unfortunately, it hasn't provide so far Deliverable papers & performs its research concentrated on terrestrial antennas beamforming issues instead of satellite systems which present additional issues like the impact of non-linear operation of their RF transmission equipment over HTS beamforming.

The project in total, served a significant number of scientific papers which can be used as a generic base for solving & evolving mathematical optimization problems equations in order to produce future beamforming techniques which theoretically can be applied in both 5G/6G terrestrial & space network segment. [14], [15]

- **SaT5G** (**Sa**tellite and **T**errestrial Network for **5G**) (2017- Feb 2020)

SaT5G was an EU-funded project offering a roadmap for satellite system's integration within 5G networks by determining, possible use cases and physical layer improvements. It promotes several recommendations for satellite and terrestrial network providers for a feasible 5G operations migration. [16], [17]

The projects innovation is that covers many scientific fields such as technoeconomic evaluations like business models for efficient use of satellite system capabilities and their considered best value for money use cases. It also presents state-of-the-art network slicing and virtualization techniques through SDN & NFV in order to produce a prototype of an automated orchestration mechanism. [18], [19], [20]

The project may be using all of the current state-of-art information to produce a future plan for a feasible satellite integration into 5G, however it's reported only in general 5G/6G technologies like software-defined satellites and optic intra-satellite links and it doesn't analyze their impact in aspects of CAPEX & OPEX reducing and optimization of total Quality of Experience (QoE) Index. [17], [18], [19]

In total, the project gives a large scale analysis of a feasible industry plan about 5G satellite – terrestrial networks combination into one heterogeneous form, progressively automated by related computer science technologies, under specified use plan cases for improved efficiency and uninterrupted network coverage to the end users. [20], [21], [22], [23], [24], [25], [26], [27], [28]

- **5GENESIS** (**5**th **G**eneration **E**nd-to-end **N**etwork, **E**xperimentation, **S**ystem **I**ntegration, and **S**howcasing) (2018 UNTIL JUNE 2021)

The 5GENESIS was an evaluation project funded by EU to produce actual results of performance of a testing 5G network implementation in several cities across the Europe. The systems deployments focuses firmly on the urgent drive to facilitate execution of 5G network trials, so that to stimulate new connectivity-based ecosystems through experiments and demonstrations and in this way accelerate the digitization process and the advent of novel business models.

The 5GENESIS was one of the first reported to create an actual testbed network by bringing together results from a considerable number of EU projects as well as the partners internal R&D activities in order to realize an integrated end-to-end 5G infrastructure with 5G satellite component, in the 5G test platform in Limassol City of Cyprus and four more metropolitan networks in European cities.

The project's platform report in Limassol didn't mention the possible benefits from transmitting at other bands from Ka in its evaluations, supplementary it isn't mentioned the possible impact of the usage of a supplementary LEO constellation in the mentioned services scenarios such as maritime handover service during sea traveling or moving away from Limassol's port.

In total, this project proved that it is possible to create an operational hybrid testing 5G network that actually fulfills the 5G requirements and the corresponding QoE. Based on project's results the state-of-the-art global industry can put up the base for future deployments of 5G network across the world, heterogeneous depending on the applied area without quality discount on 5G offered services. [30], [31], [32]

- **5G ALL-STAR** (**5G** **A**gi**L**e and f**L**exible integration of **S**a**T**ellite **A**nd cellula**R**) (2018 – 2021)

5G ALL-STAR was a contribution project between EU's & South Korea's industry's in order to publish a report of feasible and operational plan for future 5G network networks across S. Korea with operational interaction between satellite & terrestrial networks.

The project developed a set of technologies and validates system interoperability to provide global connectivity and support mission critical applications of interest in both European and Korean regions. To this end, it was developed selected technologies targeting a set of Proof-of-Concepts (PoCs) to validate and demonstrate in a heterogeneous network's real setup. The project served various proposals about multi-connectivity support based on cellular and satellite access for the users of the network, spectrum sharing between cellular and satellite, proposing multiple satellite topologies usage for all types of applications.

The project doesn't report anything about the beneficial of future satellite optoelectronic communications and its impact on use cases which can be serve in the future.

In conclusion, 5G ALL-STAR was a successful example of a theoretical and practical research similar to SaT5G in order to provide guidelines into telecommunications industry on 5G network implementation in specific regions, in this case of South Korea's cellular networks. [33], [34], [35], [36]

- **5G-VINNI** (5G Verticals INNovation Infrastructure) (2018 – 2021)

5G-VINNI was a R&D project to study the feasibility of operating a beta-testing automated & hybrid 5G network ecosystem across Europe.

5G-VINNI scope was to accelerate the uptake of 5G in Europe by providing an end-to-end (E2E) facility that validates the performance of new 5G technologies by operating trials of advanced vertical sector services. The project is progressing beyond state of the art in the domains 5G radio access by improved spectrum, E2E automation, and satellite integration into 5G ecosystem. The project developed infrastructures across many capital European cities some of them with the use of satellite communications for backhauling in order to prove the feasibility of 5G implementation and operation. [37], [38], [39]

2.3 SATELLITES EVOLUTION TOWARDS 5G ERA

According to our research, most of the satellite internet systems until 2016 were based on GEO/MEO satellites that were noted negatively by their big Round Trip Time of a transported RF signal back and forth to Earth. Supplementary the usable spectrum bands were much smaller comparable to the current infestations by public and private sector solutions. OCEAN & RIFE projects presented that state-of-art with GEO-based solutions and the corresponding problems because of their characteristics the total performance was comparable to copper broadband internet connections like 3G/3,5G and ADSL. [3], [8], [40]

The backhauling scenarios were considered as very expensive use for satellites at the time and in order to build more responsive systems, new key concepts had to be identified in order to create satellite networks to compete the terrestrials ones not only keeping up the pace to compete at that timeline the state-of-the-art 4G networks by means of speed and latency. Although the most of the projects at that timeline weren't proposed satellite systems to fulfill all of the 5G requirements, they predicted upcoming technologies for cellular systems complement e.g. data caching non-exclusively for Content Distribution Networks (CDN) but for tower feed in cellular networks as well in order to serve popular multimedia content in higher speeds than 4G. [3], [8]

Despite the variety of 5G offered services the requirements in terms of bandwidth can be extremely high, especially in the case of content distribution. In order to fulfill the need for excessive bandwidth the satellite industry has created the last decade a new class of satellites that can reach over Gbps of total bandwidth, the class of High-Throughput Satellite (HTS). The concept of HTS was to become a system that can transmit every kind of multimedia content, offering many kinds of services (e.g. in critical situations - disasters) with the availability to transmit it over a specific area and not only in a widespread area (wide-beam satellite). In order to achieve those goals HTS had to evolve in many terms, their main are simplified us follows: [3], [8], [9], [10], [11]

- Beam forming – Satellite's Earth footprint is splinted into several zones instead of a unified footprint for improved efficiency, less power loss, ACM schemes application and circular re-use of available frequencies similar to LTE cellular network antennas.

- Inter-Satellite connections – the total capacity of a satellite network in a form of constellation can be multiplied with reduced latency by lower amplitudes (MEO/LEO) direct space communications. To conclude, space makes suitable environment for easier application of classical RF transmission and usage of line-on-sight free space optical communications.

- Extreme throughput – The HTS systems are designed for total throughput in terms of Gbps and by the implementation of the latest multiple access techniques and DVB standards are planned to exceed within this decade the bridge of Tbps of total channel capacity even by a single satellite, forming a new class of satellite the Very-High Throughput Satellites (VHTS).

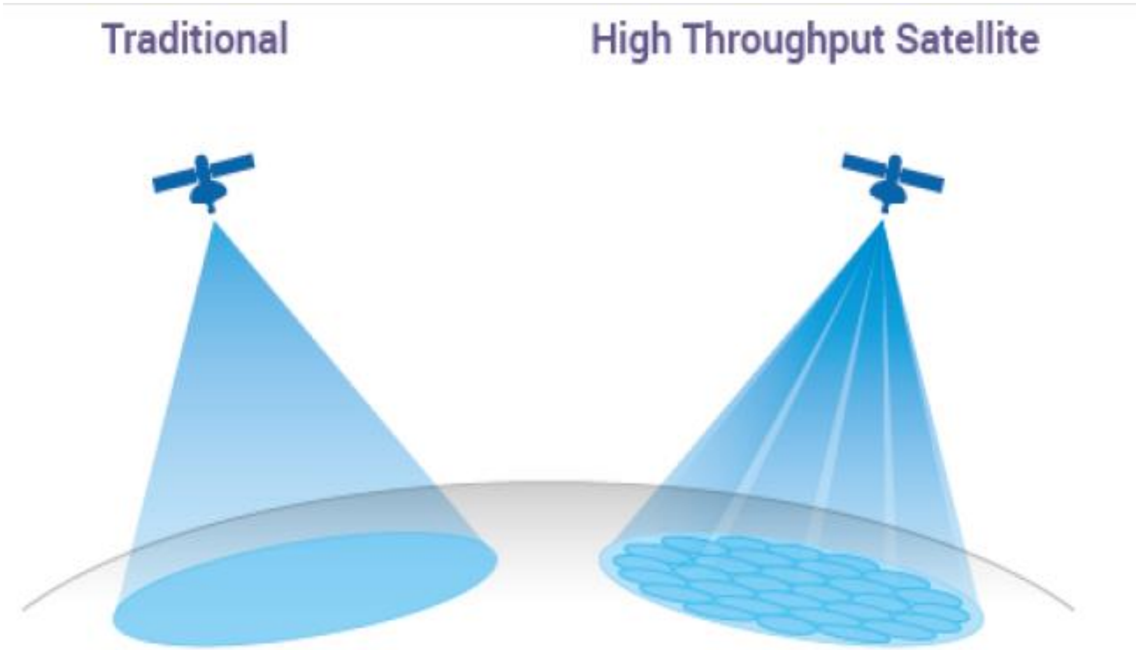

Figure 3: The HTS systems produce improved service solutions, partially due to frequency reuse similar to state-of-the-art terrestrial cellular networks [43]

Many R&D projects have proved that the evolution of satellite DVB standards is a key factor for channel efficiency that compete the terrestrial ACM standards. Supplementary due to the significant increase of satellite internet users across the globe (either by means of home customer or a cloud service / CDN provider) TDMA techniques must also evolved to improve spectral efficiency. To conclude the following measures have taken into account:

- **DVB standards**
    - The potential of satellite systems in terms of channel capacity can match the theoretical Shannon limit though the use of DVB-RCS2 & DVB-S2X standard in satellites downstream, supplementary amplified DVB-RCS2 transmissions in the uplink mitigates the inequality between the available MODCODs of the two standards until DVB manages to present in the future an extension of RCS(x) standards. [10]

- **Multiple access techniques availability**

  - The usual implementations of TDMA aren't presenting an efficient way to optimized usage of a satellite channel in the case of multiple users' access. Among the studies for evolving hybrid TDMA based techniques the most promising has been proved is MxDMA MRC (Cross-Dimensional Multiple Access - multi-resolution coding) an evolved version of Multi-Frequency TDMA (MF-TDMA) that unites SCPC (single carrier per channel) efficiency and TDMA's (time-division multiple access) lower power consumption. Mx-DMA has a hybrid scheme of multiple access by means of under a specific time period the system operates similar to a FDMA, the users take a predefined portion of the available spectrum and by a constant time period the portions are reconfigured in terms of spectrum according to the content demands of each user combining the ACM schemes of DVB standards. [10], [72], [205], [206]

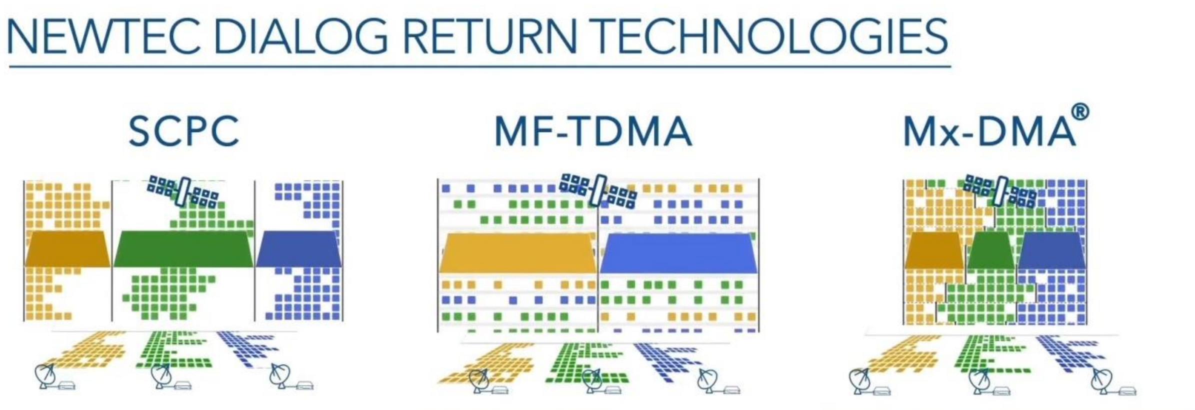

Figure 4: Multiple access techniques that are being used in satellite transmissions in communication systems like NEWTEC DIALOG platform (e.g. for mobile backhauling) (ST Engineering iDirect, Newtec ® 2017) [206]

The future transmission payloads for satellites will be designed depending upon the application environment, to operate as MF-TDMA or to switch over traditional TDMA in the occasion of a critical situation like bad weather conditions during maritime applications. Supplementary our research has found that experimentations are occupied for the implementation of OFDMA in the downlink but also as an Single Carrier-FDMA scheme in the uplink (SCPC-OFDMA as SC-FDMA) not only because is more energy-efficient for bad weather conditions, since it is measured that the electronics used can consume less power instead of TDMA-based schemes of access, supplementary it will turn into more compatible satellite systems with 4G/5G cellular networks since that technique is already being used in 4G uplink channels. [10], [72], [207]

- **Multi-band re-use**

  - The oldest systems were using L, S, C and X bands for simple internet, voice and navigation services. In order to compete the terrestrial communication systems, the state of the art satellites are using up to Ku/Ka bands for broadband internet connections, combined with advanced beam forming techniques for reducing any possible frequency conflicts between the terrestrial 5G networks antennas (terrestrial eNodeB). Advanced studies are being occupied for usage of mmWave channels in Q/V & W bands for spectrum expansion with the implication of optoelectronic mixers in order to reproduce RF signals through the variation of optical wavelengths (analyzed in Chapter 6). [14], [73]

Within the 2010s advanced physical layer experiments have been conducted in order to provide additional physical layer technologies, the most promising trend for 5G & 6G studies is optical free space communication. Until today this technology was used for intra-space communications between satellite systems or between satellites of the same network, with the early implication of satellite industry in 6G studies (e.g. HUAWEI's space tests) it is expected that until 2030 with the commercial availability of 6G networks new technologies for light wavelengths modulation will appear for earth-to-space communications, resulting in THz bands spectrum expansion. [41]

2.4 SATELLITE POSSIBLE USE CASES THROUGH STANDARDIZATION

The specifications has been concluded within the last 3 years and a big number of testing projects is occupied even today in order to evolve the capabilities and the specifications of future satellite systems to achieve a key role in 6G era as well. [10], [29]

The technologies the satellite internet systems can play a key role in many applications either inside the 5G networks or in parallel to them. Through the standardization of satellites as a 5G network component the following use case scenarios have been determined: [7], [10], [16], [29], [42], [43]

- **Edge delivery & offload for multimedia (Hybrid Multiplay)**
  - Vertically integrated Control Plane with network and content
  - New form of network management infrastructure (MNO) for providing network and content provider deploying caches and content
  - MNO deploying NFV for network and storage serving content providers

- **Satellite fixed backhaul (backhauling & tower feed)**
  - Deploying satellite backhaul where fixed is either not possible of un/less economic

- **Satellite to premises (Trunking & Head-End feed)**
  - Satellite to augment limited performance on ADSL.
  - Use case of flexibility to include content caching in the home router.

- **Satellite to moving platform backhaul (Communications on the Move)**
  - Updating content for on-board systems and grouped media request by the moving platform company.
  - Broadband access for passengers and individual media requests.
  - Business and technical data transfer for the moving platform company.

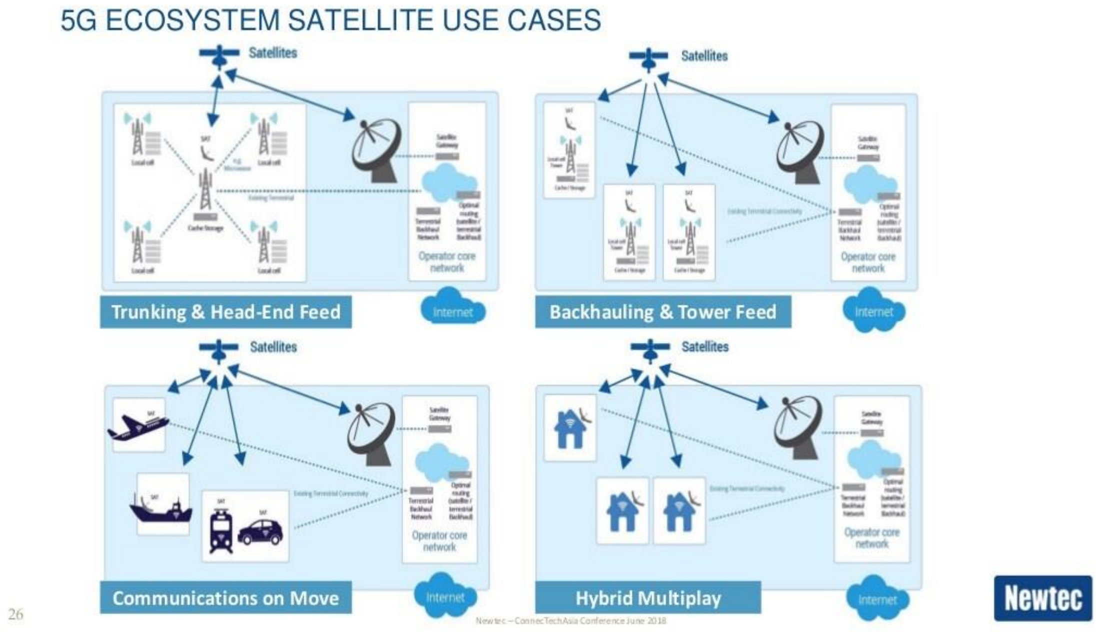

Figure 5: The most suitable use cases for satellite systems have been summarized into the four basic illustrated in the picture above. [43], [57]

This use cases have been determined by a vast number of projects based on specifications determined by 3GPP organization, most of them can be found in [45]. The TR & TS that we mention prove that is feasible with the current state-of-the-art and under development satellite systems to complement the upcoming 5G networks with the required performance. There are many Technical Report (TR) & Technical Specifications (TS) papers from 3GPP which have produced a set of regulations for using satellite systems within a 5G network, because the specifications produced are too many to describe them in this thesis we mention their numbers and their main aspects for further study under the list below: [29], [42], [44], [45], [46], [48], [49], [50], [51], [52], [53]

- **TS 22.261 - Service requirements for the 5G system**
  - Adapts most important 5G SATCOM requirements as part of overall 5G system requirements.
  - Determines the appropriate signal propagation delays for all types of satellite orbits
  - Determines a set of rules for achieving sustainable & stable QoS for all possible use cases

- **TR 22.819 - Feasibility Study on Maritime Communication Services over 3GPP system**
  - Considers maritime communication services as one of 3GPP vertical applications.
  - Proposes use case on satellite access to support maritime communication services over 5G system

- **TR 22.822 - Study on using satellite access in 5G**

  - Provides 12 possible use cases for namely service continuity, service ubiquity, and service scalability
  - Recommends functional requirements for each use cases e.g. propagation delay & average latency depending on geographic coordinates

- **TR 23.737 - Study on architecture aspects for using satellite access in 5G**

  - Considers the system architecture issues including roaming between terrestrial and satellite networks and fixed backhaul to 5G core networks.
  - Considers 10 key issues on satellite operation for 5G complement operation and proposes the most suitable solutions
  - Proposing solutions for handover issues for Non-GSO satellite systems e.g. satellite-cell handshake modifications for improved operation and adaptive QoS

- **TR 24.821 - Study on Public Landline Mobile Network (PLMN) selection for satellite access**

  - Considers the key issues and the respective solutions related to the support for network selection procedure that accommodates 5G systems using satellite radio access networks.
  - Considers modifications to the legacy PLMN selection procedure to address the specifics of the satellite access networks with respect to the legacy 3GPP access networks

- **TR 28.808 - Study on management and orchestration aspects of integrated satellite components in a 5G network**

  - Identifies the main key issues associated with business roles, service and network management and orchestration of a 5G network with integrated satellite component (whether as NG-RAN or non-3GPP access, or for transport)
  - Studies related solutions for minimizing the impact and complexity of satellite integration in the existing business models and in management and orchestration aspects of the current 5G networks.
  - Identifies the potential requirements, issues and solutions for network slice management, satellite systems management & monitoring

- **TR 36.763 - Study on Narrow-Band Internet of Things (NB-IoT) / enhanced Machine Type Communication (eMTC) support for Non-Terrestrial Networks (NTN)**

  - Proposes the essential minimum functionality of both NTN NR and NTN IoT (both NB-IoT and eMTC)
  - Considers of the necessary features & adaptations for enabling the operation of the IoT NTN for 5G with priority on satellite access.
  - Identify scenarios applicable to NB-IoT/eMTC including sub 6 GHz bands under all types of satellite systems

  - Identifies the key issues & the necessary changes required to support NB-IoT and eMTC over satellite

- **TR 38.811 - Study on New Radio (NR) to support non-terrestrial networks**

  - Provides a comprehensive technical study on feasibility of 5G NR for 3GPP non-terrestrial networks.
  - Provides a study for the possible use cases of satellite systems within 5G with a deployment scenarios study (Complements TR 22.822 use cases study)
  - Recognizes key impact areas on 5G NR to support non-terrestrial operation are related to: propagation channels, frequency planning, power limitations, network cell pattern modelling, delay characteristics, mobility of users and infrastructure, service continuity, and radio resource management
  - Provides an evaluation including requirements for key issues e.g. Doppler shifts, delays, antenna patterns, and channel models.

- **TR 38.821 – Solutions for NR to support non-terrestrial networks (NTN)**

  - Recognizes the necessary features & adaptations from 5G in order to enable the operation of the New Radio (NR) protocol in non-terrestrial networks under 3GPP Release 16 and above with a priority on satellite access. Access network based on Unmanned Aerial System (UAS) including High Altitude Platform Station (HAPS) could be considered as a special case of non-terrestrial access because of its lower delay & Doppler Effect value and variation rate.
  - Recognizes the potential impacts over the physical layer & define related solutions were needed
  - Introduce performance assessment requirements of NR in selected deployment scenarios (LEO based satellite access, GEO based satellite access) through link level (Radio link) and system level (cell) simulations
  - Study and define related solutions were needed on proposed RAN architecture and related interface protocols

Supplementary, ETSI has taken part in 5G satellite component the most representative result is TR 103.611 which takes into account both satellites and HAPS connectivity capabilities for 5G. Concluding, the reports concerning the satellite systems applicability over 5G network by 3GPP & ETSI implicate indirectly the newest physical layer techniques but also directly them referring in applications beyond backhauling like Narrowband-IoT communications. Supplementary, standardization also implies the intrusion of computer science technologies to support network slicing, system management & monitoring operations. Most of the TRs & TSs are designed for 3GPP releases 15, 16 & 17. Further development is expected within the next couple of years, 3GPP is expected to finalize release 17 officially in 2022 and the releases 18 & 19 at least after 3 years from now. [54], [55]

2.5 PROOF OF CONCEPT BY TESTBED PLATFORMS

Over the last 7 years there have been developed a big number of tests either of simulations form or real time applications not only to promote the feasibility of an operating 5G network infestation but to prove by state of the art provided technology the power of satellite systems in assisting either the coverage of the terrestrial networks or the traffic load management (off-loading) mostly by means of backhauling. The R&D results can be summarized as follows:

- **Satellites in a 5G network**
  - Satellite networks will operate in several topology conditions, defined into the following: [4], [9]
    - Moving Site (Train) – this use case covers mobile networks which are mostly in the coverage of terrestrial networks but may frequently lose the connection to the backhaul (due to tunnels, or simply moving through shadowed or not covered areas). Pure terrestrial network communication has its drawbacks due to specific operator coverage (i.e. a large number of roaming agreements required) or due to the speed of the devices in which terrestrial only communication is highly inefficient (i.e. high speed devices). In case the terrestrial backhaul is improved, which seems realistic to happen in the near future, satellite backhauling will lose its advantage.
    - Moving Site (Plane) – this use case covers fast moving mobile networks which have the satellite network as a single backhaul alternative for most of the time and have nearly always an unobstructed link to the satellite. Changing to terrestrial backhaul is possible only at specific locations.
    - Moving Site (Cruise Ship) – this use case covers slow moving mobile networks which most of the time have the satellite network as the only backhaul alternative and have nearly always an unobstructed link to the satellite. For this use case a terrestrial backhaul is available temporarily (when close to shore), providing a temporary capacity boost. This includes all the cruise communication as well as slow mobile networks in low coverage areas (e.g. mining trucks or balloons).
    - Isolated location – this use case covers fixed networks which are isolated due to the specific terrain geography and where the satellite network represents the only backhaul alternative. This use case includes oil exploration platforms, nature or space observation sites (e.g. Antarctica, Amazon jungle, Himalaya).
    - Rural location – this use case covers fixed networks which are isolated due to the large costs of establishing a terrestrial backhaul or having only very low capacity backhauls. This includes populated areas in which the satellite network provides the main backhaul alternative, especially remote human habitats such as villages on top of mountains, in swamps and on isolated islands (e.g. Philippines).
    - Urban location – this use case covers fixed networks which can swap between terrestrial and satellite backhaul when needed. The

satellite backhaul provides the advantage of being a single autonomous system for establishing the communication, ensuring a specific end-to-end security and uniform delay. This makes satellite backhaul ideal for specific enterprise communication as well as for M2M use cases, as it ensures that there is no network preemption coming from other devices (e.g. factory communication, enterprise logistics synchronization, medical information synchronization, etc.). Additionally, satellite network may play the role of high availability backhaul taking over the overspill in case of congested terrestrial networks. This scenario also includes nomadic eNBs which may be used to boost the network performance for certain occasions such as open air concerts with 50000 users within one square km.

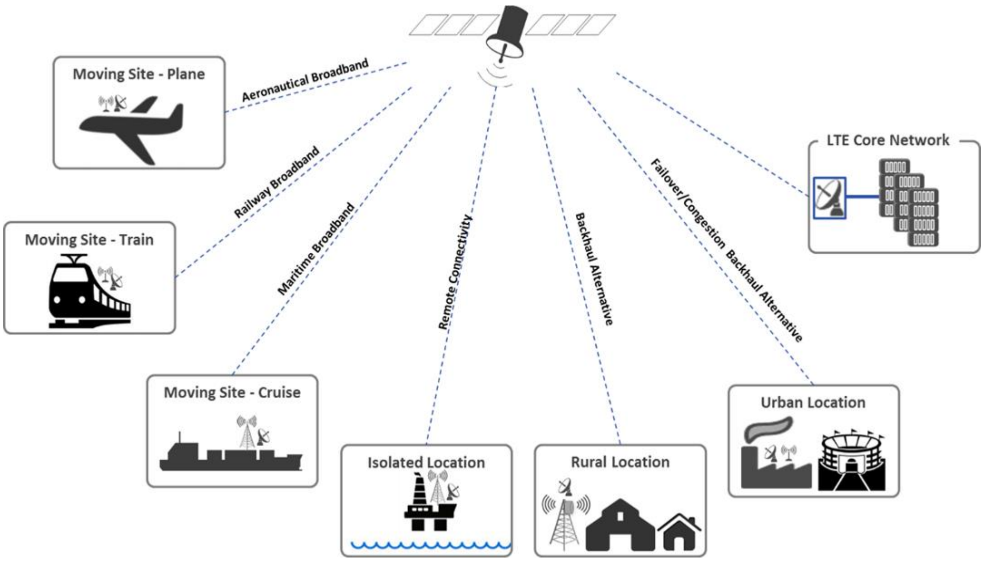

Figure 6: Satellites have many potential uses in future 5G networks in terms of backhauling and the corresponding application area [4]

- Different offered services per Country/region
  - Countries like North Korea so far don't mention in R&D projects the need for exclusively backhaul coverage, maybe due to the rapid evolution of terrestrial ones in the area. Other tests occurred in European regions (e.g. Germany & Cyprus) implicate 5G satellite component for distant areas communication (e.g. drone or maritime communications). [3], [4], [11], [12], [13], [22], [25], [26], [32], [34], [35], [39]
- SDN/NFV technologies application is obligate for automation and simplify the construction and operation of future satellite systems, supplementary it preserves the QoE in several network applications like video streaming (analyzed further in Chapter 2) [6], [9], [10], [18], [37], [38]

➢ **Tested satellite systems gaps from 5G network performance requirements**

- Most R&D projects until today were experimenting by GEO-based satellite systems to determine the future capabilities for 5G backhauling, rarely mentioned future satellite technologies like space optical communications which could give in the future responsiveness similar to terrestrial networks. Although a small number of LEO constellations systems are currently under development in the period until 2025 there will be launched over 8000 satellites either by ESA/EU funded projects or private sector initiatives like SpaceX's STARLINK and TELESAT's Lightspeed constellations. [25], [26], [32]

- Most of the projects were experimenting in DVB-S2 & DVB-RCS standards combined by classic TDMA which is not optimal for state of the art needs. There are a small number of tests than mentions standards and access techniques like OFDMA for downlink and a combination of MF-TDMA, Mx-DMA and or SC-FDMA (most popular mentioned as Single-carrier-per-channel over OFDMA access scheme) in the uplink combined with the latest DVB standards. [4], [10], [19], [58], [59], [72]

2.6 CONCLUSIONS & FUTURE TRENDS

According to the projects we notified the period between 2016 and 2021 as a period for 5G network testing, the most famous examples that implement satellite network as a 5G component have been spotted in rural areas of North Korea, Germany, Luxembourg and Cyprus. In the mentioned areas the studies have been limited to GEO-based satellite systems for simple backhauling solutions it is predicted that in the next few years there will be new R&D projects not only to determine future needs and services but also to test future 5G networks performance.

Most of the projects are about to finalize and publish their results within 2021. Testbeds from projects like **SATis5** showed the feasibility of operation of a 5G heterogeneous network with satellites. Supplementary a set of R&D tests are under progress to investigate the future developments of the satellite systems, projects like **SATNEX IV** and **5G4SPACE** assisting the standardization bodies (e.g. 3GPP, ETSI) for developing technical reports for the newest version of 5G networks within this. ESA's **ASCENT** & **GADGET** will investigate technical aspects of a 5G network e.g. spectrum sharing in different types of offered service (fixed or mobile), supplementary the need to create and implement software solutions for aspects like software defined radio (SDR) caused the investigation from R&D projects like ESA's GADGET to perform test platforms for all methods of user's network access. The projects will finalize their results within 2023 as reported from the projects published data. [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68]

After the Joint Statement signed between ESA and satellite industry companies in 2017 for future technologies for satellite integration with 5G network a set of funding projects have been occurred and some of them still ongoing e.g. ESA's **5G METEORS** will assist in terms of technoeconomics the satellite industry to produce a set of technologies, not only concerning the upgrade of state-of-the art 5G integration status but also will assist both ESA & EU developing projects for 6G technologies compensating the effort by reaching a more competitive state against other industries, for instance in China Huawei in collaboration with other Chinese firms has announced in 2020 its first tests with GEO satellites for THz transmission for its future 6G implementations in 2030. Considering the ESA's official agenda the satellite industry will begin developing R&D projects for 6G applications and technologies in a few years from now, commencing officially a new technological journey to the 6G Era. [41], [69], [70], [71]

3. INTEGRATION OF SDN/NFV IN SATELLITE SYSTEMS

Over the last 7 years ESA & EU have produced a set of R&D projects for declaring the role of SDN & NFV inside a satellite network, considering the CAPEX reduce, the simplicity in satellite integration in 5G and their impact over QoS & QoE under multimedia services and the corresponding reduce of OPEX.

Since the softwarization of a network seems to be obligate, not only to reduce the cost of the CAPEX & OPEX but also for future automations in networking e.g. Traffic engineering we decided to dedicate the chapter 3 in the evolutions that SDN & NFV technologies will bring in terms of automation, efficiency & end user’s Quality of Experience (QoE).

In this chapter we examine the consequences of SDN & NFV into satellite systems based upon the project reports we found from ESA Artes & EU CORDIS and related research papers. We report the projects historically in order to determine the timeline of procedures been occurred for SDN/NFV integration and we mention the technologies that are coming forth into satellite systems from SDN & NFV, supplementary we perform a report of the tests that have been completed until nowadays as a proof of concept.

In the end, we present the future trends that will be occurred moving towards to 6G Era as reported from our relevant bibliography.

3.1 R&D PROJECTS TIMELINE

In many countries European Union and ESA has funded research programs by the Horizon 2020 funding program for researching the impact of SDN and NFV technologies on future cloud services over 5G networks and the software platforms for better management of satellite systems as a 5G satellite. The ESA's projects that express a distinct interest in SDN & NFV integration into satellite systems are sorted in historical order and we describe them in summary as follows:

- **CLOUDSAT** (Scenarios for integration of satellite components in future networks) (2014-2016)

The CloudSat was a project to determent the applicability of emerging virtualization and softwarization technologies to satellite communication platforms and their benefits and the challenges associated with the integration of satellite infrastructures into future software-based networks in order to reduce the CAPEX and the OPEX of LTE networks.

The project is one of the first it acknowledge the need of satellite communication platforms follow the transformation to whose resources can be abstracted via virtualization mechanisms, unified, dynamically pooled and offered in a Satellite-as-a-Service form. It has determined the applicability of these technologies to sitcom by identifying specific use cases/integration scenarios and studies their techno-economic efficiency, supplementary it proposed integrated virtualized satellite/terrestrial architectures for producing a feasible roadmap and recommendations for future virtualization-capable satellite networks. In order to prove it, there have been validations upon lab environment simulations to determine their actual impact on several kinds of services like video distribution. The project's report comes along with a technoeconomical analysis to study the possible CAPEX & OPEX reduction from the corresponding equipment that can be used for SDN & NFV.

The project's plan is a feasible plan for 5G implementation but it doesn't take into account upcoming physical layer technologies and their corresponding impact such as DVB-S2X and OISL's that would cause lower drawbacks of the corresponding service quality.

To conclude, the project has established an extended report of a preview hybrid 5G self-controlled network in order to serve uninterrupted cloud services altogether with corresponding recommendations for satellite industry. [74]

- **INSTINCT** (Scenarios for integration of satellite components in future networks) (2014-2017)

INSTINCT project was an ESA's research in order to determine if its state-of-the-art technical and economic conditions could make satellite networks attractive to be integrated with terrestrial IP cloud-networks for improved efficiency.

The project's innovation was the determination by its state-of-the-art satellite systems the technical & technoeconomical requirements in order to promote for satellite &

terrestrial network industry, possible use cases, recommendations to corporate actions for the standardization of a future 5G component SDN & NFV enabled.

The project considers the usage of all possible combinations of satellites with a mixture of all available multiple access techniques and existing DVB standards, but it doesn't mention the significance of future OISL links and optoelectronic links with ground stations with the corresponding future offered services like cloud processing over satellite. [75]

The EU's similar projects in historical order are the following:

- **VITAL** (VIrtualized hybrid satellite-TerrestriAl systems for resilient and fLexible future networks) (2015-2017)

VITAL was a R&D project created to study the beneficial of SDN &NFV technologies in terrain and space networks with executed simulations in order to create an automated platform for adaptive improvable network's performance for several types of applications e.g. video distribution.

VITAL's experiments create a proposal for addressing the combination of Terrestrial and Satellite networks by pursuing two key innovation areas, by bringing NFV into the satellite domain and by enabling Software-Defined Networking & SDN-based federated resources management in hybrid satellite-terrestrial networks. The project's considerations was that enabling NFV into SatCom domain will provide operators with appropriate tools and interfaces in order to establish end-to-end fully operable virtualized satellite networks to be offered to third-party operators/service providers, supplementary by enabling SDN-based, federated resource management will create a unified control plane that would allow operators to efficiently manage and optimize the operation of the hybrid network.

Unfortunately, the project's website has tiered down by unknown reasons so it's difficult to retrieve at this time deliverables about the proceedings of the project. On the other hand, their group has published many scientific papers & reports upon the concept of SDN & NFV implementation on the internet. [77]

In conclusion, VITAL studied the benefits of the appliance of SDN & NFV into satellite networks and produced information which can set up the base for future automation technologies critical to maintain a stable QoE index on 5G services. [76], [82], [84], [85]

- **MATILDA** (A HOLISTIC, INNOVATIVE FRAMEWORK FOR THE DESIGN, DEVELOPMENT AND ORCHESTRATION OF 5G-READY APPLICATIONS AND NETWORK SERVICES OVER SLICED PROGRAMMABLE INFRASTRUCTURE) (2017- 2020)

MATILDA was a generic R&D project to study the specifications and benefits of implementing SDN, NFV & Software Defined Radio (SDR) technologies in a future 5G ecosystem supplementing satellite communications in the ecosystem.

MATILDA proposed an architecture that will bridge the gap between application-level orchestration and the Network Providers mechanisms that have to guarantee end-to-end connectivity, network-aware applications, supplementary provided recommendations to speed up the extension & evolution of the “cloud” proposed infrastructure to the 5G ecosystem, intrinsically bridging the application and the network service domains, including satellite components through the technique of slicing in the 5G hybrid network. [78], [79], [88]

3.2 SDN, NFV & SDR’S ROLE IN SATELLITE NETWORKS

Because of the extensive of the technical information available considering the SDN & NFV impact over satellite networks, we mention in brief the main key point indicators that fulfilled with their integration into the satellite systems for co-operation with 5G terrestrial networks and the corresponding changes into satellite operation architecture.

3.2.1 SOFTWARE DEFINED NETWORKING CAPABILITIES

Software Defined Networks (SDN) represents a new abstraction of networking into satellite systems, enabling the remote programmability of network nodes from a logically centralized control plane. The main technological characteristics of SDN are flexibility/programmability through logical centralization of the control plane, usage of all-purpose data path components and abstraction of the complexity. From a technical perspective, the main advantages of any centralization are related to the coordination of the different operations on nodes of the same or different type. Several alternatives were proposed in the past including the one currently implemented in which different nodes are collaborating on a link based control or in a comprehensive network structure. For both in data path solutions, it is already known that it is very hard to produce convergent information from large-scale dynamic systems, resulting in major inconsistencies, especially in large-scale traffic engineering. [18], [80]

Centralization brings synchronization. It gives the opportunity to enforce network rules in a proactive manner, “programming” at the same time the data path nodes towards a specific behavior. Additionally, a central management system can fast react to different changes coming either from the data path or from administrative triggers. As it may constrain the modifications only to the affected nodes, thus providing an additional consistency level also for reactive operations. The programmability provides the means to a higher flexibility level into the deployment of the different networks. [80], [81]

Features such as deployment of new protocols, new networks or new parameters inside a running network, which were previously contained into a management system and supposed to be rarely modified, with SDN become part of a newly developed control plane in a new hybrid form similar to plug-ins into VoIP networks. In the last years, the flexibility technological advancement was proposed as the basis for a very large number of use cases, which are shortly described in the following: [76], [82], [90]

- The SDN’s flexibility can be used for providing a dynamic network management plane through which network functions can be dynamically deployed and connected through virtual or re-configured physical networks. Due to the same factor, multiple network environments can be deployed in parallel, slicing the physical network infrastructure for the different communication needs. Through this, virtual networks can be deployed and configured on-demand giving the opportunity for deploying independent, fully customized, complete network infrastructures for each tenant.

- Provides the means for controlling in an appropriate manner the traffic management operations, by having an immediate reaction to the specific needs, which can be contained to the specific network area to which the specific operations are required. Through this means, the carrier grade features of the virtual network infrastructures can be provided. As all the SDN environment is programmable, it is rather easy to converge the management systems, especially addressing monitoring, resource and fault management, for providing a single full environment overview with a synergetic overview of the complete environment. As multiple sources of information are available, fault detection as well as resource consumption can be further optimized and thus resulting in fast reactions.
- Provides the means to control at a very low granularity level (flow based) the different operations in the network and thus to use the SDN as a basis for the individual subscriber communication paths. Due to the control centralization, the operations are rather efficient, similarly to PCRF operator’s functionality. Through the means dynamic data paths are implemented depending on subscriber specific profile, application profile as well as network conditions (load balancing, service localization, etc.). Thus, this flexibility level can be used within the control plane of the networks for the specific operations acting in parallel or in accordance with the existing system.
- A logically centralized point for control gives the possibility for a simple management as well as for an easy presentation status of the end-to-end system, simplifying the administration of an already too complex to maintain ecosystem. This factor gives the opportunity to further manage complex systems and to further extend them, providing that the trust in the technology is gained.

However, compared to the traditional systems, there are some major issues in the SDN environment, which should be further considered. First, in a centralized control plane, there is a single point of failure represented by the control entity. Even though this may be implemented with high availability, it may not be enough in certain major error cases (e.g. a complete data center failure), requiring a further advancement on the distribution and reliability features. Secondly, the distribution at logical level does not presume that the appropriate delay for the specific operations is maintained.

The removal of the control plane functionality from the data path provides the possibility to use all-purpose data path components. Through these means, the cost of the data path components development is reduced and a larger volume may be deployed. As the lower network layer does not include any intelligence, there is no need for functional extended components, requiring a low number of interoperability features. Additionally, through the usage of a rather uniform set of entities on the data path, it is easier to scale up a network infrastructure. The centralization of the control plane functionality also provides the possibility to add from a functional perspective more entities to the data plane and thus to extend the size of the overall system with a complete new layer of execution entities. [76], [90]

The usage of all-purpose data path components has to be still proven as feasible for a large amount of deployment scenarios. Passing from the current dedicated components is foreseen to produce an increase in delay of the processing as well as in compute capacity required, due to features, which are currently executed in hardware and may have to be passed to software components. The proportion of scenarios, which are efficient for being run into an SDN environment and the amount of flexibility to be used, will be the decisive factor for the adoption of such technology.

SDN provides the features for abstracting complexity of the network system. SDN provides a graceful way of integrating a large number of data path components using a centralized controller. Additionally, due to the centralization, the complexity of the underlying network infrastructure can be completely transparent for the upper control applications. Thus, it enables the network functions to be deployed in a no-topology environment having only some generic limitations (e.g. the link between two network nodes cannot have a delay lower than 100ms due to the specific technology used for the physical environment). [76], [85]

Through defining an appropriate set of policies for running the end-to-end virtual system, a major part of the SDN network operations can be automated and autonomous to the human administration. Through this means, the flexibility provided can be supported by the SDN platform in a large proportion, thus further simplifying the complexity of the running network functions (e.g. the weight concept for MME processing is not anymore required as the flexible deployments and the load balancing can be supported in a self-organizing fashion by the SDN environment). Through this, the functional complexity of the running applications is reduced, giving the opportunity to create new customized services.

However, with passing to a more complex environment in which the control entities are distributed close to the data path components and with the addition of high availability support, it is foreseen that the control plane functionality will become very complex, close to the current complexity levels.

3.2.2 NETWORK FUNCTION VIRTUALIZATION CAPABILITIES

Network Functions Virtualization (NFV) represents a new paradigm into networking which enables the deployment of network functions as software on top of common network infrastructures. It is a key assistant in the representation of the network components into a network abstraction, which provides the support for the deployment of the different network functions on top of data centers complementing the hardware abstraction layer being developed for the network resources through SDN technology and its corresponding protocols. For this purpose, NFV uses cloud networking technologies as well as an advanced form of network functions management (i.e. dynamic OSS/BSS) which is appropriate to the cloud environment. [16], [18], [82]

The Cloud networking uses virtualization technologies such as virtual machines and containers to isolate the different running functions and virtual networks to interconnect them as well as to schedule them appropriately on top of data centers, functionality represented by hypervisors, supplementary it provides the means for the life-cycle management of the virtual machines and automatic adaptation for different network conditions including monitoring, resource schedule, fault management and administration. [83], [84], [85]

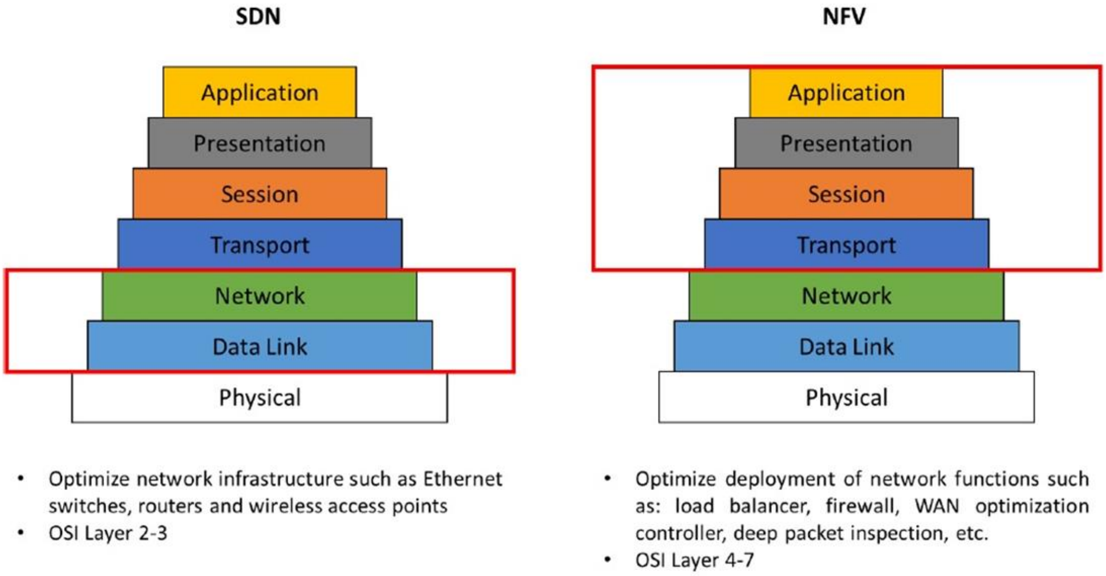

Figure 7: The major difference between SDN & NFV technologies is the fact that they don't offer virtualization in all OSI layers of a network. [18]

From a technical perspective, NFV provides the means to run network functions as software only. Compared to traditional dedicated box infrastructures, this gives a very high programmable configurability to the network functions, as well as a more open way of interoperability (i.e. based on APIs and not on protocols and interfaces). Softwarization gives the possibility to have highly customizable network functions as the source code of management software can be easily re-parameterized and new APIs can be rather easily opened (e.g. RESTful services representation which is commonly used in SDN operations as well). This gives a high software re-usability rate as well as interoperation needs and creating a more flexible (and currently more fragmented) market. From this, a new set of cloud native network functions is expected to be developed which rely on libraries and functionality using in the most efficient manner the cloud infrastructure especially for parallelism and customization of network operations. [83], [84]

3.2.3 SOFTWARE DEFINED RADIO IN SATELLITES

Satellite systems through SDN achieved the ability to operate in a new form of Satellite Cloud Radio Access Network (SatCloudRAN) in order to establish a new definition of radio access. SatCloudRAN concept implements the separated baseband functionalities in a centralized cloud-based processing platform. This separation between the virtualized and the physical components can be achieved at various layers of the satellite architecture model such as the network layer, the MAC layer, the physical layer, or up to the radio frequency front-end of out-door unit. It seems worth pointing out that the project's proposed approach to virtualize the satellite network shows a high level of similarities with the approach that is conducted in the current virtualizing of terrestrial RAN networks. This point is however leveraged by the fact that network architectures in terrestrial and satellite systems are quite different. [86]

The main difference between those variants concerns the distinction between the functions that would remain located in the satellite hub and those that would be moved to the centralized and/or virtualized infrastructure. Additional alternative decompositions where the split is made within the physical or within the baseband gateway functions could be relevant. Satellite network operators are looking for new business models to increase their customer base and extend the reach of their services offering. They are moving toward opening their infrastructure to be shared by multiple tenants, such as Satellite Virtual Network Operators (SVNOs) and offering pay-per-use models instead of single-owned and used infrastructures. Multi-tenancy in infrastructure sharing model enables multiple tenants to cohabitate while being assured they can manage their own space in an isolated, flexible, and secure fashion. [85], [86], [87]

The SVNO model has emerged over the last few decades as many efforts have been made to open the satellite system to a new coming operator that can share cost and infrastructure with a host network operator. Different levels of granularity for controlling satellite system are already proposed. The ‘managed services’ offers a first step toward network control and bandwidth management for the service provider who wants to have a certain control on the underlying resource provided by the satellite operator. [84], [85]

The ‘SVNO model’ allows a virtual network operator to get leased bandwidth with partial hub infrastructure control and management from the hosting satellite operator. SVNO can perform service provisioning, common network operation, and has full control of its own slice of network and end user. The ‘hub colocation model’ (full SVNO) allows a SVNO to co-locate hub infrastructure in its teleport allowing greater control of the installed network equipment.

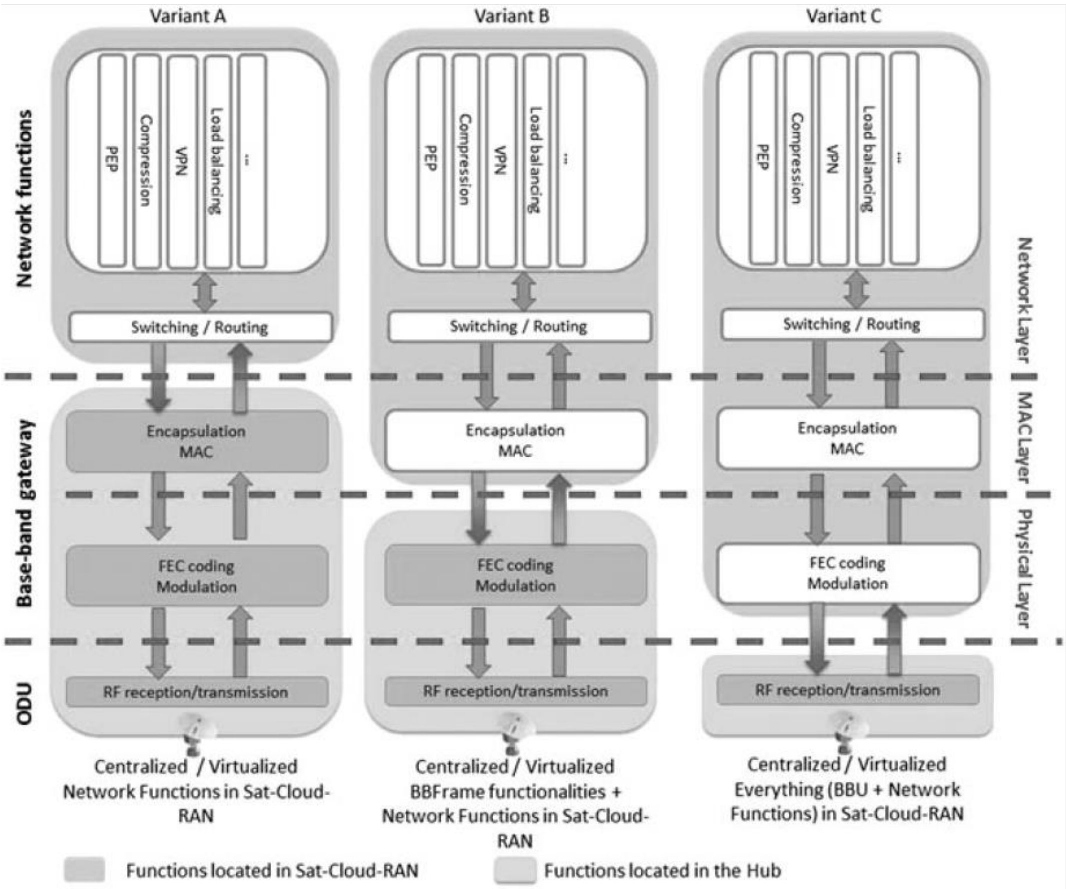

Figure 8: The variations of SatCloudRAN implementation depends upon the requested level of virtualization & centralization. [86]

The aim of this separation is to enable the creation of an environment with fully virtualized capabilities allowing flexible management, installation, maintenance, and operation of resources and services. This would thus facilitate the integration of a satellite network in hybrid networks as a virtual layer infrastructure that could be managed with the same interfaces. Therefore, the proposed SatCloudRAN helps SVNO providers to enter to market faster and at lower cost while gaining advanced control, more flexibility, and programmability of its allocated resources. [81], [84], [85], [86]

3.2.4 RESOURCES FEDERATION FOR SATELLITE SYSTEMS

Hybrid access networks are those combining a satellite component and a terrestrial component in parallel. Such a combination can improve service delivery in areas where QoS/QoE delivered by terrestrial access alone may be not satisfactory (e.g. higher speed broadband Internet access in low density populated areas with limited xDSL or fiber coverage). Unfortunately, the centralization from SDN in data plane & traffic management orchestration seems that cannot operate as panacea in case of heterogeneous networks e.g. in the eventuality of critical networks operation like a fatal system crash or resources monitoring. In this case there must be way for several systems (e.g. the satellite ones) not only to operate as semi-independent in 5G use cases, supplementary there must be a framework in which terrestrial & space networks must achieve the ability to co-operate in a emeritus scheme (or peer-to-peer like) in order to combine the synchronization and orchestration of SDN with a flexible semi-autonomous management scheme for generic network operations. [76]

One promising approach to address the integration of satellite and terrestrial networks for hybrid access is **network federation** through their resources. Specifically in satellites case, federation refers to the pooling of network resources from two or more domains in a way that slices of network resources distributed across the different domains can be created and used as one logical domain enabling easier control of them.

Federation of network resources in heterogeneous and multi-domain scenarios is has being addressed in several EU research projects for many types of networks mostly on 5G supported terrestrial & space networks. Specifically, the expected development of federation capabilities in satellite communications is regarded as pivotal for providing additional resources, features and services by Service Network Operators (SNOs) to customers. Reconfigurability, evolvability and programmability are three key characteristics that can facilitate the achievement of the federation challenge, while SDN and NFV are the most promising enabling technologies. By embracing SDN, the satellite network can expose a vendor-neutral, universally supported open interface, enabling unified management with terrestrial networks. Similarly, the NFV techniques simplify the provision of value-added networking services in the satellite communications systems, by expanding the terrestrial NFV management framework to satisfy the needs of the satellite domain as well. This is in line with the 5G vision, which encompasses federation of heterogeneous access networks in a transparent manner. [83], [84]

From a networking point of view, four key services are provided from a federation orchestrator: [84], [87]

- **Provisioning**: this capability enables the set-up, release and modification of connections in the network. Its most basic feature is to set up a point-to-point connection between two locations. However, there are other characteristics that a client interface can achieve :

  - Excluding or including network nodes
  - Defining the protection level
  - Defining its bandwidth
  - Defining its disjointness from another connection

- **Topology discovery**: this functionality requires unique identifiers for the exported network topology information. Network identifiers (such as IPv4 headers or DATAPATH-IDs) help to carry out path computation and to integrate the nodes for an end-to-end scenario. Further, the local controllers can provide information about the links in the domain (physical or virtual) or even their utilization. It is clear that the more information is shared, the less abstracted the network appears. So it is important to highlight that the North Bound Interface (NBI) of the orchestrator should be more abstract than the NBI of the controller.

- **Monitoring**: to collect the status of the connections that have been created is very useful in a multi-controller scenario, where after a failure in one domain, the domain's controller may request another connection.

- **Path computation**: Global path computation is an important feature because individual controllers in each domain are only able to share abstracted information that is local to their domain. An orchestrator with its global end-to-end view can optimize end-to-end connections that individual controller cannot configure. Without a path computation interface, the orchestrator is limited to carrying out a crank-back process.

Federation can also create a new market, where the federation from a business perspective is supported by a third party e.g. a broker, which offers added value federated network services supported by the underlying federated networks.

3.3 SDN/NFV-ENABLED SATELLITE NETWORK ARCHITECTURE

The physical and hardware separation between control and data forwarding nodes is one of the main principles behind the SDN implementation. Its implementation is based on three different functional planes: the management plane, whose purpose is to compute resource allocation strategies to provide each user with the required QoS, depending on the user's policies and current status of the network, the control plane aims at computing and enforcing forwarding rules to a number of data forwarding nodes in order to properly route traffic flows, the data plane, composed of the nodes of the underlying network infrastructure, whose only purpose is to forward the incoming traffic flows by following the given rules. [76], [78]

The aim of NFV is to decouple network functions from dedicated physical devices, making it possible to run such functions on general-purpose servers that could be deployed in network operators' data centers. In this way, more precise hardware resource allocation and sharing can be achieved, implementing virtual network functions (VNFs) on virtual machines and assembling and chaining VNFs to create services.

These concepts can now be employed in satellite communication networks, providing the following capabilities: [76]

- Intelligent delivery and deployment of new services in a flexible and programmable way

- Decreased energy consumption, by virtualizing the functions performed by the ground segment of the satellite infrastructure and consolidating/activating/deactivating them on remote data centers
- Capital expenditure (CAPEX) decrease by exploiting general-purpose hardware components to deploy virtualized functions
- The flexible embedding of satellite networking functionalities in the creation and dynamic adaptation of network slices, along with the required resource provisioning at the level of the satellite network operator (SNO)

Most of the projects we have studied have come to a conclusion that there must be a SDN/NFV-based framework for integrated satellite-terrestrial communication networks, which exploits the centralized control of SDN, in order to assist produce a strategy to distribute the three planes of the SDN paradigm in the various network nodes of a multi-layer satellite network. The management plane acts as the orchestrator of the overall network in the satellite network management center (SNMC).

The control plane in satellite systems can be divided into two parts: the space part, dealt with by the space controller in satellites, and the terrestrial part, in charge of the terrestrial controllers implemented inside data centers and satellite gateways (SGWs).

The data plane can also be divided into space and terrestrial parts, and is composed of the satellite, SGWs, and other intermediate terrestrial nodes, such as SDN switches.

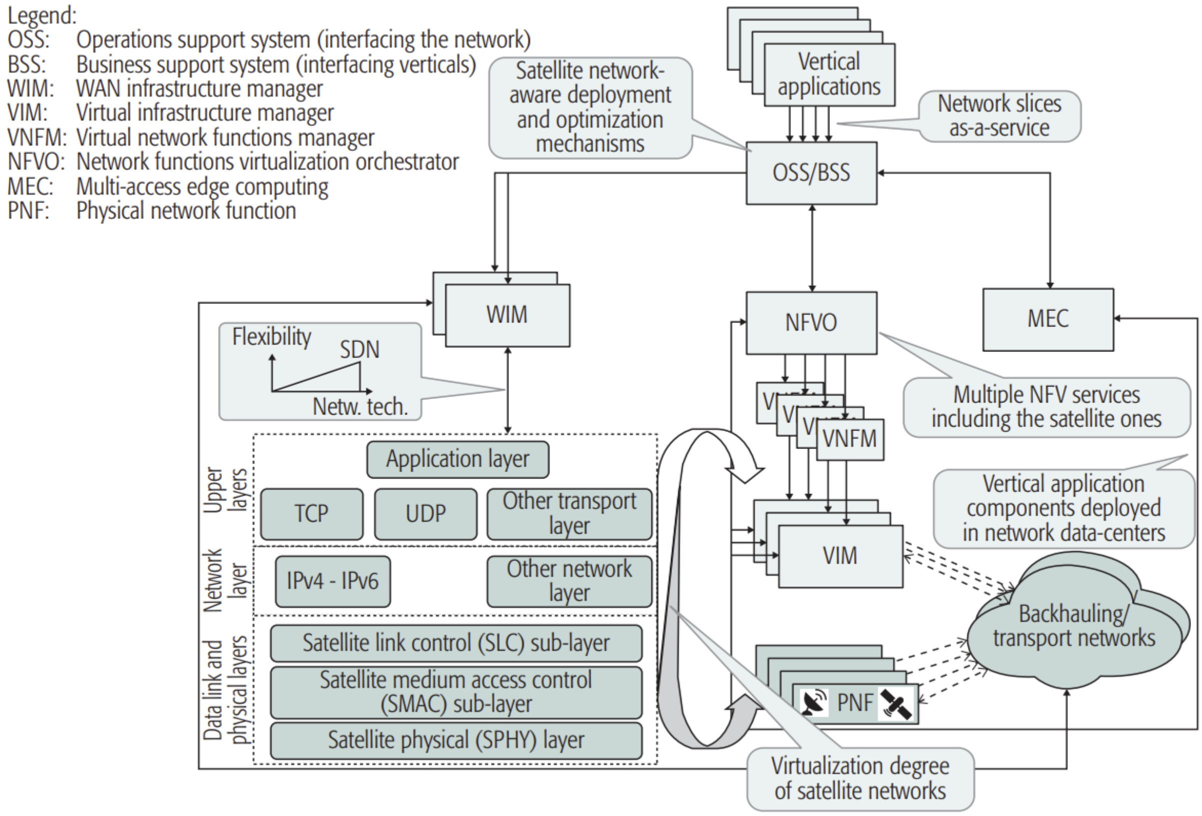

Figure 9: Simplified Architecture of SDN/NFV enabled satellite terrestrial node without federated orchestration [83]

Three different virtualization levels are identified: network layer functions, medium access control (MAC) layer functions, and physical layer ones up to the radio frequency front-end of SGW outdoor units (ODUs): [83]

- In the first level network functions such as performance enhancing proxy (PEP), admission control strategies, and QoS policies management are performed in a centralized hub. IP packets are sent to the SGW.
- In the second level, the unencoded DVB or Mx-TDMA frames (also called BBFRAMEs) are created remotely and then sent to the physical gateway.
- In the last level, data packets forwarded to the ODUs are physical layer frames (I/Q symbols). This framework could allow full virtualization of the satellite delivery chain and its provision as a service to multiple tenants, contributing to the satellite network as a- service (Sat-NaaS) network scheme.

The research occupied from CLOUDSAT & VITAL has determined the applicability of SDN and NFV technologies in order to define and validate integrated virtualized satellite-terrestrial architectures. The network architecture is composed of the following subsystems: [69], [71]

- Infrastructure, including the virtualization-capable equipment on which network services are deployed: switches and routers of the satellite terminals and gateways
- Infrastructure management entities, based on distributed management paradigms, such as virtualized infrastructure management (VIM) entities for the SDN/NFV enabled segments and the satellite segment, and a wide area management (WAN) entity
- Orchestrators, in charge of the deployment of services and resource allocation within each network segment
- The federated manager, representing the interface toward each orchestrator, as well as the interface toward final users.

The VITAL's proposed system architecture seems to be the one that fulfills the most of the KPI's and it is consistent from the following building blocks: [71], [76], [83]

- Physical network infrastructure with virtualization support entities: This building block consists of the virtualization-capable physical network elements on top of which Virtualized Satellite Networks (VSNs) are deployed.
    - NFV Infrastructure-Point(s) of Presence (NFVI-PoP(s)) for the deployment of VNFs. The main resources in these NFVI-PoPs are network, computing (CPU) and storage. There could be several distributed NFVI-PoPs, including a lightweight NFVI-PoP at the satellite terminal side. Resources in each NFVI-PoP are managed by a Virtualization Infrastructure Manager (VIM). NVFI-PoPs can also include SDN and non-SDN based network elements, which provides the programmable network interfaces that will provide the connectivity establishment and will support the VNF chaining within a NFVI PoP.
    - Satellite Baseband Gateway (SBG) Physical Network Function (SBG-PNF). A SBG-PNF hosts the non-virtualized part of the satellite baseband

gateway and is directly connected to the ODUs for satellite signal transmission/reception.

- o Transport network between the several NFVI-PoPs (backhaul), between the NFVI-PoP where the VNFs are run and the location that hosts SBG-PNFs (fronthaul), and cross-domain interconnection links. Each transport network segment is managed by a WAN Infrastructure Manager (WIM), potentially including the SDN and non-SDN network control.

- ➢ Satellite Terminals (STs), which provide the satellite connectivity and interworking between the satellite connection and a premises network on the terminal side. A lightweight NFVI-PoP can be co-located with the satellite terminal.
  - o Virtualized Satellite network (VSN): The VSN is a satellite communications network in which most of its functions are supplied as VNFs running in one or several of the NFVI-PoPs of the physical network infrastructure. Several isolated VSNs can be deployed over the same physical network infrastructure. The non-virtualized functions of a VSN are provided through one or several SBG-PNFs, which could be dedicated to a given VSN or shared among several VSNs. The operation of each VSN could be delegated to the customer/tenant, acting as a satellite virtual network operator (SVNO). Each of the VSNs may be customized to the customer/tenant's needs, including a variety of different network services running as VNFs (e.g. PEP, VPN, etc.).

- ➢ Management components: This contains the set of functional entities needed for the provision and lifecycle management of the VSNs. In particular, VSNs can be instantiated, terminated, monitored, and modified (e.g. scaled up/down, VNFs added/removed, satellite carriers added/removed, etc.) through the following management entities:
  - o NFV Manager. This is the entity responsible for the management of the VNFs that form part of the VSN, taking care of the instantiation, the dimensioning and the termination of the VNFs. The NFV manager receives appropriate commands from Service Orchestrator (SO), which include the Network Service (NS) descriptors. The NFV Manager maintains a complete view of the whole virtualization infrastructure of the domain; it keeps a record of installed and available resources, as well as of the infrastructure topology. For scalability, the NFV Manager maintains only a high-level view of the resources and the services, while the detailed mapping of services to resources is undertaken by the local managers of each NFVI-PoP (e.g. Virtual Infrastructure Manager - VIM).
  - o Service Orchestrator (SO). The role of the Service Orchestrator (SO) within the VITAL architecture, is mainly to provide service composition and to provide support for the OSS/BSS functionalities independently of the nature of the service (virtualized or not). Regarding the service composition, the SO decides, for example, on the capabilities and the composition (VNFs and PNFs configuration) of the VSN. On the other hand, regarding the OSS/BSS functionality support, this means that the SO will provide support for the FCAPS functionalities of VSNs. The SO which normally closely interacts with (or ideally is integrated in) the SNO's OSS/BSS, which may include other components such as

dashboards/customer portals that the customers of the SNO can use to order the provisioning of VSNs and related SLA management.

- Federation Network Resource Manager (FNRM). This element is in charge of multi-domain service orchestration. It consists of two separate components: a Federation Manager (FM) and a Federation Agent (FA). The FM hosts the logic to federate different domains and orchestrating Multi-Domain Network Services (MD-NSs). It is assumed that each domain is capable to orchestrate its own intra-domain NSs. Indeed, the FM acts as a super-orchestrator, having an overall view of the underlying orchestrators and domains. On the other hand, the FA is a component intended to handle the heterogeneity of the various underlying orchestrators and management entities of each domain, interfacing them with the FM. In addition to the FM and FA, a dashboard/customer portal is included as part of the FNRM to perform MD-NSs deployment, instantiation and orchestration.
- SBG-PNF Controller (SBGC). The SBGC manages the pool of SGB-PNFs. Through the SBGC, the SO can request the allocation of SGB-PNFs resources (e.g. forward/return channels) for a given VSN. To that end, the SBGC is in charge of slicing the resources of the SBG-PNF so that a logically isolated portion of those resources is allocated to a particular VSN. In addition, the SBGC may provide a SDN abstraction of the allocated resources so that control and management of these resources can be integrated within the VSN.

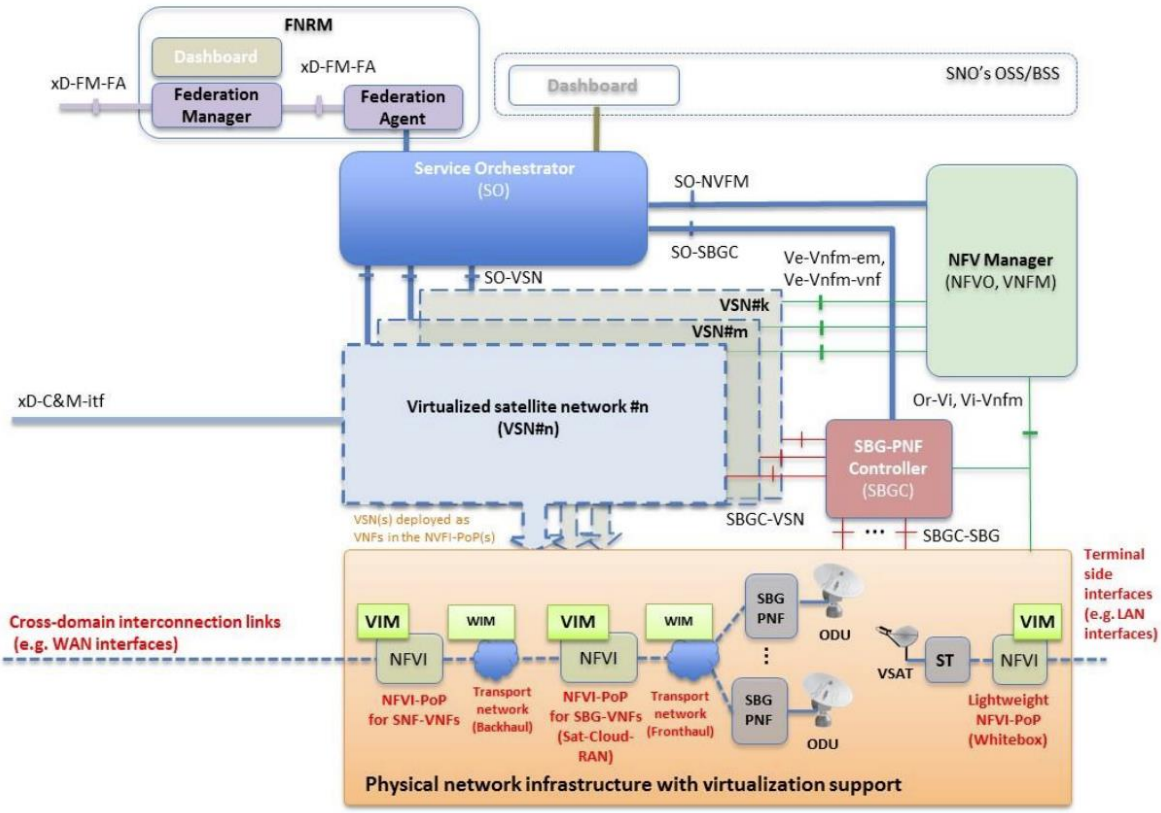

Figure 10: VITAL's basic scheme of proposed architecture for SDN/NFV-enabled satellite network, focused on virtualization and sharing of satellite communication platforms [76]

VITAL project's proposal has produced three main scenario clusters, identified as following: [71], [76], [83], [84]

- "Virtualization and sharing of satellite communication platforms": to expose the extension of Network Function Virtualization and SDN techniques to satellite domain
- "4G/5G Satellite backhauling services": to explore the cost-efficient implementation of satellite-based backhauling services into the integrated 4G/5G backhaul domain mainly leveraging the federated virtualized infrastructures
- "Satellite-terrestrial hybrid access services": to explore multi-domain operations and the federation/orchestration aspects in multi-domain network management

The main use cases of satellite systems mentioned from standardization in Chapter 1 with SDN/NFV implementation can now been modified into the following:

Table 1: Possible SDN/NFV-enabled Satellite Use Cases Including 5G Based on VITAL's Research [76]

Scenario #	Use Case #	Operation Focus
Scenario 1 Virtualization and sharing of satellite communications platforms	UC1.1 SDN-based flexible satellite bandwidth on demand	Flexibility and customization of the provided satellite network services
	UC1.2 Satellite Virtual Network Operator	Support of slicing and multi-tenancy in the satellite ground segment
	UC1.3 Satellite Network as a Service (SatNaaS)	Cloudification of the satellite ground segment
Scenario 2 4G/5G satellite backhauling services	UC2.1 Enhanced control and management of satellite backhauling capacity	Improved integration and management of satellite backhauling services
	UC2.2: Extending satellite backhauling with edge computing services and multi-operator sharing	Extension and coupling of the backhauling service with virtualization capabilities at the satellite terminal that allow for the delivery of mobile edge computing services.
Scenario 3 Satellite-terrestrial hybrid access services	UC3.1 SDN-based flexible federation of Satellite and terrestrial networks	Enabling dynamic and flexible traffic steering and forwarding by SDN techniques between satellite and terrestrial access network when needed according to the best reception or the least utilized network or other conditions
	UC3.2 Media distribution over Federated SDN/NFV enabled terrestrial and satellite network	Advances created by the federation of SDN and NFV-enabled satellite and terrestrial domains for complementing content distribution networks
	UC3.3 Customer functions virtualization over Federated Terrestrial and Satellite network	The aim of this use case is the operation of a VNF-as-a-Service (VNFaaS) paradigm and assumes the dynamic offering of virtual network appliances to customers in the form of VNFs.

In scenario 1, use cases are focused to a single domain of a Satellite Network Operator (SNO) and does not consider a Federation Manager/Broker, since this scenario refers to the case that a SNO offers wholesale access to network resources (bandwidth) up to further offering a high controlling level on network equipment and management of high and low level functionalities (example configuring the time/frequency plan) to the extent the SNO's network infrastructure can be partitioned into logically isolated virtual networks (slices). From the involved business actors, the SNO is involved as NFVI provider toward opening its infrastructure to be shared by multiple Tenants as it is commonly the case on cellular network model. Depending on the level of virtualization, the SNO will host VNFs provided by the VNF providers in order to selectively expose resources and operations in their hosting network to external Tenants (i.e. resellers and other providers). The tenants may exploit the network slice for own internal use or may also in turn act as service providers themselves and exploit the slice for offering a service to their customers. In this case, the model also includes Users, who receive the application/content over the slice. The existence of the slice is totally transparent to the EUs, who interact only with the offered application/content. [76], [84], [88]

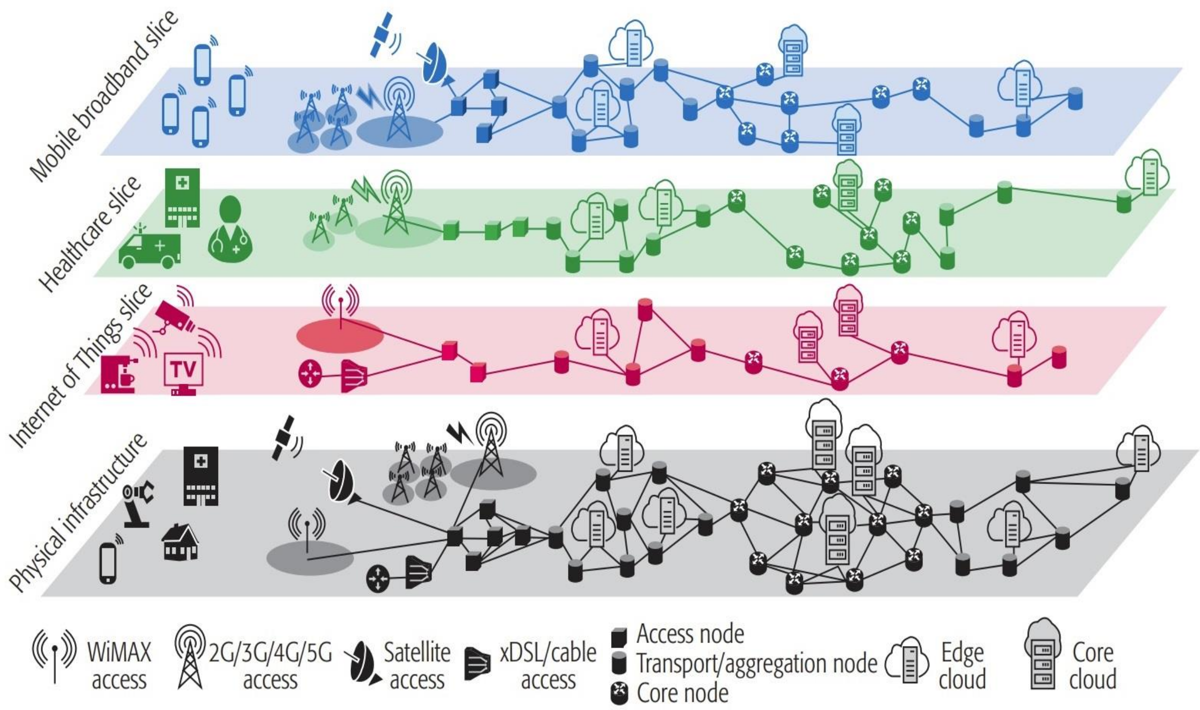

Figure 11: Example of satellite's support in 5G networks through network slicing [88]

In scenario 2, cellular networks backhauling is taken into account. Backhauling through satellite links is one of the most compelling scenarios for the integration of the satellite component in a terrestrial 4G/5G infrastructure. While mobile satellite backhauling solutions are a reality today, the high cost of satellite bandwidth and the technical complexities concerning the integration of satellite links into the mobile networks have largely restricted the use of satellite backhauling to remote or hard to reach locations and low traffic settings (e.g., backhauling of a base station site mainly used for the delivery of voice communications and very low data rate services). The Satellite Network Operator (SNO) offers the dynamic backhauling service in a flexible and virtual slice way. The VNF providers are suppliers of virtual appliances as a function to the NFV Infrastructure of the SNO. In this scenario the Tenants are practically the Mobile

Network Operators (MNOs), which use the satellite segment to extend network coverage. Generally, this scenario does not target to (retail/residential) users, while a Federation Manager/Broker is applicable but not a requirement since federated network services are not considered necessary component for satellite-5G communications.

This scenario baseline architecture considers that there is a SDN/NFV-enabled satellite ground segment infrastructure, owned and operated by a SNO, and a terrestrial network infrastructure for mobile communications, owned and operated by a Mobile Network Operator (MNO). The delineation of the two infrastructures is depicted as SNO and MNO domains. This view could represent the case of a MNO backhaul that is provided with a Virtualized Satellite Network (VSN) that can be integrated within the MNO mobile network for mobile backhauling. Therefore, the deployment of VSNs, as a business actor, specialized for the delivery of mobile backhauling services is envisioned within this scenario. Such specialized VSN is conceived as a VSN purposely designed to handle the specifics of the data, control and management interfaces to be deployed between a 4G/5G Core Network (CN) and a 4G/5G Radio Access Network (RAN) (e.g. S1 and RAN OAM interfaces in the context of LTE and the evolution of these interfaces in the 5G context, denoted as S1*/OAM* in the figure 11. Potentially, the VSN can be also designed to handle the interfaces used to interconnect nodes within the RAN itself. [76]

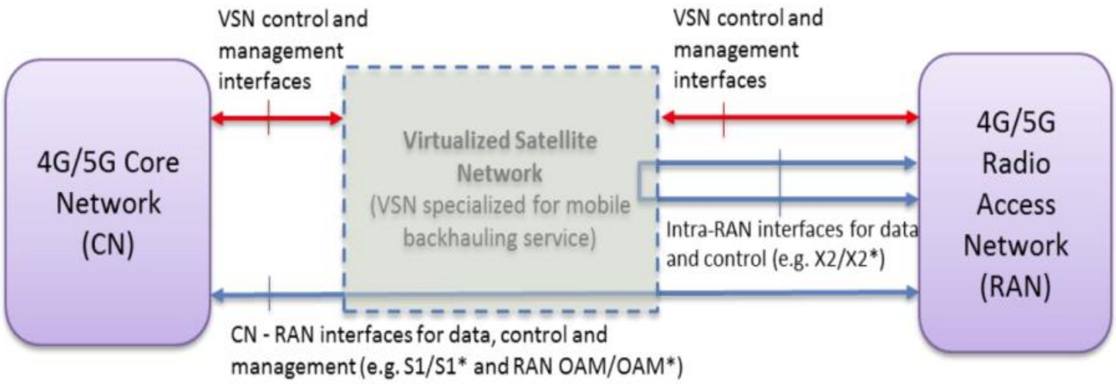

Figure 12: VSN operation diagram for 4G/5G backhauling, it shows how VSN is transparent from the edge networks and the users [76]

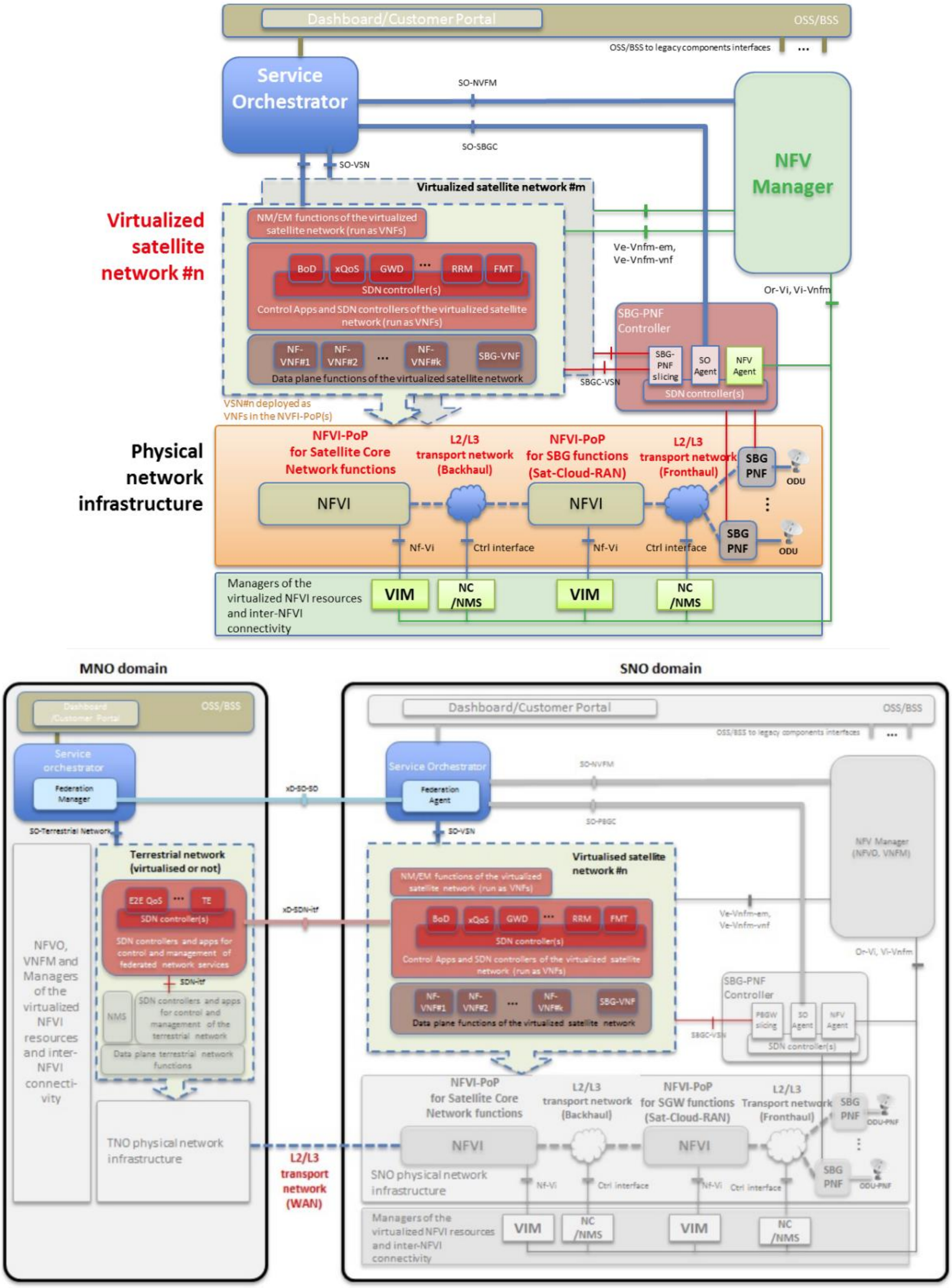

Figure 13, 14: Architectural differences of direct SO communications (Scenario 1) in terms of operational network components from using SO for backhauling (Scenario 2) [76], [82], [89]

Alternatively, the VSN can be tightly integrated within the MNO architecture. In this case, the VSN resources and their control and management functions will appear as an extension of the MNO local resources. The MNO will have the responsibility to seamlessly integrate VSN resources to constitute a single virtual resource available at end-to-end level. Together with the transfer of CN-RAN and intra-RAN interfaces traffic, a set of control and management capabilities of the VSN are also anticipated to be exposed / integrated to the MNO so that the whole end-to-end chain (CN, VSN and

RAN) can be jointly operated in consistent manner. It is also envisioned that this specialized VSN could embed diverse network functions for the optimization of the mobile backhauling service (e.g. TCP optimizers in the S1/S1* data plane) as well as diverse network functions for service extensions that might be relevant for MNOs (e.g. CDN components, MEC services, traffic offloading). [76]

Finally the scenario 3 focuses on the federation of satellite and terrestrial domains and the provision of a hybrid satellite/terrestrial access network slice to a tenant, which may in turn act as a service provider for content distribution. In this scenario, one or more Network Operators are considered (e.g. SNO, MNO, TNO), who operate the terrestrial (including Mobile) and satellite access network segments. These service providers and network operators exploit virtualization mechanisms to partition the network and lease slices to the Federation Manager/Broker. The latter acquires the slices in order to offer federated services to its tenants/customers, who are equipped with either single- or hybrid-access terminals (i.e. attached simultaneously to both satellite and terrestrial/mobile access network). Normally, the tenants are assumed to contract only with the Federation Manager/Broker for the hybrid service provision and not individually with each network operator. Detailed information about federation processes can be acquired through repositories and deliverables in [76], [77], [80].

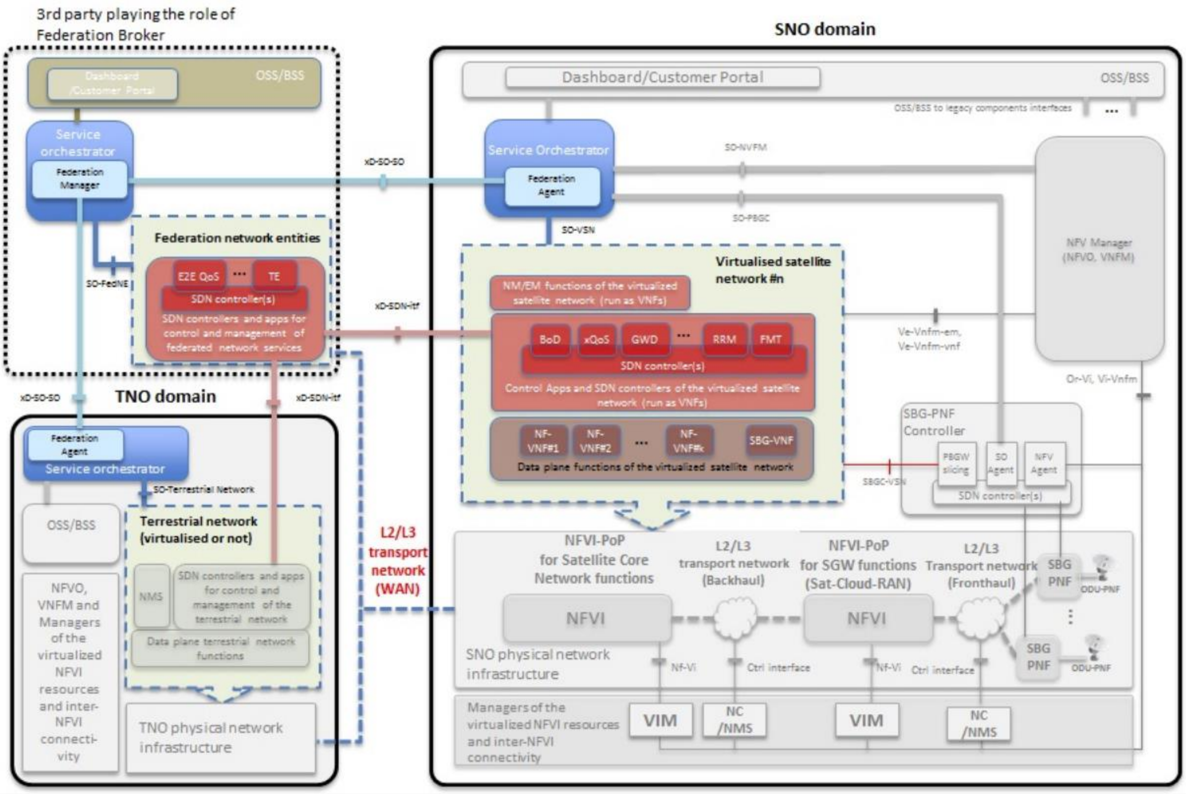

Figure 15: Architecture model for Satellite-terrestrial hybrid access services (e.g. integrated 5G-Satellite network with federation functions provided by a 3rd party entity) [76]

These architectures can provide a good base for providers as well as for virtual operators that plan to enter in the business of acquiring a part of the currency flow. They also provide the necessities that hybrid satellite-wireless architectures need to undertake when they have to provide access and backhaul services to the end users. The also present the benefits that the enabling technologies of NFV & SDN bring to the whole spectrum of actors and telecoms businesses. These technologies enable new business models for network and service providers, and they bring the base for creating new opportunities for existing and new service providers.

3.4 EVALUATION REPORTS

According to the tests data there are significant improvements e.g. in terms of quality in content distribution the algorithms used for quality reinstating are becoming a lot faster than traditional implementations. Supplementary, the experimental findings are in line with the expectations and that the backhauling wan optimization software is working well in a VNF context, achieving sufficient performance enhancement in controversial to non-NFV environment. Thus, it is proved in cellular backhauling cases that the softwarization of the specific function does not affect the performance of network functionality, the establishment of VNF Uploading services allowing a VNF Provider uploading its own VNFs, fast VNF detection from the FNRM entity and make it available in Customer User VNF catalogues within seconds supplementary an SNO can set up and deploy a NS using a VNF uploaded by VNF Provider within 10 seconds as measured. The VNF administrator can also have full control e.g. in case of deleting the service, freeing associated resources at involved domains and cleaning User accounts from references to deleted service. Analytic information is public available in [74], [77] & [85].

In terms of CAPEX & OPEX studies in [74], showed a major reduction in the CAPEX of terrestrial satellite system infrastructure. Particularly, within a 5-year period of deployment the CAPEX of GEO base station / gateways can be reduced up to 18% from reducing the cost of traditional transmission equipment (e.g. Encapsulator/Multiplexer, Return Link sub-system, GW Management & Access Control) combined with a transition to software-defined equivalent solution [e.g. Satellite Hub Generic Server HW, NFVI-PoP SW & HW (servers) & Orchestrator]. In similar, in a MEO system with 10 gateways the CAPEX the reduction can reach up to 29% and in a 50 gateway - LEO satellite system the reduction up to 41%. What is worth mentioned is that the values above are assuming that with the state-of-the-art technologies available the SDN/NFV Cost Reduction factor (per year) is 52% for each individual payload in terrestrial equipment e.g. by the transmission equipment according to the technoeconomic assumptions made by the projects. Supplementary, the overall CAPEX reduction rate seems scale-like related to the SDN/NFV scalability in complex network systems, in other words the reduction rate attends to grow similar to the complexity of the network or at least at the number of gateways.

In terms of OPEX, the calculations that we discovered are mostly based on GEO solutions. Under normal operation, the following results have occurred: [74]

- In virtualized satellite networks communication cases the investment becomes positive in cash flows within 2nd year of operation (Breakeven Year) and after 2.5 years reaches its Payback point (having make up for CAPEX and OPEX so far). This means that the investment is profitable within the 5 years period, reaches an IRR of 70% approximated, Profitability index 6.9 and a ROI of 26% upon initial investment and variable costs.
- In backhauling use cases, the investment becomes positive in cash flows within 2nd year and after 3.5 years reaches its Payback point. This means that the investment is profitable within the 5 years period with an IRR 27%, Profitability index 2.1 and a ROI of 25% upon initial investment and variable costs, approximated.
- In hybrid access cases the investment becomes positive in cash flows within 1st year by low OPEX figures, and after 2 years and 10 months reaches its Payback

point. This means that the investment is profitable within the 5 years period with an IRR 32%, Profitability index 1.98 and a ROI of 153% upon initial investment and variable costs. The high value of ROI points out the fact that from Year 1 there is a very high Cash Flow since Revenue is much greater than corresponding OPEX due to the zero leasing cost of satellite bandwidth in controversial, on the other scenarios there is the need to lease fiber optic lines in order to compensate bottleneck issues during satellite communications especially for backhauling purposes.

3.5 CONCLUSIONS & FUTURE TRENDS

The softwarization of the satellite networks has taken shape in many applications with the corresponding consequences in the CAPEX, OPEX and the profitability. The funded projects from ESA & EU offers many information for satellite network architectures including SDN, NFV, SDR & resources federation and their dynamic roles depending the use case are being implemented with significant benefits for CAPEX & OPEX reduce and improving the overall QoE in future 5G networks.

As the satellite industry transcends from 5G to 6G era new technologies will appear with their corresponding R&D testing projects. There is a non-stop process in terms of R&D projects & tests in concern to solve SDR issues, implementing AI, at first in form of Machine learning algorithms and producing software based solutions for future satellite network design & construction:

- **SDN/NFV in future tests**

Most of the projects studied are concerning the automation of MAC & NR in 5G network access mostly funded by ESA. **5G-GOA** develops and implements the necessary modifications in the 5G New Radio standards to enable the direct radio access of terrestrial communication networks via satellite with software & hardware prototype using protocols like OpenAirInterface for the prototyping of future 5G terrestrial systems. Supplementary, **5G METEORS** & **SDRmakerspace** are starting to produce their first results for SDR SW & HW in order to assist the spectrum expansion of 5G satellite component and with processing power produced only by x86 CPUs, without further assistance from ARM architecture or GPU acceleration. The generic equipment prototype being created (e.g. digitizers, computing hardware), assists industry to achieve all application specific functionality that resides in Virtual Network Functions being executable in containers in the generic cloud hardware. Their activities are supposed to be finalized within 2022-23 and implicate R&D activities from Greek industry & academic institutions (e.g. Libre Space Foundation Greece). [71], [72], [91], [92]

Finally, **VIBES** project outcomes (not available during thesis syntax) will allow reviewing the role of Performance Enhancing Proxy (PEP) agents (server infrastructures), redesigned as a set of Virtual Network Functions, namely vPEP. In this innovative perspective, the vPEP is following a top-down orchestration approach to flexibly satisfy the requirements of each application, on a "slice" basis. The proposed approach will assist the industry in services innovation & modifications through software-based deployment of functions, in order to satisfy possible evolving requirements with automated processes for many types of communications within 5G networks (e.g. M2M). Supplementary, **EdgeSAT** studies the global alignment of edge computing capabilities for satellite remote terminals in a global uniform network currently being developed in 5G by identifying and reviewing satellite systems connectivity scenarios that benefit from edge networking capabilities, formulating a set of recommendations and strategic actions necessary for the European & Canadian industry to be able to address identified opportunities & contributions to standardization bodies as and where applicable. [93], [94]

- **AI/ML's role in future networks**

Toward 6G era, AI implication is crucial in order to achieve maximum efficiency within a network, in order to establish that AI must be implemented in all OSI levels of the network not just over the top as the current state of the art. Scientific research from ESA has started to take into account the benefits of machine learning implementations for automation.

MLSAT & satAI projects aim at investigating the applicability of Artificial intelligence and Machine learning concepts and techniques in the field of satellite communications. In particular, it defines and analyses the applicability in a set of use cases (addressing any phases in the lifecycle of satellite communication systems). The use cases cover existing problems, and new concepts that could eventually enable new capabilities for satellite communication systems in terms of automation it studies the concepts of automatic interference detection using deep learning to automatically identify the presence of an interferer in an RF signal, even though it is cross-polarization interference, the flexible payload configuration in the presence of interferers by ML adjustments & user demands (congestion) prediction. [95], [97]

The outcomes of **MLSAT** project has already assisted in ML-enable satellite systems prototype deployment. On September 2020 ESA in contribution with Spire Global UK company, has announced the launch of two LEO machine-learning capable communication satellites for industrial applications e.g. A.I.-assisted geographic calculation of ships location. So far from the official data the overall processing power of these two satellites can reach in network with other constellations of up to 2 Teraflops and can be used in various applications e.g. financial predictions. [102]

Supplementary to satAI, **ANChOR** projects studies the design and implementation of an integrated infrastructure for 5G Satellite-Terrestrial networks, with data-driven orchestration techniques applied to the optimization of a multi-domain network, the project aims to investigate satellite-based extensions to 5G architecture and corresponding use cases, targeting eMBB and mMTC services, analyzing new business models and multi-domain deployments combining NR and satellite networks by building an orchestration solution, compliant with ETSI NFV and 3GPP standards that adopt ML techniques for a dynamic and data-driven resource allocation and slice management with self-optimization and self-adaptation capabilities. The evaluation of ANChOR solution involves Over-the-Air tests for Geostationary (GEO) backhauling scenarios with eMBB services, combined with NR simulations for a Low Earth Orbit (LEO) access modelling applied to NB-IoT communication scenarios. Both projects are attended to finish their research until 2022. [96]

- **Satellites system tools & reprogramming capabilities**

Satellite industry based on SDN/NFV technologies has attempt to create software solutions for networks design & monitoring, the consequences of these technologies are now applied also to the satellites themselves end the corresponding payloads.

Carnot-Sat project develops a software utility that enables the planning and deployment of heterogeneous terrestrial/satellite networks, necessary to underpin the quantitative design and evaluation of such networks and open up the market for satellites in 5G by focusing on the benefits to the terrestrial network operators. The toolset itself will allow network operators to produce and optimize a 5G radio access plan enabled by new network morphologies and to produce a transmission plan (backhaul plan) for satellite and terrestrial (fiber, microwave) networks that support these radio access networks. Supplementary, network planners are expected to be able to carry out trade-off cost analyses of different backhaul options, model the 5G network performance from a 5G application and RF coverage perspective, and utilize a 3D viewing capability that enables line of sight analysis. To avoid disrupting the pre-existing network planning tools, the project includes the delivery of a tool which integrates into existing terrestrial RF planning tools to maximizing market uptake by existing operators. [99]

MCC-SO project, develops a software tool that for deploying future VHTS in order to manage their capability of spectrum resources and also the major and complex aspects of a satellite system e.g. satellite fleet operation, flexibility capabilities, mobility, site diversity & dynamic resources management to improve total SNOs experience. The project will be finalized in mid-2022. [99]

Project **QUANTUM** heralds a new era of commercial satellite service, where government organizations will be able to actively define and shape the performance and reach from a satellite, as needed. In July 2021, ESA launched its first of a series of commercial GEO Ku-band satellites to have a fully flexible payload that can be remotely configured by software from SNO premises. It can be controlled not only by Eutelsat, the satellite constructor but also by the satellite operator, but also by the client, who can control their payload and implement operational scenarios according to their mission requirements. Unlike existing satellites, which typically have individually customized payloads, this line of satellites are otherwise identical and programmed by software for each specific mission and can even be re-purposed once in orbit or moved to a new orbital position. The satellites will operate in geostationary orbit some 36 000 kilometers above Earth. The fully reconfigurable OneSat product line features major innovations and disruptive technologies, including the latest digital processing and active antennas that enable several thousand beams per satellite. This satellite series will fully deployed in space until 2023. [100], [101]

4. THE SATELLITES CONTRIBUTION IN IOT NETWORKS

The Internet of Things (IoT) and Machine-to-Machine communications (M2M) have been widely predicted to present a significant growth opportunity for the telecommunications sector, with forecasts of billions of interconnected devices. These devices will be deployed globally to serve a wide range of application areas. With the satellite's broad geographic reach, proven reliability, and inherent efficient broadcast capability, a number of sectors and applications naturally lend themselves to satellite-based M2M networks.

State-of-the-art satellite systems can meet the needs of a vast range of applications, which exhibits one or more of the following characteristics:

- IoT/M2M devices that are in remote areas (underserved by terrestrial networks) or are dispersed over a wide geographical area (e.g. regional or global)
- IoT/M2M devices that are mobile (regularly/continuously moving between geographical locations) and therefore in need of a single platform solution
- A need for redundancy at critical sites
- Group-based communications to ensure connectivity across many devices
- Connected via other network technologies but require backhaul via satellite
- High degree of security and reliability

Europe has funded special purposed projects for interconnecting IoT networks mostly based on sensors and periodical packet transmission with satellites with and without the intervene of 5G networks (e.g. NB-IoT). In order to improve this connections a set of studies have performed focusing in the usable spectrum and internet protocols beyond traditional transfer and application ones (e.g. RESTful).

In order to describe the spectrum of this research, we present in this chapter the R&D projects related to IoT applications chronologically and by their scientific research topic in order to offer a preview of the proposals have been done in improving the Non-terrestrial IoT communications. We describe in brief the satellite technologies that are focused for NTN-IoT communications and the most suitable internet protocols during operation.

Finally, we present through open projects the future trends concerning the NTN-IoT research.

4.1 FUNDED PROJECTS TIMELINE

ESA and EU have funded over the latest years R&D projects to study the evolution potential of IoT communications with or without engaging direct communication with a 5G network. The projects in historical order are described as below:

- **ESA funded projects**

- **M2MSAT** (Demonstrator of Light-Weight Application and Transport Protocols For Future M2M Applications) (2015-2017)

M2MSAT was an ESA funded project in order to study the satellite systems potential to serve IoT applications either by backhauling or parallel operation from 5G networks.

The innovation of this project was to critically review, propose improvements and apply them in a satellite network testbed occupied by light-weight application and transport protocols proposed exclusively for M2M/IoT communications. In order to perform all the project attempted to identify the most recommended M2M/IoT protocols, to define reference M2M/IoT future satellite network scenarios for , identifying possible optimizations, modifications, and lower layer convergence procedures for the selected protocols for enhanced performance in selected reference M2M/IoT satellite network applications. Under the PoC, it demonstrated via implementations in a network testbed, the enhanced performance of integration procedures proposed for the selected M2M/IoT protocols in the selected reference M2M/IoT satellite network scenarios. [103]

- **M2MSATNET** (Realizing Future Low Cost and Large Scale M2MSatellite Networks) (2017- Feb 2020)

M2MSATNET was a project built to investigate the technical aspects required for M2M satellite communications and their applications in 5G IoT applications. The project continues the work of the M2MSAT by proposing through testbeds, future infrastructures for IoT applications over hybrid 5G terrestrial-satcom networks.

The project studied potentially upgrades of existing infrastructure & next generation M2M satellite networks which could be realistically put into operation by 2023, supplementary it has Identified System-level solutions that can support the satellite sector in capitalizing on the future growth in M2M service sector. Also it provided recommendations on operational environment for standardization, licensing and radio regulations among terrain and satellite networks by evaluating frequency bands for operation space architecture air interface for communication between user terminal and satellite user terminal design relevant use cases and a preliminary business plan for future Implementations. [104]

- **E.U. funded**

- **DROC2OM** (Drone Critical Communications) (2017-2019)

DROC2OM was an EU funded project in order to examine the evolution of drone communications with an end user by a hybrid form of connections between cellular terrestrial networks and satellites. The project studied the potential ability to reliably exchange Command and Control (C2) information over wireless data links between the Remotely-Piloted Aircraft Systems (RPAS) & Unmanned Aerial Systems (UAS). The DroC2om project's research concentrated upon RPAS/UAS data links in Very Low Level (VLL) airspace, for unmanned aircraft operating up to heights of 500 feet, where the use of drones is expected to bring innovation, new services for citizens, new business models and economic growth.

The DroC2om project created an evaluation report of feasibility and reliability for establishing hybrid C2 links of an UAV and the possibility of providing further service via existing radio network infrastructure, like LTE and satellite networks. In addition, the combined usage of the cellular and the satellite network to ensure availability and reliability of the created C2 links, where state-of-the-art satellite systems can sustain links of line-of-sight path between the satellite and the UAV and an indirect path where the signal is reflected on the ground. The project's results released to the public a feasible plan of operating high amplitude drones for important applications like urgent deliveries between cities, maritime deliveries & climate inspection. [105], [106], [107]

Unfortunately, the project refers to DVB-S2 & DVB-RCS standards for usage in the physical layer it doesn't mentions the theoretical improvement of using the newer DVB standards in the satellite links, supplementary it reports only some of the theoretical benefits of 5G terrestrial networks usage, it doesn't mentions the corresponding ones on satellite networks as a future 5G component.

4.2 SATELLITE SYSTEM EVOLUTIONS FOR IOT COMMUNICATIONS

A significant number of vertical markets such as transportation (including "connected car"), utilities (energy, water...), agriculture, safety domains, etc., benefit from M2M/IoT technologies to monitor and manage their assets and goods. Hence the network infrastructure shall be able to interact with a very large number of devices that can be in every place on Earth.

The IoT/M2M will definitely trigger a massive wave of connected devices (sensors and/or actuators, etc.) in the next years. A large number of them addresses the vertical markets in transport (e.g. maritime, road), energy, public utilities and agriculture domains. This requires tracking of moving sensors or data exchange with stationary sensors/actuators or sensors/actuators located beyond the reach of terrestrial mobile network infrastructures. Hence, a complementary satellite network provides a cost-effective solution to connect such devices. Among the applications, there are: [103]

- Tracking of Containers (maritime transport), of vehicles for insurance or road charging (land transport), of livestock especially in emerging countries (agriculture)

- Critical data collection from sensors providing status about infrastructures such as hydro-electrical dams, pipelines, energy grids, mining operations

- Security applications (e.g. surveillance sensors)
- Environmental Monitoring, Smart Agriculture applications, etc.

From the oldest projects we have discovered we know that typical M2M and drone communications were based in L&C band channels not only for navigation but also for data transmission either connecting devices (e.g. drones) directly to one internet core network or backhauling an LTE network due to large distance of a drone from cellular towers, supplementary in networks access techniques taken into account were considered from pre-SDN era and didn’t provide network automation capabilities (e.g. Overlay / Network Tunneling & Multi Path TCP).

While IoT applications represent core addressable use cases for satellite communications, the actual satellite market was further limited by: [103]

- High cost (even though telecommunication services via small satellites are expected to be more cost-competitive than high throughput GEO satellite telecommunications)
- Medium/High power consumption
- Low data rates (up to a few Kbps) of existing satellite communication technologies
- High latency (1-2s average) of existing satellite communication technologies (GEO)

The state-of-the-art satellite systems are using higher frequencies in combination to software-defined solutions for network access, supplementary through the widespread of RESTful services protocols and similar ones, new ones have appeared in order to reduce the data overhead for all types of internet connections (some of them already being used either in LAN or WAN topology e.g. LoWAN). In brief, satellites presents many advantages for M2M/IoT communications either for direct communication of satellites with IoT devices (e.g. drones) or performing backhauling for 5G infrastructures with correlated IoT networks like NB-IoT. The main characteristics of state-of-the-art satellites can be summarized to the following: [103], [104], [106], [107]

- Global coverage either by a small number of GEO satellites or a more responsive LEO constellation
- Secure communications
- Robustness against disruption
- Easy deployment to satellite equipment for IoT devices
- No need for extensive hardware upgrades
- Remote areas with lacking fixed terrestrial network infrastructure may have as the only available Internet access technology the satellite internet networks.

- Advanced diversions of internet protocols that can been furthermore beneficial & suitable than traditional RESTful services in order to increase the share of satellite communications in the M2M/IoT market.

- Our research has determined that the satellite systems of the future have a significant benefit in IoT communication in below 6 GHz bands for narrowband communication, more specifically using ISM900 band channels & C band. The wideband transmissions are also at discussion for big data from IoT sensors, more specifically Ku/Ka bands are being used at the state-of-the-art NTN-IoT networks with theoretical expansion to Q/V and W bands which as a consequence it might lead to possible antenna size reduce in long-term operations.

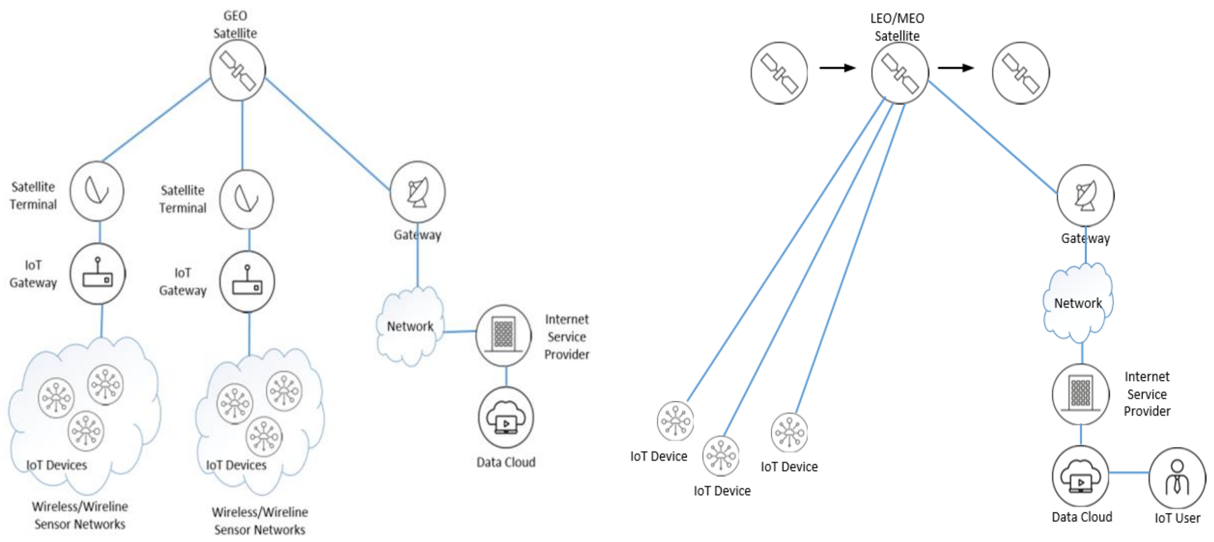

Figure 16,17: Network topologies for satellite backhauling of terrestrial IoT data & Direct IoT device to satellite communication depending the terrestrial networks configuration [103]

An IoT Device hosts sensors which detect physical quantities and converts them into digital data. It also may host actuators which move elements of a system upon reception of a command. These devices can communicate with each other or an IoT Gateway.

In backhauling scenario, the gateway collects the data from the IoT Devices or sends commands to them. The collected data is then sent via the Satellite Terminal to the satellite and from there to a Gateway. The Gateway interfaces with an external network, which is required to transfer the data to the Data Cloud. In this scenario the satellite is located at a fixed orbital position in a geostationary orbit. In direct satellite communications scenario, IoT Devices communicate directly with satellites, which are in a Non-Geostationary Orbit (MEO/LEO), which is much closer to the earth than in the first scenario. Therefore, IoT Devices send their data directly via satellite to the Gateway. For commands the same principle applies, but in the opposite direction. Another noticeable difference is that for an observer on earth those satellites are moving due to their proximity to the earth, while GEO satellites, due to the peculiarity of their orbit, seem the stand still. [103]

Communications may take place using one or more of the following communications paradigms:

- Device to Device (D2D) communication between devices
- Device to Server (D2S) devices communicate with a server or with each other via the Internet
- Server to Server (S2S) servers communicate with each other

In MAC access, ESA has proposed a set of random access techniques due to large growth of enhanced random access techniques with contention resolution capabilities. Their common concept is to perform more advanced signal processing at the gateway with memory-based iterative for successive interference cancellation. Modern RA techniques can achieve 2-3 order of magnitudes improvement in throughput with low packet loss ratio compared to traditional ALOHA / Slotted ALOHA. The most applicable of all is Enhanced Spread-Spectrum ALOHA (E-SSA). This random access technique is slightly modified version from 3GPP W-CDMA random access waveform (asynchronous burst transmission) provides enhanced processing at the gateway with sliding window & memory based & recursive Successive Interference Cancellation burst demodulator. [103], [108]

In order to perform IoT communications, lightweight & robust internet protocols are necessary to reduce the overhead over a satellite channel. On transport & application level several protocols compete for dominating the market. In terms of internet protocols our research has identified over 14 protocols available competing for potential use into the IoT networks. Accordingly to ESA reports we have concluded that the two most promising protocols for every kind of interaction between IoT devices and end users through a satellite network are the following:

- **Message Queuing Telemetry Transport (MQTT)**

The MQTT is a binary open standard publish/subscribe messaging protocol for passing messages between multiple clients through a central broker. It was invented by IBM in 1999 for satellite communications with oil field equipment and has since been standardized in 2014 at OASIS. As of 2016, MQTT has been approved as an ISO standard (ISO/IEC 20900). As its name states, its main purpose is telemetry or remote monitoring of the large networks of small devices from the cloud. The protocol itself is designed to be lightweight and easy to implement which makes it suitable for communication between embedded (resource/power constrained) devices over unreliable or low-bandwidth links where cost per transmitted bit is comparatively high. MQTT sits on top of the TCP protocol. [103]

More specifically, the protocol uses publish-subscribe pattern in user-device communication. In this pattern, a client that publishes a message is decoupled from the other client or clients that receive the message. The clients don't know about the existence of the other clients. A client can publish messages of a specific type and only the clients that are interested in specific types of messages will receive the published messages. Publish-subscribe pattern requires a broker, also known as MQTT server. All the clients establish a connection with the broker. The client that sends a message through the broker is known as the publisher. The broker filters the incoming messages and distributes them to the clients that are interested in the type of received messages.

The clients that register to the broker as interested in specific types of messages are known as subscribers. Hence, both publishers and subscribers establish a connection with the broker. [103], [109], [110], [111], [112]

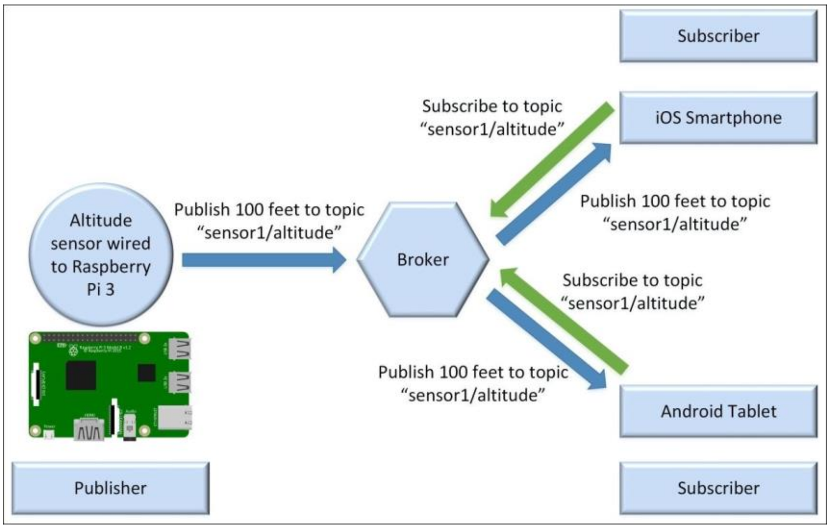

Figure 18: The diagram above summarizes the communication of one publisher (e.g. IoT sensor on top of a Raspberry) and two subscribers (end user's PC, tablet, etc.) connected to a broker (MQTT server) [103]

Each message belongs to a topic (message category). When a publisher requests the broker to publish a message, it must specify both the topic and the message. The broker receives the message and delivers it to all the subscribers that have subscribed to the topic to which the message belongs. The broker doesn't need to check the payload for the message to deliver it to the corresponding subscribers, it just needs to check the topic for each message that has arrived and needs to be filtered before publishing it to the corresponding subscribers. A subscriber can subscribe to more than one topic. In this case, the broker has to make sure that the subscriber receives the messages that belong to all the topics to which it has subscribed. In summary, the four key packet components that constitute the core concept of MQTT protocol are: [104], [112], [114]

- The Publisher
  - Connects to the broker
  - Publishes application messages
  - Disconnects from the broker (server)

- Subscriber
  - Connects to the broker
  - Subscribes to request application messages
  - Unsubscribes to remove a request for application messages
  - Disconnects from the broker

- Broker (MQTT server)
  - Accepts network connections from the clients
  - Accepts application messages published by the clients
  - Processes (filters) subscribe and unsubscribe requests from the clients
  - Stores and forwards the incoming messages from publishers directly to the subscribers

- Topic
  - Represents global namespace into which all messages go
  - ASCII string hierarchically structured with forward slashes as delimiters between different levels (e.g. home/ground floor/kitchen/temperature)

Routing and filtering of the messages in the broker is only built upon topics. In order to support memory-constrained-devices, MQTT subscribers are allowed to use multi-level and single-level wildcards leaving small code-print.

➢ Constrained Application Protocol (CoAP)

The Constrained Application Protocol (CoAP) is a web transfer protocol defined under the IETF Constrained RESTful Environments (CORE) working group, specifically designed for small memory and power constrained hardware. CoAP aims to provide connection of several devices to services made available over the Web. It can be easily translated to HTTP for the integration with the Web, while still meeting requirements such as very low overheads, multicast support, and simplicity for constrained environments. [103], [112], [113]

CoAP introduces a web transfer protocol based on traditional REST on top of HTTP. In contrast to traditional REST, it is utilizing lightweight UDP as transport protocol by default, allowing asynchronous communications. This makes CoAP more suitable for the IoT domain because it is possible to build sufficiently basic error checking and verification for UDP to make sure that messages arrived without the significant communication overhead as in case of TCP.

CoAP provides a request/response interaction model between applications endpoints supports built-in discovery of services and resources, multicasting and includes key concepts of the Web such as URIs and Internet media types. The protocol allows communication with wider internet using similar protocols for constrained IoT devices, which are termed as “nodes”. It is best suited for devices that are on same or different constrained network, as it uses the Efficient XML Interchanges (EXI) format which is space effective as compared with XML/HTML which is a binary format. [113]

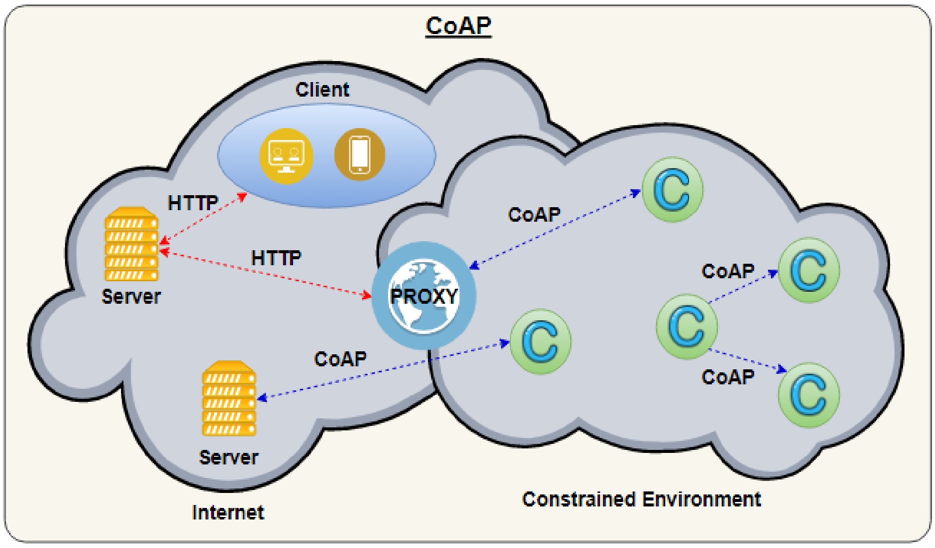

Figure 19: Simplified diagram of CoAP architecture [112]

CoAP comprises of two layers named as messaging and request/response. For redundancy and consistency of any message, the messaging layer is responsible while connectivity and communication handling is request/response layer responsibility. CoAP also facilitates multicast messaging as well as support asynchronous exchange of messages.

In terms of operation efficiency the protocols above are considered from our research as the most effective for both terrestrial & satellite networks. Unfortunately, the scientific information we gathered reports that they can be vulnerable to some types of attacks, the most important is Denial-of-Service (DoS/Distributed DoS). As a consequence security mechanisms must be applied. So far suggestions have been made for implementations of TLS over MQTT and similar mechanisms in CoAP (e.g. ECC-produced certificates and DTLS because of UDP operation) but studies have to be developed further as most of this mechanisms will be efficient for pre-quantum security era, in other words under the current state-of-art the majority of those won't be applicable in 6G. [113], [115], [116], [117]

ESA and EU studies declared that with the above standards and specifications IoT communications can became much more beneficial than the state of the art implementations. Since we haven't found it thesis research, it is considered that advanced research should be conducted though the upcoming years in order to estimate the impact of such protocols in SDN/NFV enabled 5G/6G networks, especially coexistent with RESTful-based SDN software implementations.

4.3 CONCLUSIONS & FUTURE TRENDS

In this chapter we have seen the capabilities of satellite systems for IoT/M2M communications and the corresponding impact of new internet protocols concerning IoT applications. The satellite operation is further studied in order to use SDN technologies into IoT systems, spectrum expansion and further use of LEO systems for LoWAN communications. A set of projects is still ongoing concerning this issues most of them are expected to be finalized by 2024:

- **SDR & NB-IoT over satellite**

ESA develops research concerning the operation of Narrowband-IoT backhauling with SDR-enable payload & software infrastructure both in satellite & ground station for 5G network communications. **5G SENSOR@SEA** Project was one of the oldest known to examine GEO satellites for develop, deploy and validate 5G massive Machine Type Communications for maritime applications and intermodal logistics. **IOT-SATBACK** finalized very recently, took it one step forward concerning GPU-based & SDR-enable payload dedicated for NB-IoT backhauling taking advantage of DVB-S2X and E-SSA based solutions for MAC random access. Supplementary the study took into account OFDMA & SC-FDMA multiple access techniques for more compatible satellite transmissions with the terrestrial 5G networks. [118], [119], [120], [121]

To this direction, **R3 IoT** project develops a new generation cloud system called R3 IoT system prototype, for incorporating cutting edge technologies, designing for mass-manufacture, and improving the performance of all IoT network elements to ensure the R3 end-to-end Industrial IoT service will provide utmost value to our customers across multiple markets. This project focuses on giving business solutions to gather sensor

information when they need to make informed decisions. The R3 system prototype is composed of two primary elements: the R3Cell and the R3Cloud. The R3Cell is a smart gateway that can connect to hundreds of end- devices such as sensors, probes, etc. that collect the information from a customer's operations. The gateway can process the information and backhaul it over one or more links back to the cloud. The R3Cloud hosted on public cloud infrastructure for scale and security, provides a web interface to users in order to manage multiple deployments of gateways and end-devices out in the field, as well as manage the end-device data incoming from the connected gateways.
The combination of R3Cloud and R3Cell provide will provide customers with complete end-to-end IoT solutions which when combined with large numbers of compatible sensors and other devices can provide valuable insight into remote operations. Its results are expected to be finalized by winter 2021 due to COVID pandemic. [122]

- **LEO satellites potential for IoT applications**

ESA's particular interest for the beneficial of NB-IoT network compared to other network types (e.g. SigFox) performs studies for NB-IoT-satellites communications for backhauling purposes under non geostationary systems. **NB-IoT4Space** project studies the applicability of non-geostationary satellite systems to enable the integration of user sensors over NB-IoT. For this type of communications it is necessary to develop an on-board evolved node B (eNB) capable of using a standard not originally conceived for satellite communications with adaptation and additional features (e.g. SDR payload). Moreover, the eNB must be compatible with small satellites platforms in terms of mass, power and volume since these platforms is usually the ones selected to provide M2M/IoT services. Through the development of a prototype demonstrator it studies which communication specifications between an NB-IoT User Equipment (UE) and an eNB must be adapted for satellite communications as functionally verified. [123]

GATEHOUSE (Narrowband IoT for SmallSatNetworks) project studies the operability of non-terrestrial 5GNB-IoT communication using satellites in Low Earth Orbit. Under the existing project activity (Definition Phase), its main purpose is to identify areas for which the existing terrestrial NB-IoT requires significant adaptations to operate by space communications. The following phase will include implementation of critical algorithms' Doppler compensation, synchronization, cell search, paging and access techniques. The project builds a demonstration prototype of a complete ground system set of payloads to send them in orbit in late 2021. The implementation is divided in two, a space segment which is installed on a software defined radio (SDR) payload with applicable antenna system & the solution for the UE which can be installed either on dedicated HW or be integrated into a suitable purpose specific chipset. The solution will ensure a fully commercial reliable communication between a massive number of UE on ground and the satellite constellation. The Non-Terrestrial Network NB-IoT is defined in two modes, a Transparent Mode and a Regenerative Mode. NodeB functionality is located in the satellite (Regenerative) which will support low density smallsat constellations providing IoT and M2M services. Having the NodeB located behind the ground station will require the satellite to "relay" the data and be somehow transparent towards the UE and the Backhaul. The UE equipment will support both the transparent and the regenerative mode. The first commercial applicable version of the prototype is planned for operation in mid-2022. [124]

5. SATELLITE ROLES IN CDN DURING 5G ERA

During our research we have noticed that ESA within the last decade has expressed a particular interest for satellite operation over internet-based Content Distribution Networks (CDN). This lead to a certain number of R&D projects that studying not only the access architecture for CDN and caching servers (e.g. PEPs) but also internet protocols impact in generic internet multimedia services when using satellite connection, either in cellular backhauling or direct communications.

Due to the vast range of knowledge, we decided to dedicate this chapter to report in brief the satellite systems possible roles for CDN communications and the studies occurred for the behavior of multimedia-focused internet protocols over satellite links. We start this chapter by mentioning the historical order of ESA's research. We have produced a summary report of all possible use cases for satellite communications in order to describe the application potential over CDN. Supplementary, new internet protocols have appeared that will have direct impact to the caching procedures under satellite links and also in general cloud-based applications like Google's. We present a report of studies occurred, concerning internet protocols impact over satellite links and applicable impact mitigation techniques.

At the end, we present our conclusions and the corresponding future trends concerning CDN operation and future cloud services operation under satellite internet networks.

5.1 RESEARCH ON CDN SATELLITE ACCESS

Over the latest years ESA has conducted specific purpose projects to estimate the behavior of cloud services and the benefits for CDNs by using satellite networks. The research is historically analyzed as followed:

- **MENDHOSA** (Media & ENtertainment Delivery over Hetnet with Optimized Satellite Architecture) (2014-2017)

The MENDHOSA project was R&D research developed to propose a roadmap for the satellite networks industry based on an innovative yet realistic technology roadmap, to alleviate risks and exploit opportunities for solutions in the question of “Digital Disruption” that will affect most sectors of the world economy, the IT and media industry in particular within the 2020’s decade. The project developed technical analysis and scenarios for future implementations and operation of hybrid terrestrial-satellite access to CDN networks by the cellular networks users.

The MENDHSA study has provided an analytical study of the IT & Massive Media (MM) market sector, its benefits from different possible scenarios of satellite integration in the 5G terrestrial networks, in order to provide a wide scale of future services from mobile backhauling to CDN. The different integration scenarios have been analyzed through a techno-economical study, and some scenarios have been selected for deeper analyses by future projects. Supplementary, the project’s analysis has provided based on past and current satellite design studies, different space segment configurations, along with different efficient system and network features, which all have been ranked, according to different criteria’s based upon their efficiency. Some specific features have emerged, leading to a technological gap analysis, for developing products and features improvement roadmaps. [125]

- **SCORSESE** (The role of satellite in collaborative adaptive bitrate streaming services) (2014-2017)

The SCORSESE project was R&D research developed to study the possible improvements for collaborative video adaptive bitrate streaming services delivery by combining satellite and terrestrial networks. The objective of this project was to identify and devise synergies among the mentioned hybrid satellite-terrestrial technologies and to demonstrate the performance improvements achieved by the proposed architectures, by the developed proof of concept architecture via simulations.

The project evaluated possible backhauling scenarios for the satellite backhaul over ultra-dense 5G networks for relevant use cases and home gateways in case of both Video on Demand (VoD) and live streaming applications. Supplementary, it defined integrated satellite-terrestrial video delivery scenarios using satellite for Intra or inter-CDN access network, and studied connectivity scenarios for dual (satellite, terrestrial) home users by identifying key technological components used and the interfaces, providing value creation perspectives and cost assessments for the integrated architectures. It also developed stand-alone and end-to-end proof of concepts to demonstrate the performance enhancements achieved by the integrated architectures in order to provide recommendations for future development and standardization activities. [126]

- **HTS-DBS** (High Throughput Satellite Data Broadcast System) (2016-2019)

The HTS-DBS project was an R&D research, studied a system architecture proposal for a potential future high throughput satellite-based Ka-band broadcast system as a hybrid broadcast / broadband cached system for various use cases over CDNs.

The project, analyzed the possible benefits of using broadcast services over HTS satellites and the basis for broadcasting in HTS multi-spot beam architecture, including a review based on the conceptual side of the architecture of HTS to include efficiently broadcast based applications for long term applications. Supplementary, there was a demonstrated scenario of video/audio file based broadcast services employing IP based distribution techniques compatible with non-linear video distribution services and adapted to the services and rendering devices of state-of-the-art consumer devices, simulating a novel broadcast transmission and reception eco-system aimed at the delivery of files for linear and non-linear television reception and the possible usage of video delivery on demand and profile based content discovery at the receiver side like cache-assisted content delivery through popularity algorithms like Zipf. [127]

In total, the objective of the HTS-DBS project is to study the context of a possible satellite-based content distribution network system and demonstrate the key techniques required for such a product, including file transfer to caches and the cache management techniques. Furthermore, the use cases are studied and the usage of different multi-spot beam and wideband space segment missions are considered and compared in terms of efficiency to feed content to a large network of end users.

- **MTAILS** (Mitigation Techniques for Addressing the Impact of Latency on services over Satellite Networks) (2018-2020)

The MTAILS project's overall objective was to characterize and mitigate the effect of satellite latency on the user's perceived quality of experience (QoE) for different applications describing it by actual numerical QoE values presented to the public and the industry. The team of the research split the overall objective into the following two sub-objectives:

- To measure qualitatively or quantitatively the impact of higher latency on the QoE for top applications and content servers with and without caching by Performance Enhancement Proxies (PEPs), so that telecom operators/ISPs are aware when satellite connectivity is a suitable option, assuming appropriate mitigation measures are in place.

- To identify new techniques that can be applied at satellite system level which can improve the QoE for those emerging applications that are more sensitive to latency and to contribute to the adoption of these techniques by satellite system or PEP manufacturers.

The project has aimed at providing data that supports participation at standardization bodies, in order to encourage the development of air interfaces and protocols that are less sensitive to latency, for this study the project considered different reference GEO and non-GEO satellite systems (MEO and LEO, with and without inter-satellite links) and a set of relevant user applications & services for satellite internet connections and future 5G backhauling use case scenarios, emphasizing on the impact (either positive or negative) of classic application layer's protocols, i.e. HTTP protocols, and of newer protocols like the one's Google uses for handshaking when users interfering with her web services (i.e. gQUIC). [128]

Unfortunately, optical ISL's weren't taken into account which could improve the measured QoE values, also it doesn't cover some types of use cases like VR-interactive internet gaming that have even lager needs for bandwidth and responsiveness that the mentioned scenarios.

Concluding, the MTAILS proves that in cases of user web access, video streaming, online gaming, online gaming & IoT applications the satellite systems solutions for backhauling can provide a feasible solution with respectful response with GEO-HTS and almost perfect user experience with the state-of-the-art LEO-HTS constellations. During our research we considered that it's the most complete report for actual measurements of user experience about 5G backhauling, which may guide ESA to her future research for next level of studies, like a future real-operational testbed platform with actual satellites testing like SATis5 in Europe and 5G ALL-STAR in South Korea for a future QoE measurement, instead of a simulated environment as MTAILS established.

5.2 SATELLITES IMPORTANCE IN CDN NETWORK SERVICES

ESA has conducted focused research in CDN co-operation with satellite networks and their possible integration to complement their coverage and offer better quality of service to the end users studying also caching improvements for all types content distribution network including backhauling for 5G infrastructures.

5.2.1 THE SATELLITES ROLES PER GEOGRAPHIC REGION

Media & Entertainment industry (M&E) have been revolutionized over the last years. This has come as a complement to lean-back linear TV. Even if most likely clear signs of changes were coming up, the size of the new M&E wave has been much bigger than expected by anyone of us. The biggest change driving all others in M&E is associated with the fact that the individuals themselves do not only passively consume, but interact, share, chat, talk, tweet, while walking, running, driving, commuting by subway or train etc., during their media and entertainment enjoyment. Under this influence, the M&E industries converge in all fields: [125], [126]

- Devices are expected to support M&E content with high quality and maximum flexibility.
- Video content and interactive user-experience converge into integrated platforms with a digital web-like experience.
- M&E content follows the end-user wherever is going.
- Professional productions are complemented by self-productions by the end-users on social networks, other community platforms, as well as by aggregators and service providers producing original content.
- User Generated Content (UGC) is becoming more and more used in both personal and professional environments and most of this content is stored and shared in the cloud.

- M&E convergence is enabled by several key technological developments including progressively larger and cheaper storage, increasing processing power, and better connectivity.

M&E services are consuming more and more network capacities due to higher usage and also to larger amount of data. In order to optimize the use of the network capacities, it is necessary that the on-demand resource parameters (latency, bandwidth, security, connectivity) are allocated and configurable as required by the service.
While these massive changes energize the M&E industry and its economic impact, they pose extreme technical challenges to the underlying distribution infrastructure. Future networks, and 5G in particular should be able to answer these challenges and turn them into opportunities for all stakeholders.

The different M&E use cases, as also identified in the 5G PPP White Paper “Media & Entertainment White Paper” (February 2016) the most significant in terms of multimedia services are the following: [125]

- Ultra-High Fidelity Media
- On-site Live Event Experience
- User Generated Content & Machine Generated Content
- Immersive and Integrated Media
- Cooperative Media Production
- Collaborative Gaming

ESA’s studies have conducted detailed analysis for the development and deployment scenarios of terrestrial technologies and services, as well as on the foreseen evolution, include the following suggestions: [125], [126]

- **For developed countries:**

- In West-Europe countries, the integrated operator model is dominating. Fiber is the common transport network for fixed and mobile networks (backhaul + backbone). Due to the ramp-up of powerful xDSL, 4G and fiber networks, the integration of satellite networks gets less competitive. Thus, current trend for next years is to rely on the Telco empowered terrestrial networks and disinvest in satellite networks. In the future, broadband satellite opportunity in developed rural areas is expected to decrease with the extension of fiber networks or densification of DSLAMs. However, the performance of xDSL is very distance-sensitive.

- Regarding fixed networks, fiber networks will replace more and more copper networks. Regarding mobile networks, 4G/4G+ will spread nearly everywhere. Regarding backhaul, almost all 4G sites are already backhauled by fiber and the spread of fiber networks will help to deploy 4G extensively.

- 5G networks, especially at frequency bands below 6 GHz, are likely to be deployed in developed countries by 2020. These will implement key technologies such as: Heterogeneous mobile access networks (Hetnets), Massive MIMO, aggregated carriers and interference management for increased site density. In urban areas, Radio over Fiber is investigated in order to reduce the constraints on sites and to centralize computing resources. Regarding core networks and interconnections, Virtualization and SDN/NFV technologies will bring more programmability and flexibility in the networks.

- In the years to come, there will be significant growth in 4K (UHD TV) offerings, yet most of these will be made available via OTT distribution. The real driver for mass deployment of 4K services will be live content, which requires a huge amount of bandwidth for streaming and pushes operators to adopt optimized content delivery solutions towards multicasting.

- Use of Cloud PVR technology by operators is foreseen for multiscreen applications. Multi-CDN approaches for content providers will gain popularity for live and VOD content. Virtualization technology will also be a hot topic. Content providers, especially big ones like Google and Netflix, have already started to put their own caching servers in the operators’ premises to optimize the delivery of their own content.

- **For developing countries:**

- In developing countries and partly in some East-Europe countries, the integrated operator model is not currently replicated because there is a lack of wired infrastructures and it is costly to start to deploy them (due to costs of civil works).

- Especially in Africa, fiber is in general the main technology for backbone today. There are specific countries where fixed infrastructures are very poor and/or the cost to rent capacity is too expensive and the backbone is achieved by microwave links. Regarding backhaul, in most of the cases it is done by microwave links and in some cases by satellite, mainly limited to 2G networks which are dominating today. Satellite is also used for resilience purposes in cellular backhauling.

- In developing countries, mobile sites will be upgraded into 4G networks progressively as fast as fibers will be deployed, whereas 5G networks at frequency bands below 6 GHz are likely to be deployed after 2025 horizon. Microwave links may also provide backhaul for 4G base stations in short distances. For long distance links, there is an opportunity for satellite as a backhaul technology in order to deploy 4G networks at a higher pace than fiber extension, especially in rural areas.

- In-house delivery of video content based on 4G/LTE mobile networks will grow. There will be a need for local caching at the level of the eNodeB to improve the video delivery quality in regions where the fixed network has limited capacity. Moreover, a broadcast solution is required to absorb peaks in live and/or popular content consumption. Local caches will be added to operators’ networks, and the development of local CDNs combining different types of technologies to enable a hybrid network capable of addressing all use cases is likely.

- For both developed and developing countries, 5G access networks in millimeter-wave bands (> 6 GHz) are likely not to be deployed before 2025 as they require demand growth well above the observed traffic growth. New disruptive applications and services (e.g., immersive augmented reality glasses, etc) should emerge first to justify this bandwidth demand increase in order to trigger large 5G investment decision on the network infrastructure deployment.

In a summary, the following satellite opportunities have been identified: [125]

- **Broadband access via hybrid satellite broadcast/xDSL unicast in developed countries**

    - Rural and underserved regions in developed countries, where there is xDSL terrestrial link available with a limited performance (users are located far from the DSLAM)
    - Use of satellite (broadcast or broadband access) to complement the existing broadband access link. This hybrid Satellite/xDSL opportunity can be envisaged in order to benefit from low-latency of terrestrial networks and high-bandwidth of satellite networks.
    - The hybrid satellite broadcast/xDSL unicast solution is worth considering in cases where: the network costs are high, the global number of viewers is high, the quality of the video to deliver is high, and the percentage of the population that is underserved is limited (due to the extra cost related to the satellite module in the home gateway).
    - Due to the ramp-up of powerful xDSL, 4G and fiber networks, the need for a hybrid solution combining xDSL and satellite broadcast (including a specific home gateway product line for this offer) is decreasing. As a consequence, this dissociation between terrestrial and satellite networks is likely to appear and will result to increase temporarily the number of customers eligible to pure satellite Multiplay offers in underserved areas.
    - Emergence of new technologies, such as active electronically steerable beam antennas, will facilitate the bundling of services and the overall use case.
    - Adjustments to the Home Gateway and Internet Gateway in the backbone are needed to be able to split/combine the traffic over the existing access link and the satellite link respectively. The Home Gateway should also include storage and caching capabilities. Particularly, in multi-screen environments, DRM and underlying protocol (e.g., DASH, HLS, HSS) will also have an impact on the Home Gateway design.
    - Relevant satellite architectures: GEO HTS.

- **Broadband access via satellite in developing countries**

    - Rural and unserved regions in developing countries, where there is no terrestrial link available.
    - When deploying a solution to serve these users, the choice between microwave, satellite and/or fiber should be made. When using satellite, the additional benefits from using broadcast for video content should be taken into account, and these adjusted scenarios should be compared to the microwave/fiber scenarios.
    - Relevant satellite architectures: GEO HTS, MEO HTS, LEO HTS.

- **Cellular backhauling in developing countries**

  - Extend existing coverage: Population coverage by existing 2G networks is 80% in average, but there are several countries which are far from it. Territories are very large. There are two possible solutions to investigate on the radio access segment: the first one relying on HAPs and satellite backhauling, the second on large cells and satellite backhauling.
  - Network upgrades from voice (2G) to data [broadband] networks (4G/4G+). The upgrade of certain links will exceed the capacity of microwave technologies, typically in topologies with a high number of hops because of aggregation at the backbone vicinity.
  - Resilience: Satellites are good candidates for providing resilience. This will avoid overprovisioning capacities and line-cards in case there is a failure, and will bring flexibility in the topology. But this requires deploying satellite terminals in addition to microwave, and dynamic reconfiguration able to switch from one network to another.
  - Cellular networks offload: There is an opportunity for technologies that provide extra-capacity (possibly with less constraints) in order to offload cellular networks at peak hours, in the same vein than fixed networks providing connectivity to Wi-Fi in western countries.
  - Relevant satellite architectures: GEO HTS, GEO Widebeam, MEO HTS, LEO HTS, HAPs

- **Over The Top (OTT) Content Delivery in fixed networks via unicast and broadcast resources**

  - In developed countries, in the years to come, there will be significant growth in 4K & 8K (UHD TV) offerings, yet most of these will be made available via OTT distribution. The real driver for mass deployment of UHD TV services will be live content, which requires a huge amount of bandwidth for streaming and pushes operators to adopt optimized content delivery solutions towards multicasting (e.g., multicast ABR technology).
  - As demand for streaming linear and on-demand content bogs down terrestrial networks, satellite's inherent point-to-multipoint and multicast capabilities make it the ideal CDN for OTT. The integration of satellite multicast capabilities into a CDN offers an important new delivery mechanism to OTT content providers. The satellite-based CDN will become an indistinguishable part of the Internet and a critical differentiator in OTT delivery.
  - Adjustments to the Headend network equipment and Internet Gateway are needed to select the most appropriate unicast to multicast delivery scheme.
  - Relevant satellite architectures: GEO HTS, GEO Widebeam.

- **Content Delivery to 4G/4G+ edge nodes via unicast and broadcast resources**

  - In-house delivery of video content based on 4G/4G+ mobile networks will grow. There will be a need for local caching at the level of the eNodeB to improve the video delivery quality in regions where the fixed network has limited capacity. Moreover, a broadcast solution is required to absorb peaks in live and/or popular content consumption. Local caches will be added to operators' networks, and the development of local CDNs combining different types of technologies to enable a hybrid network capable of addressing all use cases is likely.

- Multicast mechanisms in cellular networks have been defined in standardization but are not currently used.
- Adjustments to the eNodeB equipment and Internet Gateway are needed to select the most appropriate unicast to multicast delivery scheme.
- Relevant satellite architectures: GEO HTS, GEO Widebeam, MEO HTS, LEO HTS.

The rapid evolution of internet traffic toward video centric applications is clearly strengthening the case of Broadcast and Caching mechanisms to complement satellite systems. Indeed, Caching and Broadcasting are very efficient mechanisms that can greatly help optimize telecom resources for the delivery of entertainment services. However, their effectiveness is linearly linked to the size of the targeted audience, which implies that at the beginning of satellite operations, they can be more of a liability than an asset in term of resource management, depending on the situation of the operator and/or service providers. Also, as of today, their effective implementations have proven complex, partly because their induced impacts along the whole service value chain extend far beyond the satellite design into the platform software and even the copyrights issue of content providers. This is to say that the business impacts of these features cannot be convincingly proposed in isolation of a global business environment, and it was considered too complex and arbitrary to assess their business impacts in the same way that the other technological improvements. Although, as has been examined, there are strong clues that the implementation of a Caching and Broadcasting overlay could indeed become a game changer in the delivery of entertainment services via satellite, and notably help consolidate the business relevance of satellite “Fiber Like” services delivery. [125], [126]

5.2.2 EVALUATIONS FOR SATELLITE ROLES OVER CDN

The satellite systems have a key role over adaptive collaborative adaptive bitrate streaming services. The collaborative services imply the association of terrestrial and satellite network service providers to deliver services with common management infrastructure and assured quality.

ESA research has identified the following collaborative video services, along with their consumption pattern and the target devices, shown in the following table:

Table 2: List of Identified Collaborative Video Services [125], [126]

# Case	Service	Consumption type	Target device
1.	Live TV	Real time	TV, PC, tablets, smartphones
2.	Generic VOD	Non-real time	TV, PC, tablets, smartphones
3.	Catch-up TV	Non-real time	TV
4.	Connected TV/Hybrid TV	Non-real time	TV, PC, tablets, smartphones
5.	Push VOD/ PVR	Non-real time	TV
6.	Interactive service	Real time/ Non-real time	TV, PC, tablets, smartphones
7.	Location information service	Non-real time	smartphones
8.	Second screen / Companion device	Real time/ Non-real time	Tables, smartphones
9.	Cloud gaming service	Real time	PC, tablets, smartphones
10.	Virtualized corporate encoding factory	Real time/ Non-real time	Professional equipment; TV, PC, tablets, smartphones

Supplementary, research has shown many integrated satellite-terrestrial delivery systems scenarios for state-of-the-art and future satellite systems. The key criteria for identifying such scenario was the solutions that can best enable Assured QoS (AQoS) video delivery to the users by exploiting the synergies of next generation content generation and delivery protocols, CDNs, terrestrial and satellite networks.

The integration scenarios that were identified in “Deployment scenario definitions” from ESA projects reports are shown in the following table:

Table 3: Integration Scenarios for Satellite to CDN Communication [125]

ID	Description	Role associated to satellite component	Business models
S1	Satellite as hybrid backhaul for 5G ultra-dense networks	Intra-CDN, inter-CDN link	B2B
S2	Satellite for intra-CDN content retrieval for moving vehicles		B2C
S3	Satellite live/linear stream feed into local Point of Presence	Delivery to in-network caches	B2B
S4	Satellite as hybrid backhaul of home gateway		B2C
S5	Content distribution for Catch-up TV services leveraging existing broadcast channels		B2B
S6	Satellite for direct to UE communication	Access network for multi-homing UE	B2C
S7	Content caching in Set-Top-Boxes		B2C

Accordingly to evaluations from our research, the scenarios S1 & S4 are considered the most significant scenarios to be retained and detailed from their architectural point of view. [125]

In S4, a home (or building) gateway receives a selection of popular live or Video on Demand (VOD) contents from a satellite link and stores them locally, acting as an edge node of a virtual CDN. In this way, the risk of overloading the telecom networks (both backbone and last mile) during peak traffic times is avoided because several users can simultaneously access the contents available on the local cache, without the need of pulling them several times from the closest CDN cache.

The multimedia contents generated by the Content Provider, besides being pushed to a typical CDN over the terrestrial IP backbone, are also sent via a satellite link with dedicated capacity. An IP/DVB gateway takes the task of sending the multitude of files, relevant to Adaptive Bit Rate video segments. A web server running locally, associated with that local cache, serves the hosts in the Local access network (LAN), via a wired or wireless connection.

The hosts can use a standard Adaptive Bit-Rate (e.g., MPEG DASH) player. In this way, each building is deploying its own “virtual” CDN node, without the need of accessing the broadband link to retrieve contents locally available. In case the requested contents are not available locally (e.g., due to the limited size of the cache, only popular contents are expected to be stored), the gateway can act as a reverse proxy, retrieving them from a “real” CDN node via the broadband channel: in this way, the users’ “virtual” nodes become an integral part of a larger CDN. Most of the building blocks of this system are already available and part of today’s network infrastructures for content delivery: [125], [126]

- **IP/DVB Gateway**

    - The IP/DVB gateway, generally located at the satellite operator premises, has the task of collecting the multimedia contents (i.e., files representing the Adaptive Bit-rate segments) from the Content Provider and delivering in multicast to all home gateways via the satellite DVBS2/ S2X channel. The files are delivered as a continuous IP stream according to FLUTE or ROUTE protocols. Interfacing an IP-based stream (user data plane and control plane) to a DVBS2/S2X modulator can be done according to two different encapsulation mechanisms, capable of transporting generic IP packets (and therefore upper layer protocols transported as their payload, e.g. TCP, RTP, SCTP, etc.) over a DVB stream:

        - MPEG-2 TS with Multi-Protocol Encapsulation (MPE)
        - Generic Stream Encapsulation (GSE)

- **CDN network**

    - A standard CDN network is included in this system architecture. However, as the home gateway can act as a virtual CDN node, it can be seen as part of the bigger operator's CDN. Selected contents are stored in the local cache, and local user terminals shall first access that local cache for those locally available contents and then, in case of unavailability, access the regular CDN cache. This can be generally done without the need of custom applications to be run on the client.

- **Home gateway** (DVB/IP gateway, local cache and HTTP server/reverse proxy)

    - The home gateway is a consumer device to be installed inside an apartment or in common areas of a multi-apartment building, serving a number of potential users ranging from a few units to some tenths. It is connected to a satellite receiving dish and includes a satellite tuner (i.e., DVB-S2/S2X) enabling the reception of the IP streams delivered over GSE as FLUTE/ROUTE.
    - A practical limitation of this solution, when using existing software commonly deployed in caches, is related to how file names are managed: in fact, typical software for reverse proxies keep track of locally stored files in an internal database, with a proprietary catalogue associating local file names to the retrieved URLs. Therefore, the reverse proxy would not automatically identify files received via the satellite link and stored locally as associated to the same video asset, having a different file name.
    - The best (long-term) solution to overcome this issue would be updating such reverse proxy software, so that file name comparison is aware of such notation mismatch. In the shorter term, a possible workaround could be maintaining separate storage for content received via satellite in "push mode" and content retrieved on request from the terrestrial CDN network, coupling web server and reverse proxy in the home gateway.
    - The cache associated with the HTTP server is filled via the broadcast satellite pipe, independent from users' actions. Upon a request of a specific video asset (i.e., the URL associated to an MPEG DASH segment) coming from a user terminal, the reverse proxy can adopt the following algorithm:

- It first accesses its own cache and, if the file is present, serves it to the client
- If the file is not present, it redirects the request to the local HTTP server
- If the file is not present in the storage associated with the local HTTP server either, it redirects the request to an external CDN node, as a fallback. In this case, the CDN network will take care of further propagating the request to the deeper CDN nodes, if needed.
- The retrieved file is then stored on the local cache of the reverse proxy, according to the standard behavior.

Routing entity

- It is the responsibility of the routing entity the decision about pushing specific contents via satellite or terrestrial networks (it is envisaged that all contents are in any case also pushed to the terrestrial CDN network, for the users who cannot access the satellite feed). That routing entity could be under the responsibility of the content provider, the satellite operator or the CDN operator; in any case, proper information exchanges among those actors are needed in order to optimize such routing function.
- Modern CDNs operate multiple tiers of delivery: traffic is sent to core, mid-tier and edge/deep edge layers. A modern CDN can automatically decide to request route end users to specific titles to each tier, based upon popularity algorithms. These CDNs also let broadcasters override automatic algorithms and can instruct the CDN to send users to mid and edge tiers before the algorithm kicks in. The selection of those relevant contents to be stored locally is driven in the CDN content replication engine by methods possibly based on usage information collected by the CDN operator.

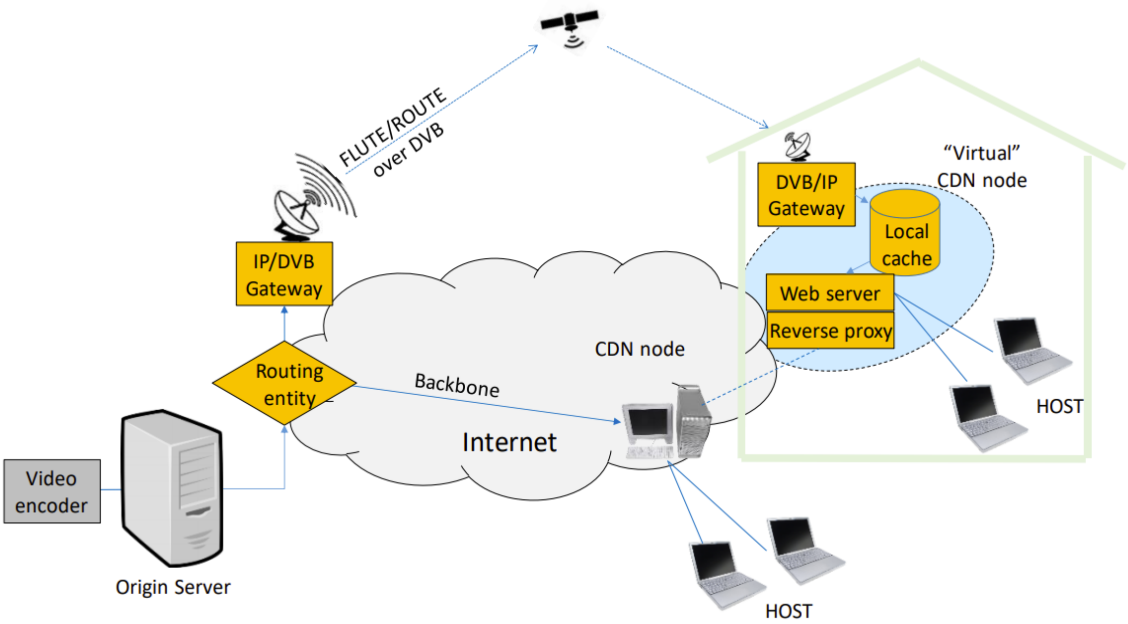

Figure 20: CDN architecture & components for distribution to home gateways, the same principles applies to 5G backhauling cases [126]

In S1, similar to S4, the multimedia contents could also be sent via a low-bit rate satellite link, instead of a traditional fiber backhaul, to caches present in the 5G cloud enabled network: [126]

The objective would be to intelligently identify which content has to be multicast via satellite and which content has to be served via traditional unicast. A routing entity which is present inside the CDN origin shield (red diamond block in figure 21) will accomplish this intelligent routing of contents and alleviate the mobile backhaul. This routing entity is like the one introduced in the previous sections.

Next, an IP/DVB gateway takes the task of sending the multitude of files. At each of the edge node, the DVB/IP gateway is a DVB-S2/S2X receiver capable of extracting the IP data stream, reconstructing the original files and storing them in a local cache. The gateways are depicted in yellow in figure 21. The caches are present at the access network of the 5G cache enabled networks. Essentially, the S1 has the same key modules as Scenario S4, namely the IP/DVB Gateway, CDN network, Home gateway and the Routing entity.

SCORSESE's research has find out that there are many similarities in system architectures relevant to scenarios S1 and S4. Hence, it was decided also to evaluate the merits of the combined scenario in its final phase. In an overall high-level architecture relevant to a combined scenario, content delivered over the satellite link can feed in the same way professional cache nodes located in the 5G edge cloud network and consumer local caches located in home gateways, managed by a common routing entity and an IP/DVB gateway. [126]

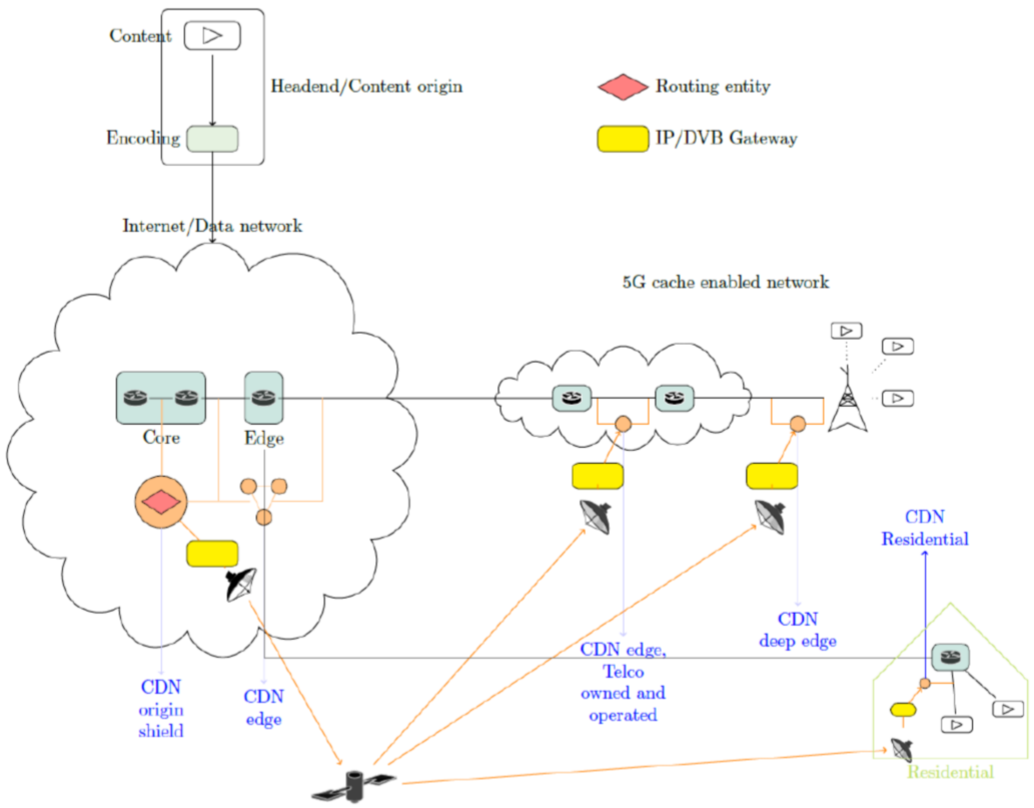

Figure 21: SCORSESE's proposed architecture for satellite-CDN communications for backhauling over 5G and home gateways [126]

The project made evaluations through simulations and produced the following results concerning the network behavior:

- For simulations of S1 with static Number of UEs occurred the following: [126]

- Live content distribution

    - When the backhaul capacity is low and the satellite capacity is high, the highest increase in cache hit ratio is observed. Conversely, when the backhaul capacity is high and when the satellite capacity is low, the lowest increase in cache hit ratio is occurred. This is to be expected, because theoretically one expects the greatest benefit of introducing satellite backhaul when the terrestrial backhaul is severely limited.

    - For the KPIs terrestrial link utilization and terrestrial link congestion there is a “reversal” in trend, i.e. the highest benefit is observed when the backhaul capacity is high, and the satellite capacity is high. The main reason for this is that at low terrestrial backhaul, even with a satellite backhaul, there is much data to be transmitted and they have close to 100% backhaul utilization. Hence, the improvements of satellite cannot be observed directly at low terrestrial backhaul capacities. The improvements can be observed at high terrestrial backhaul capacities because the utilization goes below 100%.

    - By intelligently identifying and pushing popular content to the deep edges, there is a significantly increase in cache hit ratio. From the simulation results it was found that there were cases when the cache hit ratio was increased by 3x (low terrestrial backhaul capacity + high satellite backhauls capacity). In general, it was observed that the increase in cache hit ratio ranged from 1.1 to 3 times higher.

    - The increase cache hit ratio potentially the following benefits:

        - On the network side, this reduces the backhaul congestion and backhaul terrestrial utilization. The exact reduction was quantified in the previous sections. The values were anywhere between 0%-50%.
        - On the UE/client side, a very significant increase in the playback performance is observed.
        - A significant reduction in E2E delay. Anywhere between 0-30%.
        - A very significant increase in the requested bit rate representation.
        - In certain cases, almost 5x increase in the requested bit rate representation. The values range between 1x-5x.
        - A significant reduction in playout interruption rate (0-40%) and playout interruption duration.
        - A decrease in the playout latency.

- Video on Demand

    - In VoD a very high cache hit ratio is appeared (~0.90). Although introducing the satellite link increased the cache hit ratio, the improvements were very marginal and not significant. Consequently, the benefits reflected in other KPIs because of this were not very significant. From these results it was concluded that using satellite as backhaul for pushing popular contents was more beneficial when we use it for live rather than for VoD.

- For simulations of S1 with varying number of UEs occurred the following:

➢ Live

  - The benefits of using satellite backhaul are observed with the realistic scenario of varying number of UEs in typical day backhauling and big day events. Increased cache hit ratios are observed, which in turn gives better network side performance as observed in the decrease in terrestrial backhaul utilization and terrestrial link average congestion. Therefore, it is evident that the presence of satellite backhaul reduces the load of terrestrial backhaul. At the UE side, the playback performance is improved by the increased cache hit ratios by the increase in requested video bitrate average and decrease in end-to-end delay.

- For simulations of S1 with static Number of UEs occurred the following: [126]

➢ Live

  - For live content it is not straightforward to make use of the whole capacity of a satellite channel due to granularity of video bitrates and the fact that it does not make sense to transmit live content with lower than real-time data rate.
  - The terrestrial backhaul is only slightly relieved by utilization of the satellite only with 1Gbps satellite capacity a tangible relief of the backhaul can be observed. The latter relieve is considered to be the fact due to mostly all data is pushed to the cache. So this is the confirmation of the more or less trivial fact, that if all live content is broadcasted and the cache is able to cover everything which is currently on the air, this will relieve the terrestrial network.
  - A satellite link of up to 50Mbps does not provide a significant increase in of the cache hit ratio.
  - The requested bit rate representation is only improved for very high satellite capacities. This is obvious as the live content needs to be forwarded in real-time over the satellite link. This leads in principal to the conclusion that a higher more evenly spaced granularity of video bitrates will improve the live performance of the setup.
  - Delays and latencies follow linearly the number of users, except at very high satellite capacity values
  - Caching provides a saturation effect to the interruption rate but does not mitigate interruption durations
  - Caching of live content provides a significant increase in requested bitrate for the congested backhaul link

➢ VoD

  - VoD is best suited to fully utilize the satellite capacity.

- The terrestrial backhaul is not slightly relieved by utilization of the satellite.
- The cache hit ratio increases only slightly with an increase of satellite capacity. The cache hit ratio seems to be optimum at 30 users per home GW. This may come from the fact that with more users and sessions the cache needs to be replaced.
- The requested bit rate representation is only improved at high satellite capacities of 100Mbit or more.
- Delays and latencies depend only the number of users
- The interruption rate seems to stay constant except for very high satellite capacities, where it significant drops due to the high number of cache hits.
- The duration of interrupts seems to increase with higher satellite capacity but it is assumed that this is a side-effect comes from the increasing initial playout latency.

- For simulations of S1 with varying number of UEs under daily usage occurred the following: [126]

➢ Live

- The satellite link follows the granularity of the video codecs which could lead to a waste of bandwidth
- A data rate bottleneck in the last mile seems to have more severe effects on the overall throughput than a bottleneck in the origin to edge node data path.
- A limited link to the origin leads to higher utilization of the home GW cache.
- The congestion duration increases when the satellite capacity is increased until a certain point before it decrease. This may be an artifact of dash oscillation or in other words if the satellite bandwidth is high enough (50Mbps or higher) Dash oscillation can be mitigated.
- Initial playout latency, interruption rate and interruption duration offers the sense that there is some bug in the data analysis functions.

➢ VoD

- The satellite link is almost fully used
- The backhaul usage drops significantly with more satellite capacity being available
- A data rate bottleneck in the last mile seems to have more severe effects on the overall throughput than a bottleneck in the origin to edge node data path.
- Limited link to the origin leads to higher utilization of the home GW cache
- Increasing the satellite capacity does not provide a linear increase of relief in the terrestrial network.
- Initial playout latency, interruption rate and interruption duration look like there is some bug in the data analysis function.

- For simulations of S1 with varying number of UEs under big day event occurred the following:

- Live
    - What can be observed is that the terrestrial link is relieved by the satellite capacity.
    - The cache hit ratio increases rapidly when more than 50Mbps of satellite capacity are available.
    - Also, the starting point for larger changes in requested bitrate and reduction of E2E delay seems to be 50Mbps.
    - Initial playout latency, interruption rate and interruption duration look like there is some bug in the data analysis function.
- VoD
    - The backhaul utilization does not change.
    - Congestion durations decrease with higher satellite capacity but not significantly.
    - There seems to be limit in the cache hit ratio around 60%. This drops with higher satellite capacity. The reason for this is that the cache needs to replace some of its content when it is full.
    - The requested bitrate drops with higher satellite capacity.
    - 50Mbps seems to be a sweet spot for the chosen configuration.
    - Initial playout latency, interruption rate and interruption duration look like there is some bug in the data analysis function.

For simulations of S1+S4 combination under static number of UEs occurred the following: [126]

- Live
    - The conclusion of live UE’s is like what was observed earlier for Scenario S1. By intelligently identifying and pushing popular content to the deep edges, there is a significantly increase in the cache hit ratio. When the backhaul capacity is low and the satellite capacity is high, the highest increase in cache hit ratio is observed. Conversely, when the backhaul capacity is high and when the satellite capacity is low, the lowest increase in cache hit ratio is observed. This is to be expected because theoretically one expects the greatest benefit of introducing satellite backhaul when the terrestrial backhaul is severely limited.
    - This increase cache hit ratio potentially serves two benefits:
        - Network side
            - On the network side, this reduces the backhaul congestion and backhaul terrestrial utilization. The exact values are quantified in the previous sections for different use cases. Like before the highest benefits are observed when the backhaul capacity is high and the satellite capacity is high. The main reason for this is that at low terrestrial backhaul, even with a satellite backhaul, there is much data to be transmitted and they have close to 100% backhaul utilization. Hence, the improvements of satellite cannot be observed directly at low terrestrial backhaul capacities.

Whereas, the improvements can be observed at high terrestrial backhaul capacities because the utilization goes below 100%.

- UE side:
  - On the UE/client side, a very significant increase in the playback performance/QoS is observed.
  - A significant reduction in E2E delay.
  - A very significant increase in the requested bit rate representation.
  - A significant reduction in playout interruption rate and playout interruption duration.
  - A decrease in the playout latency.

- The benefits correlate to the cache hit ratio, i.e. the highest improvement in QoS for user is observed when the backhaul capacity is low and the satellite capacity is high. Conversely, the lowest improvement in QoS for end-use is observed when the backhaul capacity is high and the satellite capacity is low.

- VoD
  - The conclusion for VoD is similar to what was observed earlier for Scenario S1. Although, there are benefits by introducing the satellite backhaul, the benefits are not as high as they are for live streaming UEs.

- For simulations of S1+S4 with varying number of UEs occurred the following: [126]

- Live
  - The benefits of using satellite backhaul are similar to what was observed earlier for Scenario S1. With the integrated scenario, the increased cache hit ratios are observed, which in turn gives better network side performance as observed in the decrease in terrestrial backhaul utilization and terrestrial link average congestion. Therefore, it is evident that the presence of satellite backhaul reduces the load of terrestrial backhaul. At the UE side, the playback performance is improved by the increased cache hit ratios as seen in the increase in requested video bitrate average and decrease in end-to-end delay.

While SCORSESE project analyzed the satellite capabilities HTS-DBS studied the improvement of caching proxy's behavior during popular content distribution through Zipf algorithm and its corresponding diversions. The project outcomes offers information about how the traditional Zipf algorithm can be manipulated in order to serve needs under different cases of daily user requests. The project, similarly to use cases scenarios from MENDHOSA & SCORSESE has evaluated the algorithm's derivations and three basic cases of application. The project focused on the cache placement phase & the delivery phase on CDN operation, supplementary was assumed that the user requests are available at the cache manager and the main need was to optimize the placement phase & the satellite channel is the only backhaul solution for CDN services, while the other works analyzed hybrid satellite-terrestrial networks. [127]

The main characteristics of cache proxies during evaluation are summarized as following:

- The caches are refreshing daily (e.g., early morning)
- The have scheduled programs from a library of specific file capacity
- For evaluation simplicity, all files have equal size
- They have a specific maximum number of files that can be sent and stored by the satellite during the placement phase in proxy servers

The 1st examined use case considers a DBS network in which a gateway sending content to a certain number of home users within the satellite coverage with the return link. A home user receives content via a satellite receiver which is equipped with a storage memory of a specific number of files. In terms of caching, each user selects a list of favorite programs, e.g., movies, next day at the night before. The motivation behind this assumption is that there are some interesting programs during the day that the user can not watch live and he wants to be cached in memory to watch later. This list will be sent from the local cache manager to the network controller (i.e. global cache management) via the feedback link. The feedback link is optional in the network in a form of a terrestrial return link. In this case the satellite link has been used for a cache placement phase to improve the users' experience and save backhaul bandwidth. [127]

The results showed, the Zipf distribution with a larger skewness factor results in higher CHR in all settings. The hybrid (using both widebeam & multi-beam) scheme achieves a similar CHR performance as the multi beam in all values of caching capacity. It is shown for both skewness values that the multi-beam satellite channel provides slightly a higher CHR than the mono-beam in terms of 10% approximate. This is because each beam in the former case is closer to the local content popularity of users in that beam. Another observation is that the gain brought by the multi-beam is larger at higher caching capacity values. This is also because of the fact that as the caching capacity increases, the popularity profile in each beam at the end of the Zipf distribution tail becomes less correlated, and thus the advantages of multi-beam becomes more relevant. Note that in this case the storage is also limited so a higher cache size can potentially lead to higher CHR, even close to 100%. [127]

The 2nd case considers a DBS network serving the users within its coverage via a number of edge nodes, e.g., base stations, which are equipped with a satellite receiver. This use case applies for villages in rural area or small business customers such as hotels and residents where only one satellite receiver/decoder is needed for each edge node (BS, AP). It has the same assumptions in caching settings expect that the users favorite schedule list will be sent to the global cache manager via the feedback link from the local cache manager at the base station. The feedback link can be through satellite link.

The users’ requests follow Zipf distribution with the skewness factor equal to 0.8. Both mono-beam and a 10-beam transmission are considered. The CHR is limited above by the caching capacity for mono-beam, multi-beam and hybrid setups. Having a cache size exceeding the caching capacity does not bring any CHR gain (CHR measured ~70%). It is also shown that the 10-beam setup achieves similar performance as the hybrid scheme and a slightly higher CHR than the mono beam, however as the requests are strongly correlated, this improvement is rather negligible.

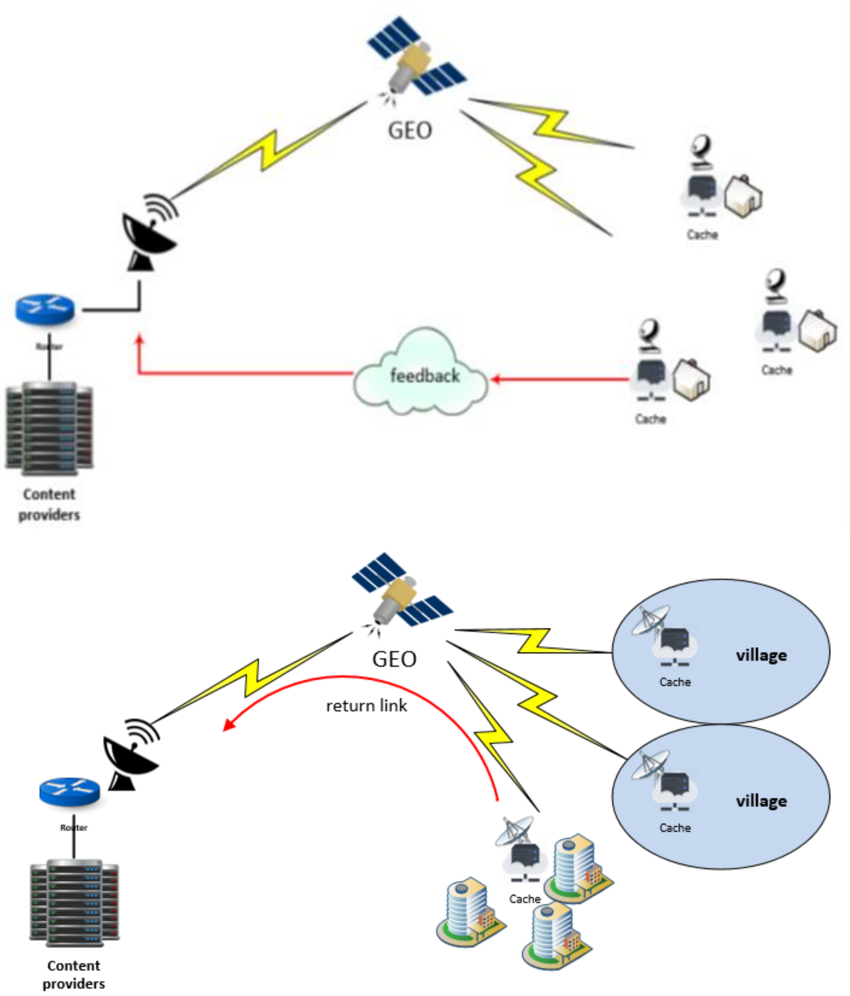

Figure 22, 23: 1st & 2nd case architecture comparison of return link [127]

In the 3rd case, the system configuration (e.g. caching) is similar to the 2nd, the only differences is that it targets urban area in which each BS serves a larger number of users. In difference with 1st and 2nd case the favorite list will be sent to the network controller via the feedback link. Based on the user preference sent to the network controller via the return link, a local preference (content popularity) is obtained which is used for caching strategy.

The users' requests follow Zipf distribution with the skewness factor equal to 0.8. The three beam schemes achieve a similar performance (CHR ~90% in large cache size). This is because all the user requests follow the same Zipf distribution hence the demands statistics in different beams are strongly correlated. Also much more users are involved per cell, which makes even the end of the Zipf distribution tail correlated among the beams. It is also shown that having a cache size exceeding the caching capacity does not bring any CHR gain. [127]

In practice, the user demands highly vary across geographical regions and time. Therefore, it is highly probable that the user requests are have lower correlations among the beams particularly in different geographical areas with different cultures, languages, religion, etc. The project received the assumption that half of the users in half of the beams are interested in the first half of the library (e.g., action movies), while the other half are interested in the rest (e.g., romantic movies). The other parameters are the same as the previous subsection. Comparing the CHR between use cases 2 and 3 for uncorrelated demands it is observed that using multi-beam satellite transmissions significantly improves the CHR for both cases and the hybrid setup achieves a better performance than the mono-beam but worse than the multi-beam. This is because the multi-beam satellite can better match the local popularity with user demands. Similar observation is obtained on use case 3 which outperforms use case 2 at the large BS cache sizes. Indeed, this initial result shows one of the major advantages of multi-beam caching with respect to the widebeam caching, i.e. the access to the geographical diversity of the content. This way, multibeam satellites can cache content based on geographical clusters with less correlated content popularity. This cannot be achieved by the widebeam satellites. [127]

5.3 BEHAVIOR ANALYSIS OF INTERNET PROTOCOLS

The 'push' delivery to the edge nodes of a modern network is going to have an increased relevance in CDN network architectures, emerging protocols could be leveraged, such as HTTP over multicast QUIC (Quick UDP Internet Connections), NORM (NACK-Oriented Reliable Multicast), CMZF (Common MeZzanine distribution Format), etc. Besides the protocol optimization, other technology developments could be effective in allowing ultra-low latency delivery, such as CMAF (Common Media Application Format). The applicability of such protocols supervene the CDN usage because their applicability has already established in many types of internet cloud services, the newest of all is Google's QUIC which hasn't fully studied in terms of traffic management & behavior during satellite network use cases. [127], [128]

In general behavior of internet satellite connections, the MTAILS project evaluated the behavior of satellites over internet multimedia services either on direct satellite links or 5G backhauling. Web page downloads can be considered as one of the most common services in the current Internet. Apart from evaluating the more established HTTP protocols (HTTP1.1, HTTPS & HTTP/2) also the following protocols and frameworks are addressed: [128]

- The Google QUIC (also mentioned as gQUIC) protocol is an initiative driven by Google that uses UDP instead of TCP. This allows reducing of the total web download time by eliminating the three-way handshake and the slow-start latencies. The protocol has been also thought for secure (HTTPS) communications. As the protocol is a Google initiative, it is supported by the Chrome browser and used by Google web-based services (such as Google Docs or Gmail). QUIC is currently under standardization by the IETF.

- To improve the performance of the download for a web site, the web content can be structured in an efficient manner to assure that the most relevant information is downloaded first and displayed as soon as possible to the user while the rest of data (secondary information) is downloaded in the background. This is done by restricting some parts of HTML, CSS and JavaScript and providing guidelines and support elements for web site implementation. In this respect, the project considered the impact of using Google AMP (Accelerated Mobile Pages) enhancements on the QoE of the users of mobile devices.

It should also be noted that for the GEO scenario the QoE is highly sensitive to the used HTTP protocol, with HTTP/2 providing generally a significant improvement when compared to HTTPS/1.1. In this sense, current trend to adopt this protocol version (already supported by most important web sites and supported by 37.4% of web sites) is very positive for this scenario, for this study the project considered different reference GEO and non-GEO satellite systems (MEO and LEO, with and without inter-satellite links) and a set of relevant user applications & services for satellite internet connections and future 5G backhauling use case scenarios, with the following main objectives: [128]

- To characterize and compare quantitatively the Quality of Experience (QoE) that can be achieved with the current baseline technology for the different scenarios, identifying performance gaps.
- To identify and analyze satellite network technology evolutions that can mitigate the effect of satellite latency in the user QoE and assess performance benefits.
- To emphasize on the impact (either positive or negative) of classic application layer's protocols, i.e. HTTP protocols, and of newer protocols like the one's Google uses for handshaking when users interfering with her web services (i.e. gQUIC).
- Based on the identified key technology gaps, performed recommendations to standardization bodies and other groups (3GPP, ETSI…) and define a roadmap regarding future technology developments and standardization needs.
- The project focuses on applications that are likely to be prevalent in the 2025 time horizon and that may be especially latency sensitive (e.g., cloud services or 360º video-on-demand). These applications are being increasingly encrypted, rendering some of the traditional latency mitigation techniques ineffective.

In order to understand the QUIC behavior the following steps have been performed to improve understanding of QUIC performance problems over satellite networks: [128]

- Client and Server tuning. Chromium Google QUIC Server allows us to compile the server using different build (debug, symbol level…) and QUIC protocol options (e.g. congestions control mechanism, buffer sizes or ACK decimation value options). Evaluating different compilation parameters at the client and server side has been considered a way to identify the proper direction of a more in-depth study.
- Regarding build options, one alternative option ("tuned build") has been evaluated.
- Regarding QUIC protocol options, the BBR protocol has been enabled instead of the default IETF/gQUIC congestion control protocol (CUBIC). Since BBR flows are in the ProbeBW state for almost the 98% of their time and the Probe_BW congestion window gain parameter can be modified, it has been selected as the parameter to be evaluated. So, a Probe_BW gain factor of 2, 4 and 12 for three different web site types has been tested:
    - Website composed of a single file of 10MB size.
    - Website which contains ten images of variable size (with an average size of 440KB).
    - Replicated Wikipedia website in a clone server
- Compare Google's QUIC vs other Google QUIC server. The LiteSpeed gQUIC Server has been included in the comparison since their results have been reported to be much better than any current implementation of gQUIC.
- The public HTTP3 LiteSpeed website has been accessed using HTTP2 and using HTTP3, and page download times have been compared. This test has been executed when accessing the website using a GEO/B model and when accessing it directly through optical fiber Internet access.
- For these tests, the local testing gQUIC web server has been updated from v043 to v046 (last stable available code), which is the version closest to the IETF

QUIC v1 release and thus gives us a more representative problem description for the final standardized protocol.

These tests have allowed us to conclude the following: [128]

- A Google QUIC Server prototype with tuned build options outperforms the out of the box build configuration on low latency scenarios. Average web load time when accessing two replicated web pages in a controlled environment is reduced significantly on those scenarios with very low latencies (50%), but, for GEO, no specific advantage is noticed from the user perspective or from the gathered analytical results either. For LEO, there are some differences when using a bandwidth on demand profile (15-20%), but not when using a business profile, with more stable latencies and bandwidth
- LEO models showed no direct benefit of using higher BBR ProbeBW values.
- BBR algorithm with a ProbeBW value of 4 has returned a performance improvement up to 8% under GEO-B models when accessing the multiple images web site, compared to the default value of 2
- For GEO, there has been no clear benefit of increasing the ProbeBW value when a single file was downloaded (since there was only a minimum difference on the connection performance) and in the case of Wikipedia, where the performance of BBR with its multiple ProbeBW values was the same as CUBIC video presentation.
- From the end user point of view, GEO improvements still have a low impact on the end user perception: web sites content nature have a key role on optimizing the connectivity.
- No clear advantage of HTTP3 versus HTTP2 was found, based on initial tests with the first publicly available HTTP3 web sites.
- In any case, due to time constraints, only a limited number of scenarios and test conditions could be evaluated from MTAILS. A more comprehensive and in-depth analysis of QUIC protocol behavior when used in satellite scenarios is needed in order to be able to provide more consolidated recommendations or propose specific changes.

Supplementary to QUIC assessments, the project covers operation scenarios like online gaming, managing files and data from the cloud and IoT use cases, proving that the most of them can be operated even with state-of-the-art GEO-HTS with the corresponding latency, but some use cases like online 3D gaming must have achieved backhauled connections at least with MEO satellites for respectful user experience. The project combines in its simulations the state-of-the-art standards like DVB-S2X and DVB-RCS2 for theoretical max throughput of 100/100Mbps downstream / upstream per satellite beam for a network provider and 20/4 Mbps for satellite home broadband connections (bandwidth on demand cases). The satellite systems are considered as part of a simulated 5G component inside the core network that includes SDN & NFV technologies for improved resources management. [128]

In summary the project performed the following tests:

- **WEB QoE EVALUATION**

In tests for web services, latency is a critical factor and a significant improvement in terms of QoE can be observed when moving from GEO satellite systems to MEO/LEO systems. Results shown ratings associated the tests performed with offline web replicas, with GEO systems rated as having an “acceptable” or “good” QoE and MEO/LEO systems rated as “good” or “excellent” & for backhauling scenarios, performance is also good or excellent. Moreover, the performance degradation associated to the use of bandwidth on demand algorithms on the return link (which lead to increased latencies) is also much less pronounced for MEO/LEO than for GEO. For GEO, use of PEPs is crucial to avoid relevant performance penalties. In any case, the best experience is achieved with LEO scenarios, which provide a QoE that can compete at equal terms with the one provided by terrestrial access means (e.g. a mobile access). Supplementary, using Google AMP (Accelerated Mobile Pages) enhancements for mobile devices proved to be highly beneficial for web QoE for all satellite scenarios. [128]

Web access tests done with initial QUIC implementations show a low web access performance in satellite scenarios (especially, GEO and MEO), when compared with HTTP over TCP. It is likely that these results are pessimistic, as they may have been influenced by implementation issues (implementations are still consolidating and they may not have been validated for the specific characteristics of satellite scenarios) and as QUIC protocol definition is still evolving. In any case, web access tests have shown that use of well-adjusted PEPs is currently essential for an acceptable web QoE. However, QUIC uses UDP and encrypts its actual transport layer headers, so that the traffic cannot be intercepted and accelerated by the PEPs. This also provides an indication that web application performance could be rather low with QUIC, especially if scenarios with high BDP are not addressed explicitly during its definition. In the long run, this could also affect key services for satellite service providers as HTTP-based streaming services.

The test has shown that QUIC doubles the Page Load Time compared to TCP for almost all replicated websites under GEO scenarios and the performance for MEO/LEO also degrades to a certain extent:

- Unexpectedly, HTTP (secured and unsecured, versions 1 and 2) has shown an overall better performance than gQUIC, both when using the benchmark configuration (LAN) and when using any satellite model (LEO/MEO/GEO). Evaluating online gQUIC through Google Services has shown similar results compared to HTTP, where there is no clear benefit of using gQUIC out of the box over satellite networks.
- Website size and number of elements have a heavy impact on the Loading Time, varying significantly the download time for each element individually.
- Page Load Time results variations for QUIC are much higher than those for HTTP.

When in MTAILS evaluated gQUIC with a controlled scenario, their conclusions are corroborated while adding some additional insights:

- Studying the evolution of sequence numbers over time, gQUIC is not reaching its maximum throughput after several seconds.
- Underutilization of the protocol is observed once the maximum bandwidth is reached when browsing the same kind of web sites.
- An increment of the total transfer size has been observed, impacting directly on the client data consumption and, as a consequence, on the Page Load Time KPI. When downloading websites with a high number of resources to be requested (i.e., 200 images), necessary headers for gQUIC functionality (required by the project's Google Prototype Server in use) start to add an additional overhead compared to HTTP.

In traditional streaming content and 360 VoD videos (single-quality and multiple-quality) were loaded on the controlled web server and accessed from a HTTP browser using DASH, for different satellite system configurations. Tests were performed initially with HTTP1.1 and then complemented with tests using HTTP2. Traditional streaming worked well for all tested scenarios (GEO/MEO/LEO), but certain performance problems were encountered with the more innovative 360º VoD streaming (with higher bandwidth requirements) when used over GEO with Customer's Bandwidth over Demand (GEO/C1).

With HTTP1.1 and DASH, there were noticeable quality switches, with the selection of too low qualities, and there were some playback freezes, mainly due to throughput variations and the occurrence of buffer underflow situations. Indeed, it was checked that the playout buffer occupancy levels significantly fluctuated during the streaming session, having an impact on the quality selection and on the playback continuity. With YouTube (which uses proprietary protocols), however, 360º VoD streaming with HTTP1.1 was rather satisfactory for the same satellite scenario and video after some time, despite some initial stalls and re-buffering events.

Use of HTTP/25 had a positive effect on the QoE, leading to an acceptable quality rating (QoE index 3/5) when using DASH. Finally, while PEPs already contributed in a relevant way to the overall streaming QoE (when compared to performance without PEPs), results also showed that some adjustments to the PEP configuration aimed at better exploiting the available satellite bandwidth would be beneficial with 360 VoD (i.e., with higher streaming rates). [128]

- **ONLINE GAMING**

The MTAILS tested online games under satellite links in order to present their capabilities for maintain good user experience. In order to present the results two scenarios were considered:

- Satellite vs Terrestrial: A satellite side player played against a terrestrial one.
- Satellite vs Satellite: both players are using satellite connections.

Additionally, a Facebook game (8 Ball Pool) was played using a browser in mobile phone emulation mode, for different satellite system configurations using backhauling.

The project's test campaign concluded that fewer than five players online a First-Person-Shooter game as Team Fortress 2 can work very well over LEO satellites, whereas even proficient players can enjoy playing these games in a MEO environment that uses a fixed bandwidth return link. In the latter case, players noted some lack of accuracy and responsiveness, but considered it acceptable. MEO scenarios with bandwidth on demand (BoD) provided more variable latency were no longer rated as adequate by some players. However, general audiences can still be comfortable playing even under MEO/BoD models, as their demand of in-game accuracy and responsiveness may not be as high as for more advanced players.

It was not possible to improve the QoE of FPS gaming for the MEO scenario just by adjusting the user profile configuration. In this case, the satellite service provider might reduce latency and improve QoE by hosting a number of popular FPS games on its own FPS gaming server, ideally close to the satellite gateway premises. In addition to the evaluated MEO and LEO scenarios, a game was played with a GEO-Business scenario, but QoE was very bad, with poor performance in terms of responsiveness. Additionally, unexpected player movements (e.g., teleporting over the map) and actions not perceived by the other player were observed.

Regarding the evaluated Facebook game, it was not too latency sensitive and performed well even over GEO. Unlike Team Fortress, Facebook 8 Ball Pool is an asymmetric time-based game, which means that both players cannot play simultaneously and that it is based on turns. These two factors make 8 Ball Pool a rather non-latency sensitive game, obtaining the same good results being played under a direct internet access or under the worst case scenario (GEO). [128]

- **CLOUD VIRTUAL DESKTOP**

Use of Google Drive and Google Docs has been evaluated for different GEO/MEO/LEO scenarios, including also scenarios with a LEO ISL link. For the experiments, the real online service (accessible through a broadband connection) was used, which currently supports the Google QUIC protocol.

The main outcomes for the different automated tests have been the following:

- Create a Folder: The times for creating a folder were larger than six times the Round-Trip-Time for all the tested scenarios, what would be more than the expected performance. Probably these large times are caused by the fact that a large amount of information must be transmitted from the server and that several RTTs are necessary to refresh the Google Drive dashboard that is visualized in the web browser.
- Writing information: Though the results provided were higher number of rights writing times compared to RTT than the expected for a writing operation (expectation was close to a RTT period which didn’t occur probably caused by the transmission and rendering of the Google Spreadsheet dashboard).
- Create an empty and a filled document: The values measured showed that there is a slight difference between all cases, which can be explained by the additional time of transmitting the content of the file. It is assumed that most of the measured time is caused by the representation of the Google Docs dashboard.
- File Upload and Download: The measured download/upload times are directly related to the effective transfer rate of the satellite link. In any case, these operations are rather delay-tolerant.

The subjective rating for this test case has been acceptable even for the GEO with Bandwidth-on-Demand case, probably because the user is aware that he is accessing the Internet and because certain operations (as creating a folder or moving a file) are only performed sporadically during a session and delays of around 2-3 seconds are not perceived as very annoying. More latency critical operations (as editing a file) are actually performed locally (with updates sent to the server only in the background), so that network delays do not have an impact on the application performance. [128]

- **INTERNET OF THINGS**

The scenario consisted of a LoRa IoT device configured to send periodic traffic to a public (TTN) LoRa server using Over-The-Air Authentication (OTAA) mechanism and confirmed transmissions. The device connected to a LoRa gateway that acted as SATCOM client. The LoRa gateway communicated with the server through an emulated GEO satellite network with BoD.

The usage of satellite networks for backhauling LoRa IoT data appears feasible for uplink transmissions; that is, for sending the information collected from the several sensors to a remote platform. However, the usage of OTAA leads to a high percentage of failures (80%). Since the OTAA message is received successfully by the TTN Server but fails when sent back (an Invalid Packet CRC message is sent to the LoRa Gateway), it seems that the fault occurs at the server. This element may be tagging as unsecure packets received over high delay networks (comparing their timestamps).
One option to skip the OTAA problem would be to use an alternative security mechanism called ABP (Activation By Personalization). In this case, the sensor devices would be configured with predefined keys and this information could be introduced offline at the LoRa server. Thus, the over the air negotiation would not be necessary. This mechanism has some weaknesses in terms of security (since the keys are hardcoded in the device and not dynamically generated), but would solve the delay impairments and could be considered as a recommendation when using satellite networks for LoRa IoT backhauling.

Since some problems concerning mostly data exchange over transport layer causing big latency and packet loss in all types of internet services, MTAILS has also taken into account the following mitigation techniques: [128]

- **TRANSPORT LAYER TECHNIQUE: FLOW QUEUE - ADAPTIVE QUERY MECHANISM (FQ-AQM)**

When the satellite link is loaded with several TCP data transfers and a PEP is in charge of managing the available bandwidth, it will correctly handle long and short transfers by adequately setting the TCP window sizes, so that the interactive traffic is not adversely affected. However, if these TCP sessions are sent encrypted and encapsulated in UDP (i.e., as when using QUIC), then other mechanisms might be needed that avoid that interactive traffic is penalized. To deal with the prioritization of short transfers, the use the FQ-CoDel (Flow Queue CoDel) packet scheduler was taken into account. This technique prioritizes short transfers in front of long ones and so will prioritize DNS queries and also connection establishments, improving application responsiveness. It can also improve the responsiveness of interactive traffic. The FQ-CoDel algorithm is a combined packet scheduler and Active Queue Management (AQM) algorithm based on a modified Deficit Round Robin (DRR) queue scheduler with the CoDel AQM algorithm operating on each queue.

In order to study the FQ-CoDel the project take into account the possible flow queuing advantages when short transfers co-exist with long lived flows. For that, it compared results using PEP with FQ-CoDel with the ones obtained with a commercial PEP, which uses HFSC (Hierarchical Fair Service Curve) queuing algorithms, when a QUIC-based web access competes with a QUIC-based bulk transfer for the available FWD link resources. The page load time of the QUIC-based web access (DLT) is taken as KPI.

It can be observed that all set-ups obtain the same DLT without background flows. With background flows, however, the set-up using FQ-Codel has a much better performance than the other set-up. While with FQ-Codel the DLT is nearly the same as without background flows, with the commercial PEP the average DLT is nearly triplicated and becomes rather variable (standard deviation of about 2 s).

Similar tests were performed also using TCP based web access and TCP background flows. In this case, it was shown that the commercial PEP also implements some kind of (proprietary) TCP prioritization protocol that provides similar performance than the FQ-Codel technique with TCP background flows. However, this technique presents some limitations with UDP-based QUIC flows that are not encountered with the FQ-Codel technique. [128]

- **TRANSPORT LAYER TECHNIQUE: EXPLICIT CONGESTION NOTIFICATION - ADAPTIVE QUERY MECHANISM (ECN-AQM)**

Another factor which introduces larger end-to-end delay is the process of packet loss detection at receiver and packet retransmission at sender for transfer protocols which use the concept of congestion window, as in TCP or QUIC. This kind of protocols exhibit a greedy behavior and try to get the maximum network resources until the network link collapses and packet losses occur due to congestion. TCP uses packet retransmissions to deal with packet losses. The TCP receiver will receive a retransmitted packet either RTT or Retransmission Timer time out (RTO) seconds after the moment it should have been received. In any case, the receiving application experiences this delay because the reading pace of incoming data is delayed during this event. In this case, RTT is not only the round trip time due to the propagation delay, but also includes the waiting times in data path queues. [128]

A solution to avoid packet losses due to queue congestion is Explicit Congestion Notification (ECN). This technique allows end-to-end notification of network congestion without dropping packets, if the network supports this mechanism. From the transport layer point of view, TCP connections between PEP's are isolated from the terrestrial segments and these satellite connections share the same path. In this context, it is possible to use ECN signaling to control each running TCP connection inside the satellite link. ECN prevents TCP from overriding the router's queues and avoids packet drops. The FQ-Codel Scheduler is considered an appropriate AQM queue scheduler with ECN capabilities, taking into account the bandwidth variations characteristic of satellite links. It should be noted that, in front of other options, the concept as presented above has the advantage to largely decouple the packet scheduler (understood as the element performing the actual queuing and scheduling) from the PEP, which could be rather independent modules (except for the need to support ECN).

While the average values of throughput and one-way-delay are similar for ECN-AQM and DropTail signaling mechanisms, the following advantages of using ECN can be pointed out:

- ECN mechanism reduces latency peaks in all analyzed network scenarios. The maximum one-way-delay is reduced a least one RTT.
- A relevant reduction of the jitter is achieved when ECN is applied, because the maximum variation in the gap between consecutive packets is reduced at least one RTT.
- Return channels with DAMA obtain a higher peak latency reduction with ECN in front of DropTail with values of almost 2 seconds in GEO cases.
- The bitrate variability of TCP flows using the ECN is much lower than in the case of DropTail, since the queue of the bottleneck almost never underflows.

Additionally, it should be noted that future WebRTC-based Applications using QUIC in the transport channel, could benefit from the jitter reduction obtained using ECN techniques.

- **TRANSPORT LAYER TECHNIQUE – SERVER TUNING / LOWAT**

Within the operating systems, the TCP layer assigns a dedicated buffer per-socket for sending data called send buffer. The problem with this buffer is that it actually serves two different purposes: it contains data that the application has written to the socket but is still waiting to be sent to the network, and it also contains data that has already been sent, but has not been recognized yet. TCP on a high Bandwidth-Delay Product (BDP) path will have a large window and a large amount of unrecognized data. The (default) automatic buffer tuning increases the size of the buffer to match the BDP and also proportionally increases the space for the unsent data to be stored. So, an over-dimensioned sender buffer is allocated per-socket. This sizing is a problem because these large buffers introduce a large latency to the sent packets at the application layer. In general, only a small buffer is necessary for the unsent data, and a larger buffer for the data sent but not recognized. [128]

Within the operating system, turning on the TCP_NOTSENT_LOWAT parameter tells the kernel to keep track of unsent data separately from sent-but-unacknowledged data. This allows deciding how much unsent data ought to be stored in the socket buffer. This socket option can be configured in code on a socket-by-socket basis, if the application software supports it, or system-wide using the system control parameter net.ipv4.tcp_notsent_lowat. It is not a standard socket option but it is implemented in Linux kernel and only recently adopted by MAC OS-X. A recommended setting from project results is in the range 16-128k. It is recommended to be set globally for a good performance on desktops and servers that have few context switches.

The streaming test showed that the technique can have a noticeable impact in terms of QoE for certain actions that imply a change of the data to be transmitted by the server (in this case, a change of the video segment to be forwarded). For the considered test, for example, time to view the new video segment was reduced from about 6 seconds to about 4 seconds (-35%). Tests were done with a GEO scenario, but the improvement will provide the same benefits for scenarios with inter-continental links even if satellite delays are lower (LEO or MEO). It should be noted that tuning the LOWAT option does not provide benefits for scenarios where the latency between the streaming server and the groundside PEP is low (for example, the GEO Business Continental scenario), as buffers are small anyway.

Project evaluation concludes that turning on the TCP-NOTSEND_LOWAT option presents a significant improvement in end-to-end delay for scenarios where the latency between the application server and the groundside PEP is rather high (intercontinental terrestrial link), in any satellite scenario (GEO, LEO, MEO). For streaming services using persistent TCP connections, this tuning can improve QoE when using interactive video (fast-forward, rewind, jump, etc.) because the less latency the better responsiveness. If adaptive HTTP streaming (e.g. MPEG-DASH, HLS) is used, protocol reaction to link variations is faster because there is less data stored in server buffers when changing to a new quality flow.

➢ **STREAMING TECHNIQUES FOR 360 DEGREES VOD**

The performance of 360º video streaming through internet can improved, especially for GEO-based scenarios with bandwidth on demand techniques: [128]

- **Optimization Technique 1: Video Segments Duration**

A first optimization technique consists of making use of longer segments when converting the video into DASH. The expectation is that longer segments will provide a higher margin in the playout buffer when requesting new segments due to a longer duration of the segments already downloaded or being played out. A value of 6s for the video segments duration has been selected (in pre-mentioned tests was 2 seconds).

- **Optimization Technique 2: Video Quality Selection Strategy**

A second optimization strategy consists of exploring the impact of the ABR strategy on the playout continuity and quality, with the expectation of getting insights for the adoption of the most appropriate ABR strategy in the scenarios of interest. The following three strategies provided by the used DASH player have been evaluated:

- BOLA strategy: it chooses the bitrate to be downloaded based on the current buffer level, with higher bitrates for higher buffer levels
- Throughput strategy: it chooses the bitrate to be downloaded based on the recent throughput history.
- Dynamic strategy: it switches smoothly between BOLA and Throughput in real time, with the goal of leveraging the strengths of both strategies.

- **Optimization Technique 3: Video Encoding Strategies**

A third optimization strategy consists in exploring the impact of the adoption of more efficient video encoding and projection techniques, with the expectation of achieving a reduction of the bandwidth consumption, and thus of the experienced delays, improving the playback continuity (e.g. in 360º YouTube videos). Use of CubeMap projection versus Equirectangular projection (currently, the most widely adopted) is proposed.

The following conclusions apply to the adoption of the considered optimization techniques in GEO scenarios:

- The use of longer video segments results in higher encoding efficiency, and thus in a reduction of the bandwidth consumption when 360º videos need to be delivered. This is proven by a reduction of 12.3% of the size of the whole DASH content when using 6s segments compared to when using 2s segments. Although the use of longer segments comes at a cost of larger startup delays, which is undesirable, it provides significant benefits in terms of playout continuity and smoothness in the analyzed GEO scenarios, especially when DASH over HTTP1.1 is used. This has been corroborated via the collected KPIs, especially in terms of playout buffer occupancy variation, and in the subjective tests.

- Regarding video quality selection strategies, taking into account the throughput in addition to just the buffer fullness level (Throughput or Dynamic ABR) seems to provide benefits. However, additional tests would be needed to fully confirm this.
- The use of CubeMap projection results in less bandwidth consumption than the use of Equirectangular projection for 360º video. In the employed test material, the DASH content in CubeMap projection is approximately 19.2% smaller than the one for Equirectangular projection. This has been proven to provide better KPIs and also better QoE.
- The activation of HTTP2 results in a better QoE. This is especially the case when using CubeMap projection, video segments of 6s, and Throughput ABR strategy, when the MOS was rated as rather Good (3-4/5), getting the same level of quality than for YouTube. This can be due to the fact to the lower delays in downloading the video segments.
- The activation of the PEP results in better performance and subjective evaluation results. This is especially the case when using DASH with HTTP1, but PEPs also have a positive impact on performance with HTTP/2.

The considered optimization techniques have improved the results in all satellite network configurations. Although it seems that for each test condition YouTube provided slightly better perceived video quality and less aggressive playout qualities changes, it suffered from important stalls at the beginning of the session. Just minor stalls and no visual anomalies were perceived when using the developed 360º player and encoded content. The improvements are especially noticeable when applying the combination of the best options for each considered optimization technique (use of PEP, use of HTTP/2, use of long segments (6s), use of Throughput / Dynamic ABR strategies, and use of CubeMap projections). In such a case, the final perceived video quality was comparable to the one when using YouTube, achieving a subjective rating of 3-4 out of 5. These are quite satisfactory results, given the demands of 360º video, the GEO scenario conditions, and also taking into account that YouTube is a major platform, which many researchers and developers working on it, and with proprietary encoding and quality switching strategies. It should be noted that although the use of longer segments and throughput based ABR strategies have resulted in larger startup delays, the use of HTTP2 and CubeMap projection compensates for such an effect. [128]

5.4 CONCLUSIONS & FUTURE TRENDS

Our research concludes that the satellite communication systems provide major benefits for internet-based CDNs, lowering the operational expanses & providing global content distribution. The context of satellite beneficial is proven that under appropriate configurations the multibeam technology satellites providing more efficient content distribution than widebeam-only satellite for many use cases including in 5G backhauling and network cache feed (e.g. tower's cache proxy's feed).

Supplementary, in our research we have spotted that caching is one of the most important technologies available during content distribution in modern internet networks and the techniques and internet protocols that will be used during CDN operation with 5G and or other networks plays key role not only on cache hit ratio but also in responsiveness of caching PEP's and end users satisfaction in terms of QoE under satellite connection implication. In terms of internet protocols the state-of-the-art research expands beyond CDN operation, cloud-based services (e.g. Google) are using new & hybrid internet protocols which their behavior hasn't fully studied, supplementary their impact over satellite links (either home satellite internet or 5G) must be revised in order to mitigate at first sign the bottleneck occurred from protocol-caused channel congestion, secondary the corresponding service time delay and jitter.

ESA is conducting specific purpose R&D projects in order to study those aspects. We have track down the most relevant to satellite operation and 5G offered services and present them by their topic as follows:

- **Google's Protocols Impact over Satellite Connections**

QUIC is a new encrypted-by-default Internet transport protocol that accelerates HTTP traffic and which has the intention to eventually replace TCP. Originally proposed by Google, the IETF is now actively pursuing work to define and standardize a series of RFCs for the first IETF QUIC transport protocol. After Google started to test her own diversions from the standardized QUIC (gQUIC) other companies have participated to IETF's works on QUIC standardization and the official release of QUICv2 (e.g. Apple & Microsoft).

Since QUIC transport's techniques fully encrypts all transport protocol headers and authenticates the endpoints of a connection, currently widely deployed Performance Enhancement Proxies (PEP) can no longer be used to improve TCP performance, at least in terms of cloud services. The real interactions of QUIC using a satellite service have not been fully explored yet. The project objectives are to identify the root causes of any shortfalls in performance of specific QUIC mechanisms, propose changes to the specification, and evaluate the new proposals using a real-time emulation test bed used already for the MTAILS project. The ESA's results are contributed as code patches, presentations and direct contributions to the IETF, primarily targeting the QUIC Working Group and the standardization procedures of the protocol. In context to research **MTAILS CCN** and "**Assessment of QUIC over Satellite Links"** projects are assisting IETF and the correlated companies in the development of the transfer protocol. [129], [130]

As an increasing proportion of satellite communication now rely on internet protocols, and with a growing desire for more secure communications, influencing the development of the QUIC protocol to be more efficient over satellite is a key factor for maintaining and growing satellite's role in future communications networks. The project research will be related into: [130]

- ➢ The Influence of IETF for QUICv1 specification in terms of wording and protocol definition, so that it takes into account the needs and particularities of satellite systems as much as possible and does not place unnecessary restrictions.
- ➢ Provide satellite-optimized extension in QUICv2, which can be crucial for the performance of satellite systems in future integrated terrestrial-satellite 5Garchitectures. The opportunity to influence the design of the interaction between QUIC and the network path it uses largely appear in in the initial part of the project as topics are prioritized for QUICv2.0 and new techniques are proposed, analyzed and incorporated into the specification in 2021.
- ➢ Raise awareness within the satellite community of the potential for QUIC, and the implications for future Internet traffic using a path that includes a satellite link. This will help them address the future development of Internet functions in satellite equipment.

In technical terms, the studies will address various areas for potential improvement of the QUIC protocol:

- ➢ A set of issues related to startup and initialization of the QUIC sender. Some issues, such as ramp-up to the available capacity are known, but have not been addressed in QUICv1 and therefore solutions require exploration before they can be proposed for consideration in the QUICv2 specification.
- ➢ Asymmetry of Capacity. This includes policies for acknowledgement generation (identifying equivalent policies to PEP ACK methods) that are intended to be a part of QUIC.
- ➢ Congestion-control and Recovery. The project is seeking to ensure that QUIC implementations are not adversely impacted by the characteristics of a satellite link.

Finally, a set of new additional features have been identified as potential new features for QUICv2 (e.g. Multipath and the impact of non-congestive packet loss and mitigation using FEC). Preliminary studies with simulated testbeds for proof-of-concept are proposed focusing on the evaluation of the applicability of these techniques to satellite systems for complementing the standardization recommendations. Their final reports are expected to be finalized until 2022. [129], [130]

- ➢ **Improving CDN Security**

MENDHOSA, SCORSESE and similar projects took into account the improvement of CDN communications over satellite under performance-only perspective. Projects like ESA's **SHINE** have been also concerned about security mechanisms in order to solve a set of security issues concerning network security and content rights management. [134]

Because the project's reports weren't available initially, our research based on a small number of scientific reports concluding that SHINE aims not only at extending to satellite-enabled scenarios for terrestrial communication networks, but also at designing innovative mechanisms for the protection from unauthorized access to content-related data, as well as for the secure distribution of real-time multimedia information across hybrid channels leveraging both the unicast and the multicast communication paradigm.

The project studies "combined coding" techniques, targeting the optimization of multicast-enabled transmissions in the presence of caching. More precisely, proposes cutting-edge solutions for decentralized random caching which, combined with an original content distribution technique based on coded multicast, will allow CDNs to attain "order-optimal" performance.

SHINE is focused around the design and implementation of an end-to-end secure infrastructure for the delivery of multimedia content over integrated satellite-terrestrial networks. The project makes use of a combination of both unicast and network-coded multicast. A number of reference scenarios are under investigation relying on in-network caching. The main aspects of the project's study are the following: [131], [132]

- Define an end-to-end security architecture for hybrid satellite-terrestrial networks allowing for the effective transmission of multimedia content
- Study the applicability of Network Coding techniques to realistic application scenarios
- Evaluate the effectiveness of the upcoming WebRTC (Web Real Time Communications) standard when applied to the streaming of multimedia content
- Perform a comparative analysis between MPEG-DASH and WebRTC, taking into account both performance and security features
- Increase of caching performance by the combined coding (under pseudo-multiplexing form) of different content chunks into every transmitted frame
- Increasing the security level of satellite enabled transmissions with coding techniques that will be resilient to network attacks (e.g. snooping & eavesdropping).

The overall architecture of the SHINE project is comprised of three main building blocks, a source encoder, a satellite-enabled broadcast distribution and an edge distribution network. This last building block is composed of two subcomponents, namely MPEG-DASH and WebRTC. The proposed architecture consists of the following operations: [133], [134]

- Receive source content files and split them into chunks
- Pre-populate edge caches with content chunks based on predefined priority knowledge of both the content popularity and the end-users' distributions (e.g. Zipf based)
- During steady-state operation of the CDN, send content chunks to the edge caches by properly multiplexing them at the source based on project's proposed network coding scheme
- After populating the edge caches, serve end-users from there by leveraging the available edge network real-time streaming capabilities under the usage of either MPEG-DASH with Common ENCryption scheme (CENC) or WebRTC with similar techniques (e.g. DTLS).

Concluding, the project's scientific reports also mention the implication of NFV technology in order to transform state-of-the-art caching infrastructures as an automated network service through VNCF, the architecture prototype will be leveraged in the satellite part of the network to implement coded multicast transmissions combined with an orchestrator prototype for deploy/operate in both core & edge cache infrastructures. Without further intelligence we assume that after 2 years of official hiatus, the project will be officially declared completed soon and the available reports will be finalized within 2022. [131]

6. CONCLUSIONS AND FUTURE TRENDS

In this chapter we perform a summary of our research, concerning the satellite capabilities during 5G era and the challenges the brings the research occurring for the transition from 5G to 6G heterogeneous networks in terms of parallel and inter-operability of satellite networks as a 5G/6G network resource component.

A number of future trends concerning technologies that have just started or will be applied in satellite systems have appeared, most of them applicable in all use cases. We have dedicated a section of chapter 6 in order to report them in summary based upon the R&D projects already take place.

Concluding, as a proof-of-concept for the future trends we produced a section in which we present the state-of-the-art and under development satellite systems that will have applicability to 5G and other internet communications.

6.1 THESIS CONCLUSIONS

As long as the communication technologies grows, the satellites during 5G era are achieving a big number of applications, not only for 5G use cases (e.g. backhauling) but also for multimedia based applications over non-5G networks e.g. CDN. Most of the standardization procedures have already completed, their results and the corresponding R&D projects & tests have proved that in the near future with the further development of elliptic orbit satellite systems, all types of satellite internet communication networks can became a resource component for 5G terrestrial networks in order to complement their need for global coverage in terms of responsiveness, range, and throughput. The standardization studies won’t stop there, since in all aspects of telecommunications industry there must be further developments for the smoothest possible technological transcendence from 5G to 6G networks in 2030.

This transition will not be cost-effective and fully optimized until computer science technologies like SDN/NFV will be fully integrated into all possible parts of network operation. Some evaluations have declared that in terms of CAPEX the cost reduction can reach up to 40% in certain deployment scenarios, with a similar cost reduction and profitability when it comes out for OPEX. Other aspects must also be studied some of them already begun like the progressive integration of machine learning algorithms in network operations e.g. for packet traffic management and A.I. in general network aspects.

Applications beyond 5G like IoT and CDN operation can be performed with satellite links, either interconnecting networks (e.g. cloud servers & data farms or between company networks) or complementing 5G coverage (e.g. complement drone connection to earth cell towers with satellite backhauling). Supplementary, new internet protocols have appeared and their corresponding impact on traffic overhead during satellite connections is being revised by ongoing R&D projects, currently focused on Google’s empowered protocols in order to mitigate possible bottleneck phenomenon in satellite links.

Finally, the transition from 5G to 6G networks, commences unofficially the beginning of the quantum cryptography era in which many of the state-of-the-art public key algorithms will become useless within the next years because of hacking capabilities that algorithms like Snore’s will offer. Security focused R&D projects have started to appear in order to propose to the industry techniques to confront quantum era issues in terms of security protocols and algorithms evolution within this decade.

6.2 FUTURE TRENDS FOR 5G & 6G

ESA and EU have funded a big number of R&D projects about satellite communications evolution some of them we have already been disgusted in previous chapters concerning A.I. implication in satellite networks, Internet protocols evolution & IoT applications through LEO satellites. The projects and the topics we present in this section have direct and indirect impact in scientific topics we mentioned in previous chapters. In summary, the projects we found concerning 5G/6G evolution we have them categorized by their area of research.

According to scientific papers and whitepapers for future networks, the 6G are considered as a new form of network operating as self-contained ecosystem of artificial intelligence. That statement means that 6G must be able to use all available at the time AI algorithms operating in all sections of a network as we previously mentioned in Chapter 3. The 6G networks demands from the industry to discover solutions that will boost the current specifications of 5G up to 10 times and 300 times more in terms of energy efficiency. Due to exponential growing needs for connectivity e.g. device density in a specific area & number of connected devices the 6G communication systems are expected to be featured by the following types of KPI associated services: [72], [135]

- Ubiquitous mobile ultra-broadband (uMUB)
- Ultra-high-speed with low-latency communications (uHSLLC)
- Massive machine-type communication (mMTC)
- Ultra-high data density (uHDD)

In order to fulfil those KPIs, the following key factors must characterize a 6G communication system:

- AI integrated communication
- Tactile Internet
- High energy efficiency
- Low backhaul and access network congestion
- Enhanced data security

It is estimated that the 6G system will have 1000x higher simultaneous wireless connectivity than the 5G system. Compared to the enhanced mobile broadband (eMBB) in 5G, it is expected that 6G will include ubiquitous services, i.e., uMUB. Ultra-reliable low-latency communications, which is a key 5G feature, will be an essential driver again in 6G communication providing uHSLLC by adding features such as E2E delay of less than 1 ms with more than 99.99999% reliability, and 1Tbps peak data rate. Massively connected devices (up to 10 million/Km^2) will be provided in the 6G communication system. It is expected that 6G aims to provide Gbps coverage everywhere with the coverage of new environments such as sky (10,000 km) and sea (20 nautical miles). Volume spectral efficiency, as opposed to the often-used area spectral efficiency, will be much better in 6G. The 6G system will provide ultra-long battery life and advanced battery technology for energy harvesting. In 6G systems, mobile devices will not need to be separately charged. [135]

Satellite communication is a must to provide ubiquitous connectivity. It can support a seamless global coverage of various geographic locations such as land, sea, air, and sky to serve the user’s ubiquitous connectivity. Hence, to provide always-on broadband global mobile collectivity, it is expected to integrate terrestrial and satellite systems to achieve the goal of 6G. Integrating terrestrial, satellite, and airborne networks into a single wireless system will be crucial for 6G. Supplementary, the satellites must achieve the potential to provide 3D beam connectivity under a global 6G ecosystem. The 6G system will integrate the ground and airborne networks to support communications for users in the vertical extension. In this ecosystem, the 3D base stations are provided mostly through low orbit satellites and UAVs. The addition of new dimensions in terms of altitude and related degrees of freedom makes 3D connectivity considerably different from the conventional 2D networks. The 6G heterogeneous networks will provide 3D coverage. The decentralized 6G networks with the integration of terrestrial networks, UAV networks, and satellite systems genuinely realize the global coverage and seamless access, even for ocean and mountain areas.

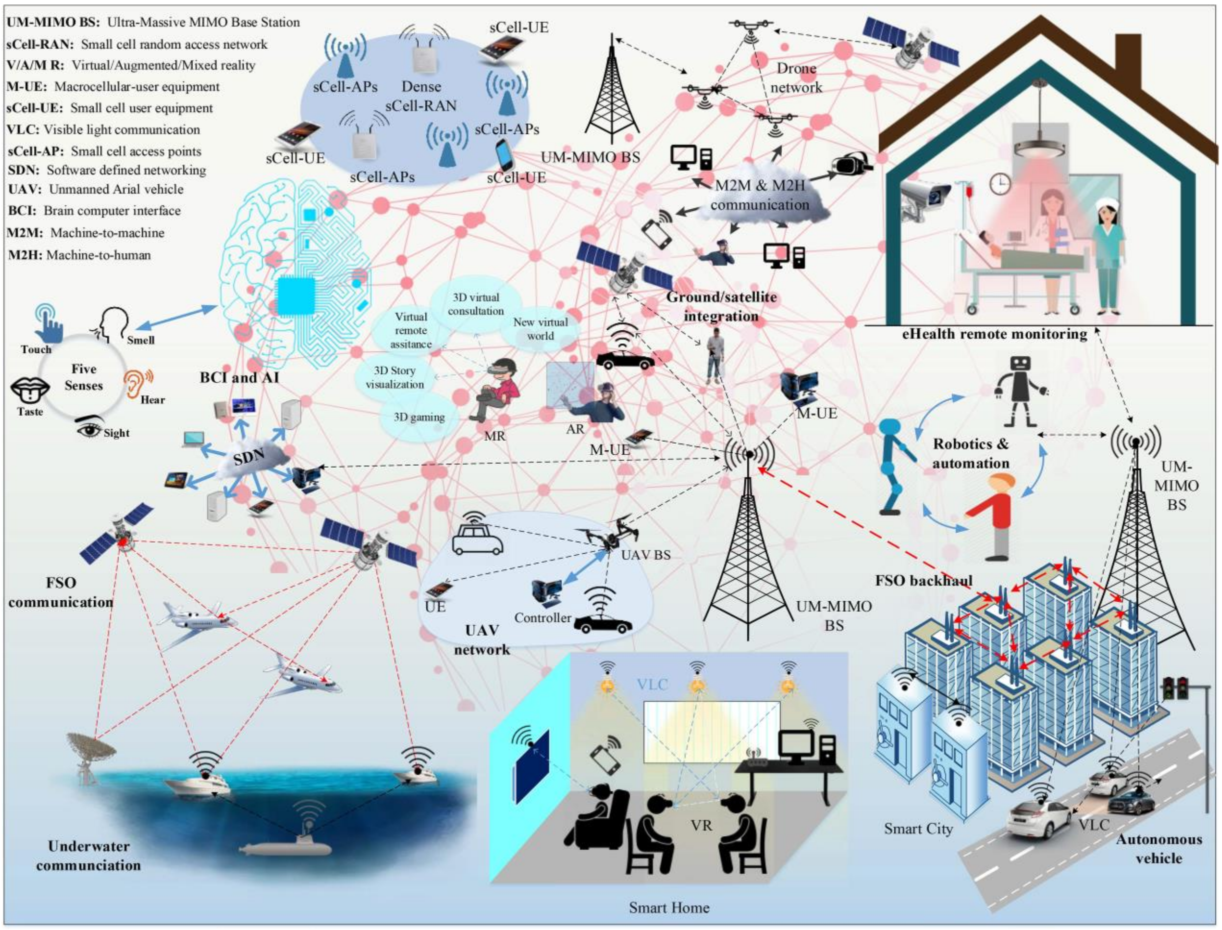

Figure 23: Generic diagram of 6G network architecture, focused on connectivity [72]

In order to study the feasibility of creating 3D connectivity with satellite systems in 6G & expansion of 5G connectivity he tracked down the following trends in physical layer evolution and other aspects that we haven't dedicated our research until this point. We summarized the main trends we spotted related to the satellite operation in 5G & 6G as follows:

- **Optical free space communications over satellite**

The history of optoelectronic payload for satellites goes back to the first testbeds since NASA's and ESA's first testbeds in the 90's. The state-of-the-art optical free space equipment for satellites have started to applied since 2014 upon the time period ESA launched EDRS system. Accordingly to 6G vision reports, the 6G evolution aims to push the boundaries of the frequency band to THz to meet even higher future demands. The RF band has been almost exhausted, and now it is insufficient to meet the high demands of 6G. The THz band will play an important role in 6G communication. The THz band is intended to be the next frontier of high-data-rate communications. [136]

The THz waves, also known as submillimeter radiation, usually refer to the frequency band between 0.1 THz and 10 THz with the corresponding wavelengths in the 0.03 mm – 3 mm range. According to the recommendations of ITUR (ITU Radio communications Sector), the 275 GHz–3 THz band range is the main part of the THz band for cellular communications. The capacity of 6G cellular communications will be increased by adding the THz band (275 GHz–3THz) to the mmWave band (30–300 GHz). The band within the range of 275 GHz–3 THz has not yet been allocated for any purpose worldwide therefore, this band has the potential to accomplish the desired high data rates. Of the defined THz bands, 275 GHz–3 THz, and 275 GHz–300 GHz lie on the mmWave, and 300 GHz–3 THz lie on the far-infrared (IR) frequency band. Even though the 300 GHz–3 THz band is part of the optical band, it is at the boundary of the optical band and immediately after the RF band. Hence, this 300 GHz–3 THz band shows quite similar characteristics with the RF. THz heightens the potentials and challenges of high-frequency communications. The critical properties of THz interfaces include widely available bandwidth to support very high data rates & high path loss created by the high frequency effects from earth’s atmosphere (highly directional antennas will most probably be indispensable). The narrow beam widths generated by the highly directional antennas can reduce in part the interference. [135], [136]

Optical Wireless Technologies are envisioned for 6G communications in addition to RF-based communications for all possible device-to-access networks, these networks also access network-to-backhaul/fronthaul network connectivity. OWC technologies have been used since 4G communication systems. However, it is intended to be used more widely to meet the demands of 6G communication systems. OWC technologies, such as light fidelity, visible light communication (VLC), optical camera communication, and FSO communication based on the optical band, are already well-known technologies. These communication technologies will be extensively used in several applications such as V2X communication, indoor mobile robot positioning, VR, and underwater OWC. Researchers have been working on enhancing the performance and overcoming the challenges of these technologies. [72], [135]

Communications based on wireless optical technologies can provide very high data rates, low latencies, and secure communications. Technologies like LiDAR, which is also based on the optical band, is a promising technology for very high-resolution 3D mapping in 6G communications. OWC confidently will enhance the support of uMUB, uHSLLC, mMTC, and uHDD services in 6G communication systems. Advances in light-emitting-diode (LED) technology and multiplexing techniques are the two critical drivers for the OWC in 6G. It is expected that both microLED technologies and spatial multiplexing techniques will be mature and cost effective in 2026. White light based on different wavelengths will beneficial to accelerate the throughput performance via wavelength division multiplexing, leading to potentially 100+ Gbps for ultra-high-data-rate VLC access points. The addition of massive parallelization of microLED arrays will enhance the further data rate to the target Tbps of 6G communication. [72]

So far in terms of 5G evolution, the funded R&D projects studies issues like the size and weight of electronic payloads. EU funded projects like C3PO and LASERCOMB have offered intelligence for future development quantum-based optoelectronic transmission equipment with reduced size and weight than the state of the art free space implementations. OPTIMA project (co-funded by EU & ESA) took it one step forward and demonstrated new types of electronics e.g. optoelectronic mixers for producing both traditional RF carriers (Ku/Ka bands) and THz carriers for future applications. Projects like SODaH are started to taken place as PoC that SDN & SDR technologies will integrate inside future optoelectronic satellite payloads. Supplementary, Projects RETINA & ORIONAS are some of the most notifiable for metamaterials study that can be used for free space communications, the results are expected to be finalized within 2021. There are also advanced studies under development for mitigating the atmospheric impact to free space communications the most noticeable projects we discovered are OpticalSpaceLink & VERTIGO which will terminate their activities until 2022. [136], [137], [138], [139], [140], [141], [142], [143], [144], [145], [146], [147], [148], [149], [150]

ESA, after many studies has created a major R&D project for developing free space communications over state-of-the-art & future satellite systems called ScyLight (SeCure and Laser communication Technology) investigates two aspects, the evolution of optoelectronics for satellites by providing information to the industry and quantum physics-based security in terms of cryptography algorithms & techniques. We discover that the project's activities have caused a big number of similar R&D projects who study the technical aspects of free space optoelectronics, because the vast of knowledge available we are mentioning them under the following list: [151], [152], [153], [154], [155], [156], [157], [158]

- **OTUS** (Optical Technologies for Ultra-fast Signal Processing on Silicon Platforms, completed in 2019)
    - Design and demonstration of laser-based optoelectronics for free space applications with 10Gbps maximum data rate
- **FOLC** (Feeder Optical Links for Constellations, completed in 2019)
    - Laboratory assessment of optical links sensitivity under space applications
    - Optical equipment evaluation for satellite use under traditional RF Earth-space-Earth transmissions
- **HALO** Gateway (High Altitude Laser from Orbit Gateway, completed in late 2019)
    - Study for creating optical links between satellites and HAPS
    - How all types of HAPS can operate as hybrid air gateway
- **LEOCAT** (Optical Communication Optical Head, completed in late 2020)
    - Design and testing of a low SWaP scheme optical head for free space optical communication
    - Optical head for satellites based on InGaAs-based optoelectronics
- **OT4NGsat** (Optical Technologies for Next Generation Communication Satellites, research under progress)
    - Studies topologies and architectures for optical-enable satellite systems depending the optoelectronics area of applicability
    - Technoeconomic evaluation for the mentioned scenarios

- **Skylight's UltraAir** (Research under progress – expected to end in 2023)
    - Evolution of optoelectronic payloads for GEO satellite in order to expand in data rate above 1,8 Gbps (mono or duplex) and communications range beyond 40000 Km
    - Payload for earth-space, intra-satellite & inter-satellite links
    - Prototyping in 2022 and commercial available solutions after 2023

The results & ideas of the previously mentioned projects will be applied in order to help ESA in the construction of a prototype optical enable system the ordination of the procedures are performed by a Skylight's pet project called HydRon (High ThRoughput Optical Network prototype). Its official mission is to create a technology called "Fibre in the Sky" will be integrated in terrestrial networks and offer a satellite network hybrid which will reach Terabit capacity and become demonstrated by European and Canadian Industries by 2025. [159]

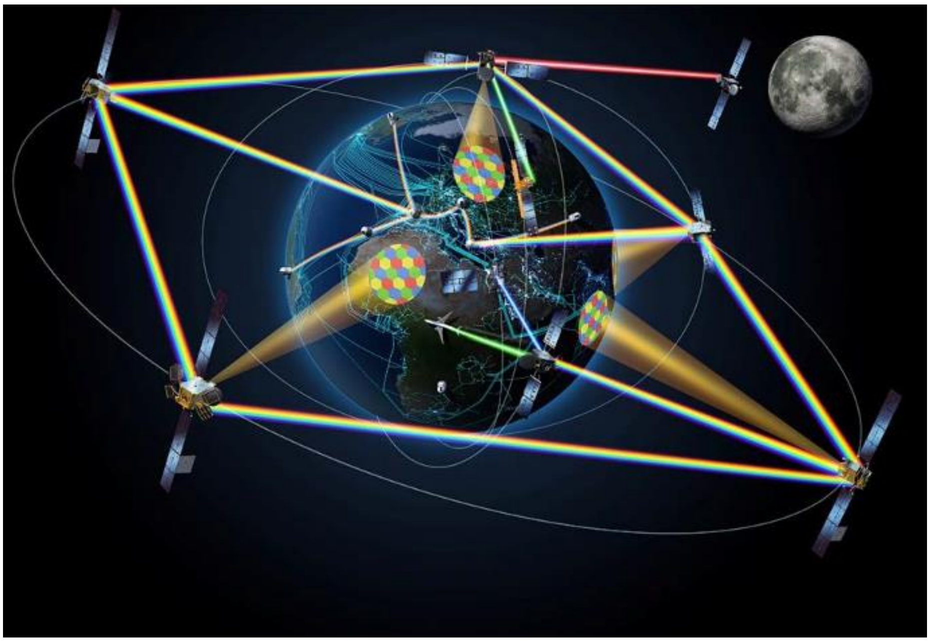

Figure 24: Artistic impression of the HydRon vision of an all optical space network integrated into terrestrial network infrastructures. [159]

Officially, the project is at Phase A study in which investigates the end-to-end system architectures of a high throughput system that will reach speeds in Tbps range (minimal per satellite 100Gigabit/second), identify the key elements of the system architecture (e.g., optical feeder links, high data rate Wavelength Division Multiplexing (WDM) optical inter-satellite links, on-board (all optical / regenerative) routing / switching of optical signals, seamless integration into the terrestrial fibre network, etc.), and provide an overview of the potential enabling technologies required. The project also will define an in-orbit demonstration mission (or a set of staggered missions spread out in time) in LEO / GEO orbit (or in a mixed LEO/GEO scenario) to demonstrate the feasibility and evaluate the communication performances of the critical elements, including the technology development roadmap and associated schedule / cost analysis. [157], [158], [159]

➮ Quantum Security

The factor of security is critical in satellite networks and requires studies to create new mechanisms and algorithms that will sustain their efficiency in quantum cryptography era. Both EU & ESA have proceeded in studies who take advantage of the optical communication technologies available in order to produce quantum-physics based algorithms and physical layer cryptography. Quantum Key Distribution (QKD) is a technology allowing the exchange of a cryptographic key based depending on the application in discrete or continuous variable protocols that are less sensitive in channel transmission than state-of-the-art continuous variable mechanisms. A system that uses such mechanisms will be secure even after the development of a quantum computer, which is thought to efficiently break current key exchange mechanisms based on public-key cryptography. While most current QKD implementations were planned to be fiber-based, its intrinsic limitation to some hundred kilometers, due to fiber losses, makes satellite QKD a crucial technology for the establishment of a secure link at a world-wide scale. [72], [135]

In summary, because of their research topics the project we discovered we mention them upon their historical order: [160], [161], [162]

- **QPSA** (Quantum key distribution Protocols for Space Applications, finished in 2021) (ESA-funded)
    - The project studies a QPSA-QKD prototype system in order to operate as a part of one satellite payload. The project aims to solve the problem of key exchange by the use of quantum mechanics based on discrete variable QKD (DV-QKD) and offers the potential of ensuring "unconditional secure" key exchange for encrypted communication.
- **Satellite CV-QKD** (Continuous Variable - Quantum Key Distribution, finished in 2021) (EU HORIZON funded)
    - The projects research on satellite QKD has mainly focused on discrete variable (DV) protocols, which are less sensitive to channel transmission but require single photon detection technology. Continuous variable (CV) protocols are based on standard telecom detection technology, which is much faster and more efficient. Recently, CV protocols have shown to work well in high losses fiber-based environments. This action aims to extend the CV scheme to the free-space domain, implementing a full, self-referenced CV-QKD scheme on a free-space channel, as a first step for a future satellite implementation of such technology.
- **QUANGO** (cubesat for QUANtum and 5G cOmmunication, open until 2023) (EU-funded)
    - Design and launch of a LEO nanosat-class communication system prototype that uses QKD for secure transmission of NB-IoT signals over a 5G network.
    - Nano-satellite study with both QKD and 5G capabilities for low orbit (~600Km altitude) satellite-to-ground communication.
    - Prototype system to be launched between 2023-24

Finally, ESA's studies have led in 2018 in a contract agreement with Arqit Company for join studies, construction & launch of a LEO satellite prototype called QKDsat that will use QKD for safe internet communications. Its launch is expected in mid-2023. [165], [166]

6.3 STATE-OF-THE-ART & FUTURE SATELLITE NETWORKS

The satellite industry has developed many digital satellite communications systems over the last 30 years. In this section we provide technical information, concerning their innovations and their present and future capabilities in assisting terrestrial networks in data feed or backhauling e.g. 5G. In historical order we notify the following:

- **EDRS** (European Data Relay Satellite constellation) (funded by ESA)

EDRS is an ESA contribution with Eutelsat & Airbus Companies for creating a Pan-European data traffic GEO network to interconnect all kinds of satellite systems that can't connect directly with light-on-sight optical links in combination with Ku/Ka RF links. At the current state-of-art it consists of EDRS-A & C GEO satellites but in 2024 is expected to complement with EDRS-D launch and the launch of EDRS-E a few years later. The system is the first commercial that uses the 2nd generation laser communication terminals (LCTs) which are developed and qualified by Tesat Spacecom Company in Germany. [163], [167]

The system's operation is mostly occupied by its main client, the Copernicus service's Sentinel Earth observation network. Sentinel system transmits with speeds of 600 & 1800Mbps depending on the application & the distance, satellite pictures of Earth's surface to ESA central offices through EDRS laser links for further investigation of Earth's environment e.g. pictures from the latest fires occurred in many areas across Greece this year. Supplementary it transmits through Ka bands on earth-space & satellite-to-satellite with pick data rate of 300 Mbps. [168]

The system is expected to achieve full duplex capabilities with the operation of EDRS-D satellite, in this case the satellite's total traffic will reach 3,6 Gbps (1,8 Gbps symmetric & full duplex using 2 wavelengths) in a maximum distance of 45000 Km in near-Earth's space expanding current EDRS capabilities. So far it doesn't operate directly relevant 5G services like backhauling. [168]

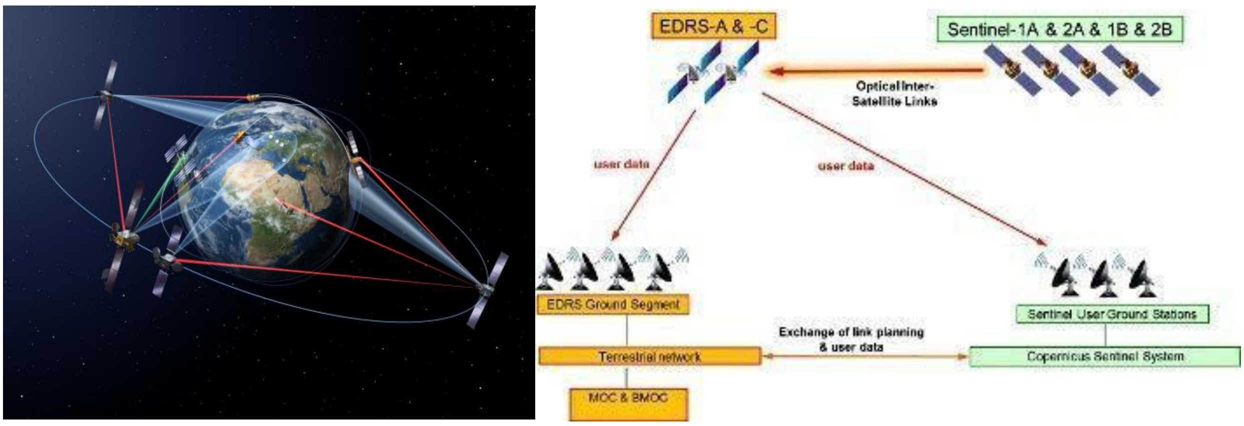

Figure 25, 26: Architectural images of EDRS communicating with LEO systems and space stations using Optical ISLs [167], [168]

- **NSLComm LEO** (also known as NSL-1) (funded in part by EU)

A telecommunications company in Israel called NSLComm has been funded from EU under HIGDARS project (High Bandwidth Flexible Satellite communication System for 1 Gigabit/sec communications) in 2018 to study new types of payloads for LEO satellite systems. The objective of the HIGDARS project was to develop a commercial broadband Telecommunication system, based in Ka band, with small LEO satellites at its first stage of deployment, using an innovative Expandable High Bandwidth parabolic Antenna with a smart error correction and optimization (Beam Shaping) sub reflector. The project has funded a research on using metamaterials for a low mass and small volume when stowed antenna, which developed through SMP-based structures (shape memory polymer). This material offers the opportunity to create a very low mass foldable antenna that requires no mechanisms or mechanical parts. [172], [173], [174], [204]

This system is designed to provide a link of 1 Gigabit per second from nanosatellite constellation in class of 6U cubesat, which it was considered 500 times better from the best system available in 2018. The system can handle applications such as HDTV, Ultra HDTV (4K), Mobile TV, In-flight & broadband Internet connections and bi-directional satellite to cellular device communication (5G) across Israel, amongst others, who are driving insatiable demand for satellite communications bandwidth. According to official data, the system has access to 600, 620 & 640Km (and others around 500 & 600Km) altitude in order to operate theoretical a maximum of 9 satellites in particular amplitudes, some recent studies referred that in the next 2 years the company will launch up to 60 satellites in total with some news reports referring for up to 80 within this decade. [170], [171], [183]

The system after its full deployment it will provide cloud space service as the company has signed in 2019 an agreement with Amazon AWS for using a new cloud-based ground station network to operate its nanosatellites. NSLComm will be funded by Amazon for common effort on deploying and operate satellite gateways, allowing NSL to operate its satellites under Amazon cloud services, supplementary Amazon will extend its cloud services further in Israel. Also it will complement the lack of internet broadband connectivity in distant areas like South Africa. [169], [172], [174]

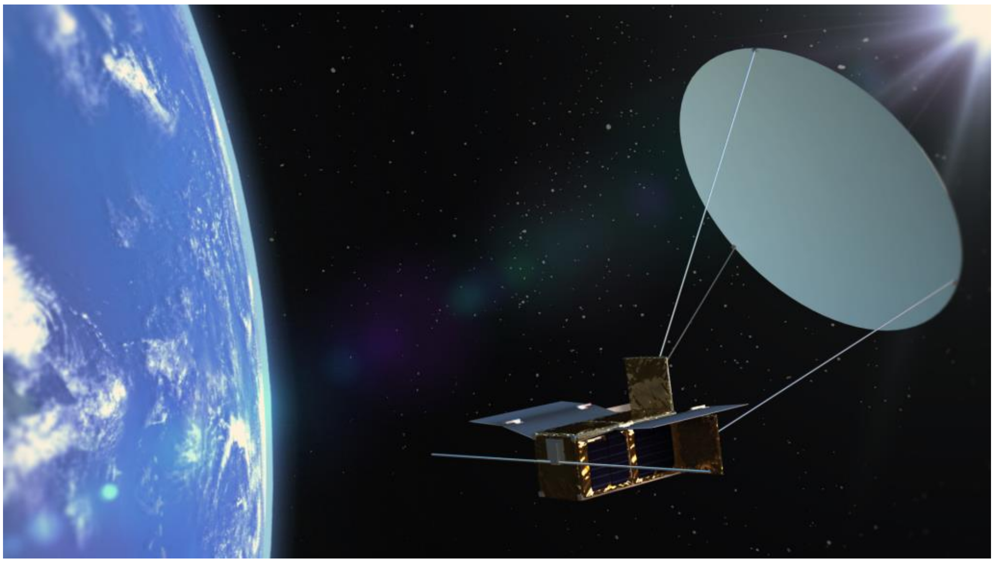

Figure 27: Artistic impression of an NSLComm LEO satellite under operation [204]

The project has concluded its R&D operations in 2018 and proceeded in July 2019 to schedule a set of satellite launches in order to start building the LEO constellation. Officially only one has been launched & the next are expected within 2022, the satellite launches so far have been postponed in 2020-21 due to the COVID-19 pandemic. [172], [175]

- **SpaceX's STARLINK** (Private initiation – partially funded by U.S.A government)

STARLINK is a satellite internet communications system based in LEO satellites. Its first satellites have launched in mid-2019 and until now it has over almost 2000 satellites in orbits between 540 & 570 Km. It is being used mostly for home satellite broadband internet connection but it is under debate that it will progressively be applied in cloud networks inter-connection and cellular backhauling. The system is expected to reach half of its capacity in 2024 and it will reach maximum potential in 2027. Supplementary it is expected to reach amplitudes between 300 & 600Km & between 1100 & 1300Km. [176], [177], [178], [183]

In terms of cloud services SpaceX has already started collaborations with Google and Microsoft. More specifically, SpaceX announced in May 2021 a partnership with Google, where SpaceX will ground terminals with Google Cloud data centers, SpaceX will install ground stations within Google's data centers for its Starlink broadband satellites in order to provide direct connections between data farms. The companies said they would provide new services based on this partnership later this year. Moreover, SpaceX made a set of agreements with Microsoft, one of which allows the use of Microsoft Azure's orbital emulator, a digital environment that allows its user visualize a satellite network's architecture & test satellite designs with artificial intelligence algorithms. Supplementary on 2020 Microsoft announced the expansion of its cloud computing services for the space industry. In business agreements Microsoft achieved with SpaceX & SES, the company will offer mobile cloud computing data centers that can be deployed anywhere in the world and connect to SpaceX's Starlink and SES' O3b MEO networks. Ground stations come out of this deal are expected to be set under full operation until 2025. [179], [180], [181]

The system so far from the official evaluations can reach in home satellite internet service, speeds of up to 150Mbps in Downlink and 20Mbits Uplink with average of 50ms of latency in some US areas has been measured even in 35ms making it comparable to 4G connections. With the addition of the next generation of SpaceX satellites the speed and the responsiveness are expected to become comparable to 5G/6G. It is designed by SpaceX that after the approval of future permissions from U.S.'s F.C.C. that in 2027 will reach more than 30000 satellites across the arranged amplitudes of constellations that SpaceX is permitted to operate. [176], [177], [178], [182], [183]

The future of STARLINK seems really promising because within the next generation of STARLINK satellites. Currently the system is on its way to 32nd launch of its v1.0 satellites which currently transmit to users within Ku/Ka bands and up to V band channels in satellite-gateway communication. On launch #28 in April it was announced that SpaceX will put on operation 10 satellites in polar orbit, the first with optical ISL capabilities in STARLINK network. SpaceX announced that the 2nd version of Starlink satellites they will provide from 2022 and after, satellites with optical ISLs capabilities and further RF spectrum expansion until system's full deployment in 2027. [182], [184]

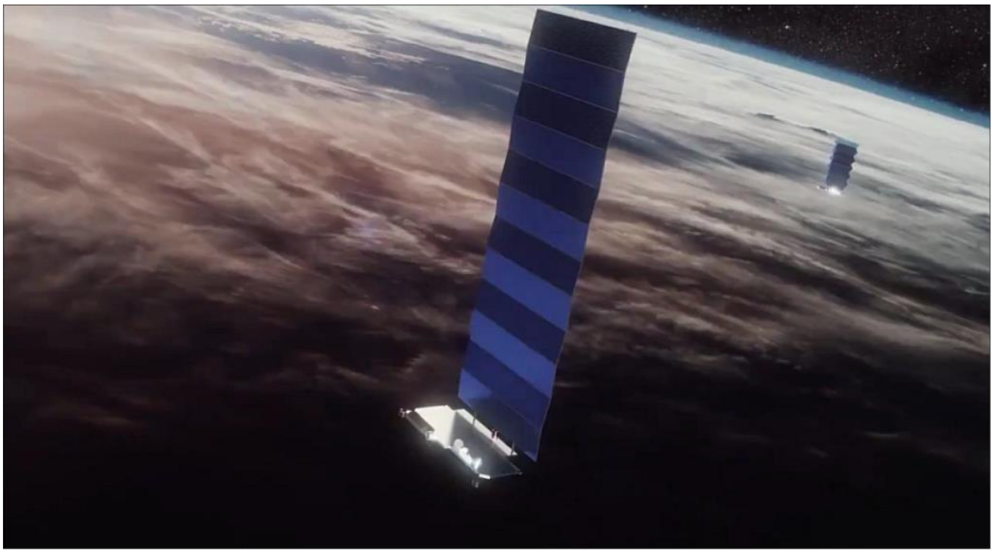

Figure 28: Artistic impression of STARLINK satellites [177]

- **TELESAT LIGHTSPEED** (Partially funded by ESA)

LIGHTSPEED is a Canadian industry LEO communications system from TELESAT. It is designed for offering satellite internet broadband connections across Canada for cloud services & 5G backhauling. The first TELESAT major launches will begin in 2023 system is expected to become fully operational before the end of the decade. [185]

The constellation of the system is expected to consist of 298 satellites at 1325 Km altitude, 78 of them in polar orbit at 1015Km. The system has 4 main characteristics: [186], [190], [196]

- Optical ISL capabilities - From the beginning of the constellation deployment, all satellites will have optoelectronic payload for Inter-satellite links
- PHASED ARRAY ANTENNAS - Sophisticated antennas on each satellite with hopping beams scan the earth to provide full coverage and can dynamically focus of satellite capacity precisely where users require it, the antennas development is being funded in part from ESA’s ARTES programs for applications in future systems.
- DATA PROCESSING IN SPACE - Full digital modulation, demodulation, and data routing occurs in space, resulting in higher capacity and flexibility along with regenerative capabilities
- HYBRID ORBITS: Satellites fly in an industry-first combination of polar and inclined orbits, resulting in complete global coverage, including polar areas, with higher capacity where most of the world’s population lives

TELESAT has already signed up agreements for deploying her own cloud services, in April 2021 there was announcement for financial agreement with Netcracker company in order to implement its cloud-native digital Business Support System/Operations Support System (BSS/OSS) software suite to support Telesat’s latest technologies in LIGHTSPEED constellation, opening an opportunity for introducing SDN/NFV-enable infrastructure inside the network. [191]

In its full deployment the system will achieve 15 Tbps of total capacity. TELESAT in order to evaluate the future potential of this system has launched in 2018 one prototype satellite for PoC. The evidence so far consist that the solo satellite can achieve under specific use cases up to 1,2 Gbps capacity with variable latency between 18 and 60 ms in cases as cloud servers interconnection, 5G backhauling and up to 8K video distribution, making it competitive to STARLINK and similar constellations. [188], [189], [192], [193], [194]

Figure 29: Artistic impression of a LIGHTSPEED satellite [203]

The system has finished its financing circle in 2021 & it is expected that the first satellites will be launched into space by Amazon's Blue Origin rockets in early 2023. [195], [203]

- **EUTELSAT LEO**

EUTELSAT with the experience from older projects deployment (e.g. EDRS satellites) is deploying this year 5 LEO satellites in order to operate as an IoT communications network. Eutelsat's fleet of LEO satellites, called ELO (Eutelsat LEO for Objects), will offer global IoT coverage enabling objects to transmit data, irrespective of their location, demonstrating the fundamental complementarity between terrestrial networks and satellite technology in terms of M2M communications. The system in late 2021 will be consisted of 5 CubeSat nanosatellites around 500Km altitude in a form of constellation with maximum potential of 25 satellites within the next few years. [195], [196], [197]

Through ELO, Eutelsat's aim is to position itself as the partner of choice for IT integrators and terrestrial operators seeking to offer their customers worldwide coverage. Eutelsat has signed a strategic partnership with Sigfox, which runs a unique global narrowband network dedicated to this segment across 65 countries. Based on hybrid connected objects, whose data can be captured by both terrestrial networks and satellite, Sigfox will integrate the global coverage provided by the ELO constellation into its existing range of IoT connectivity services. This enhanced network coverage will open the door to many new use cases in areas like maritime transportation & logistics but also the safety of people in emergency situations. [196]

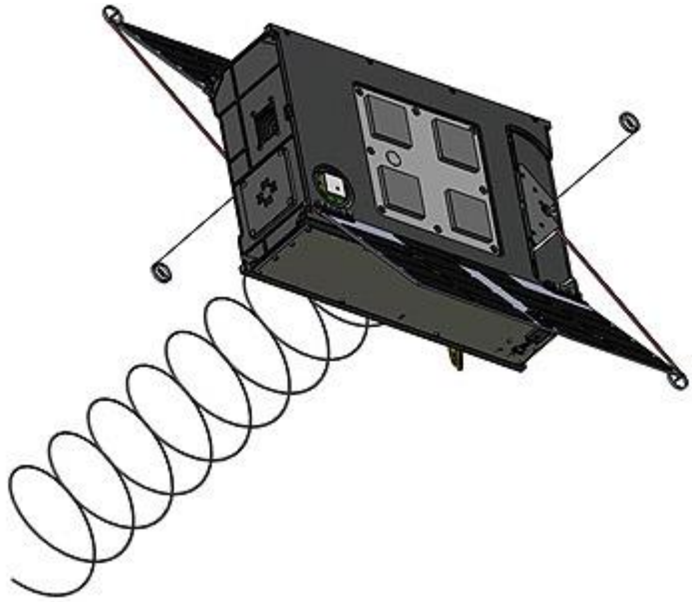

Figure 30: Artistic impression of ELO Alpha satellite [200]

In conclusion, there is a big number of elliptic orbit satellite systems that can offer directly and indirectly 5G services and as technology evolves new systems will appear (especially in LEO altitudes). We wanted to conclude in our research with satellite systems that are under deployment like Amazon's Project Kuiper and OneWeb LEO but due to lack of scientific reports we don't analyze them in this thesis. For further research we mention our discoveries in relevant scientific data in ESA's portal (e.g. [202]) and obsolete comparison studies in [187], [200] & [202].

TABLE OF TERMINOLOGY

TERMINOLOGIES	Ελληνικός Όρος
Standards	Πρότυπα Τυποποίησης
Quality of Experience	Εκτίμηση της ποιότητας υπηρεσίας που λαμβάνει ένας χρήστης δικτύου βάση αριθμητικών δεδομένων
Hardware Abstraction Layer	Συνοπτικός πίνακας πόρων υπολογιστή ή δικτύου σε γλώσσα μηχανής
Federation	Διασύνδεση πόρων ή δικτύων σε ομότιμο σχήμα, ομοσπονδιακού τύπου
Network Slice	Εικονικό τεμάχιο πόρων δικτύου για εκτέλεση συγκεκριμένων εφαρμογών (π.χ. Υπηρεσίες υγείας) σε λογική εικονικού δικτύου
Profitability Index	Δείκτης κερδοφορίας ενός δικτύου τηλεπικοινωνιών – Αναλογία ροής εσόδων από την λειτουργία ενός δικτύου προς το κεφάλαιο κατασκευής του (CAPEX)
Skewness	Συντελεστής ανισότητας στην μαθηματική κατανομή αιτημάτων σε έναν cache server

ABBREVIATIONS - ACRONYMS

IoT	Internet of Things
GEO - GSO	Geostationary Orbit satellite
RTT	Round Trip Time
VoIP	Voice over Internet Protocol telephony
SDN	Software Defined Networking
NFV	Network Function Virtualization
SDR	Software Defined Radio access
ESA	European Space Agency
LTE	Long Term Evolution networks
CAPEX	CAPital EXpenditures.
OPEX	OPerational EXpenditure
LEO	Low Elliptic Orbit satellite
MEO	Medium Elliptic Orbit satellite
3GPP	3rd Generation Partnership Project
ETSI	European Telecommunications Standards Institute
DVB	Digital Video Broadcasting organization
ACM	Adaptive Coding Modulation
RF	Radio Frequency
TDMA	Time Division Multiple Access
OFDMA	Orthogonal Frequency Division Multiple Access
PCRF	Policy and Charging Rules Function
API	Application Programmable Interface
OSS	Operational Support System
BSS	Business Support System
OSI	Open Systems Interconnection model
QoS	Quality of Service
QoE	Quality of Experience
OAM	Operations, Administration and Management interface
SNO	Satellite Network Operator
MNO	Mobile Network Operator
TNO	Terrestrial Network Operator
ROI	Return On Investment
IRR	Internal Rate of Return
ECC	ElliptiC Curve cryptographic algorithm
DTLS	Distributed Transport Layer Security protocol
B2C	Business-2-Costumer services
B2B	Business-2-Business services
BBR	Bottleneck Bandwidth and Round-Trip propagation Time
IETF	Internet Engineering Task Force
DLT	Web Download Time
VNCF	Virtual Network Coding Function
SWaP	Size Weight and Power reduction of a satellite

ANNEX

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