NETWORLD 2020

SATCOM WG

SatCom Resources for Smart and Sustainable Networks and Services

Version 1.0 25/11/2019

Contents

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Executive Summary

This white paper reports the **Research Challenges** that the Networld2020 SatCom Working group considers **strategic to be addressed in the next decade** in order to allow a **full exploitation of the satellite component** in support of the **Europe's ambition to deploy smart and sustainable networks and services** for the success of its digital economy.

In this scenario, the satellite component, also known as non-terrestrial network (NTN) in the framework of the 3GPP standardization development, has already been included as an important element in the 5G ecosystem. 3GPP Release 17 will see the normative phase for NTN thus enabling a full integration of the terrestrial and satellite layers in the 5G system. By working in full synergy, the two components will enable **unprecedented flexibility, adaptability, coverage, and resilience**. The concept of ***anywhere, anytime, to any device* is** therefore **now an achievable target**.

Looking to the future, the continuous development of new technologies and the huge increase in satellite interest and investment, witnessed in the recent time, have indeed **pushed the satellite communication potentialities towards higher limits that need now to be explored** to support the **efficient and sustainable development of new markets and smart services,** thus allowing Europe to maintain a driving role in this area also for future decades. From a pure broadcast and broadband delivery instrument SatCom is in fact becoming a fundamental tool to efficiently support new service such as IoT with its verticals, System Security and Integrity, System and Network Management, Critical Infrastructure monitoring and management, and so on.

In this perspective, the push towards new constellations, new orbits, innovative technologies, and low cost satellite production and launch have, on the one side, drastically increased the limit of the achievable performance and addressable markets and, on the other side, augmented the complexity of the system itself that has to be transparently integrated into the overall next generation global wireless system, i.e., beyond 5G or 6G system. To this aim, several main dimensions need to be fully addressed by the research and development activities in the next decades to ensure that this momentum is kept, and **the overall wireless community can benefit from the availability of such a powerful component as the SatCom one**. These new R&D dimensions are detailed in Section 3 of this white paper that represents the core of the document itself. In particular, the R&D actions that need full attention and full support by the Community have been identified in the following macro areas: **Spectrum usage**, **Radio Access Network for beyond 5G and 6G**, **Network function virtualization**, **Optical based Satellite Communications**, **Software defined payloads**, **Machine Learning for SatCom**, **New Constellations and system architectures**, **Antennas technologies**, and **Security**.

It is a firm belief of the entire SatCom Community, fully represented in the Networld2020 SatCom Working Group, that **the successful realization of future Smart Networks and Services can only be achieved by the harmonic development of several fundamental components one of which is now widely known to be the Satellite Communication one**. The research challenges reported in this white paper aim at supporting its development in order to enable all of the potentiality of a seamless integrated satellite and terrestrial infrastructure.

1 Motivation

Europe's ambitions to deploy smart networks will efficiently support the digital economy. The Communication on "Connectivity for a Competitive Digital Single Market – Towards a European Gigabit society" [1] sets out strategic connectivity objectives for 2025, which Member States are working on. It is necessary to invest in digital infrastructure to reach these strategic objectives and contribute to a balance between rural and urban developments, improve coverage in underserved/unserved scenarios (e.g., maritime and aeronautical), and, in general, broaden the market towards new sectors.

Satellite communication systems (SatCom) are fundamental components to help deliver reliably ICT (Information and Communication Technologies) services, not only across the whole of Europe, but also in all regions of the world, and at an affordable cost. Therefore, SatCom should be part of the future **smart networks**, where innovations are required to develop techniques/technologies to ensure also **sustainable ICT**: economically viable, eco-friendly and yielding social benefits. This document has been prepared by the SatCom Working Group of NetWorld2020 in order to present how the satellite community faces this challenge by identifying advanced research topics that need to be carried out.

1.1 Where are we now?

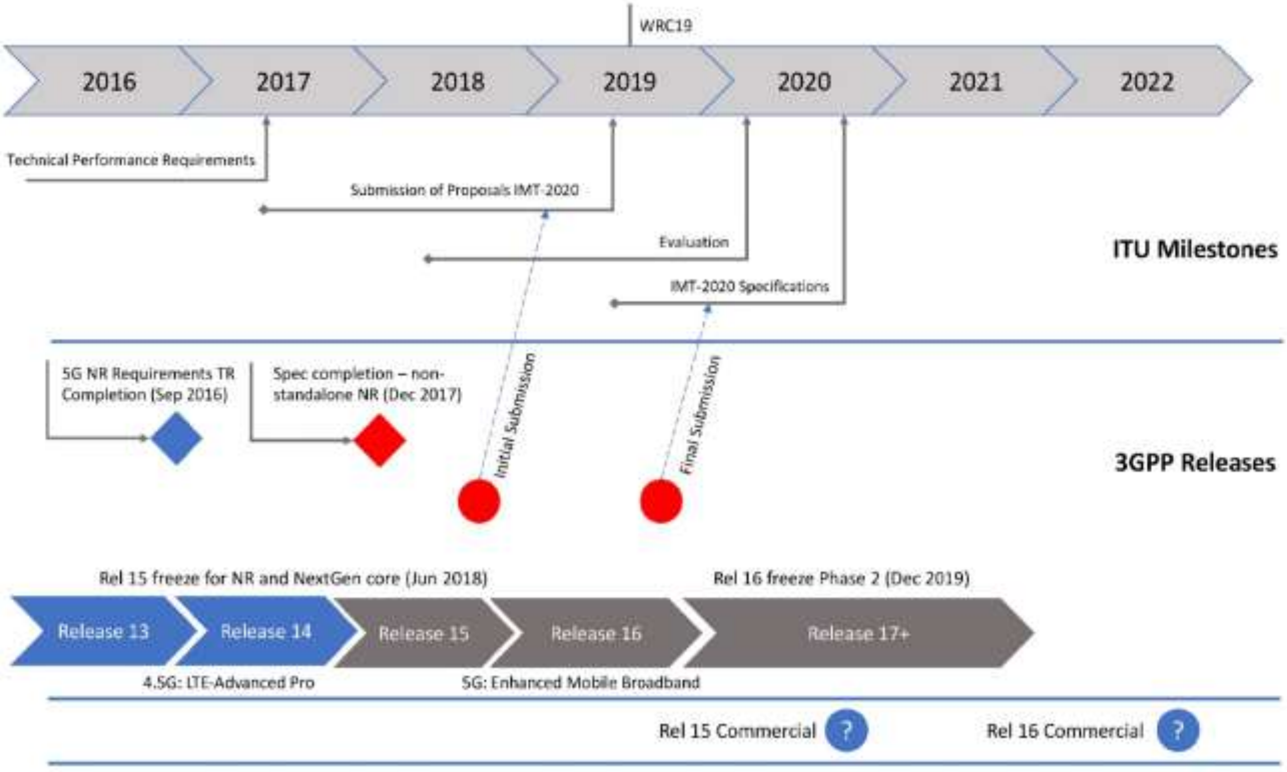

Figure 1. ITU and 3GPP Timelines for 5G
(source https://www.eletimes.com/5g-need-can-expect-see-action)

5G is inherently designed to be a network of networks that gives flexible support to a wide range of services and applications. 3GPP release 15 has now been fixed and is the basis of the first terrestrial rollouts. In release 16, the specification of the 5G system already includes requirements associated with the integration of satellite networks (and more generally, any NTN - Non-Terrestrial Networks) either for direct access between satellites and user equipment, or for transport between 5G Core Network and NR-RAN. By the end of 2021 (see figure 1), it is planned that release 17 includes specifications featuring the detailed integration of 5G non-terrestrial networks, and later release 18 will incorporate posterior technology developments into 5G.

1.2 Pointing to new horizons

In order to keep Europe's leadership in smart networks and services, it is necessary to address also long-term and disruptive research topics. "Future communication systems and networks (Smart Networks) are the foundation of the Human Centric Internet. They provide the energy-efficient and high performance infrastructure on which NGI (Next Generation Internet) and other digital services can be developed and deployed," [3]. Smart networks are a combination of smart connectivity, data analytics (AI- Artificial Intelligence and ML – Machine Learning), high performance distributed computing and cybersecurity. In other words, future cost-effective and sustainable communication systems and networks, both terrestrial and non-terrestrial, will increasingly be based on AI/ML and increased "softwarisation", in addition to requiring the continued development of classical communication technologies. Therefore, it is recommended to research future communication systems in close cooperation with these domains from an overall system perspective. The Strategic Research and Innovation Agenda in [3] summarizes the different research domains to make the overall vision of Smart Networks happen. The agenda considers the importance of satellite technologies as key to have ubiquitous communications and ensure service continuity, since it is forecasted that more than 80% of the traffic will stem from mobile users. Namely, the "anywhere, anytime, at any device" concept is certainly an added value that satellite technology can offer, not only in the specific scenarios where terrestrial connectivity is not available at all, but also to efficiently offload user contents without penalising the perceived QoE of users." The role of satellite technology will also receive an important boost to support the M2M/IoT (Machine to Machine / Internet of Things) market, which is in continuous growth and therefore enables new services in this context. More specific details about the various sectors, for which satellite technologies are expected to be further developed, can be found in [3]. The contribution of this white paper is the identification and detailed analysis of new avenues for research within SatCom. European research in this sector must be intensified in order to be able to point to the ambitious expected new horizons and keep up with their growth pace [4-8]. Some important (non-exhaustive) challenges are:

- Unique global network: Future non-terrestrial network components will be based on global 3GPP defined standards. 5G has been a perfect integrator at network level, however further developments are needed to build a fully unique global network providing smart, affordable and sustainable services on a global scale. One example is to have 5G UE types (e.g. for consumer and for vehicles) that will automatically hand over between terrestrial and non-terrestrial components, working both in indoor and outdoor environment. Another example is the average traffic density that SatCom can serve, which is limited due to the relatively large satellite coverages and the fact that other terrestrial capacity-enhancing techniques are difficult to implement over satellite links. Thus, the amelioration of these traffic density limits is a key part of the required development for Beyond 5G Satellite Communications systems (for instance, via MIMO – Multiple Input Multiple Output or, by very dynamic satellite link coverage and capacity modification).

- Ultra-High Throughput Satellites: Growth in data demand (driven largely by video customized to individual users, steered by analytics) is so extreme (current growth rates are exceeding 30%/year) as to render it unacceptable not be connected, even when remote or moving. The "Ultra-High Throughput Satellites" and upcoming large (>100's of satellites) constellations address this scenario. Most of the uses cases defined by ITU belong to the enhanced Mobile Broadband (eMBB) scenario. Achieving even larger capacity is the next milestone for satellite industry in Europe, to offer enterprises and citizens an even wider range of services. Some technology enablers (non-exhaustive) to make that happen will be: Q/V or optical bands, RF-Radio Frequency/optical conversion onboard satellites and on-ground, microwave photonics onboard processing functionalities.

- Mega-constellations: Last but not least, the recent technological innovation in the field of tiny microprocessor development and overall satellite payload miniaturisation has paved the way towards the definition of new operational concepts parallel to those assumed with classical LEO (Low Earth Orbit), MEO (Medium Earth Orbit) and GEO (Geostationary Earth Orbit) systems, i.e., building on small/picosats as well as cubesats. The revolution of the space segment started with large constellations should continue in the next years, which will enable: innovative IoT/M2M missions, which can support massive random-access schemes, and low cost/low consumption user terminals or, missions that complement global ones requiring ubiquity.

These and other challenges are described in detail in section 4. Note that if a possible long-term vision of the future global communication network is that it will not only enable connectivity, but its infrastructure will be used as a sensor that will infer state and meaning to augment humans and machines. The space segment will inevitably be one part of this next-generation network, which will be the nervous system that connects all by means of different tiers (i.e. space, aerial, terrestrial, submarine). To realize this vision, fundamental strong investment in research on the space segment is needed and not only focused on the very near-term solutions.

2 Societal and economic vision: Sustainability

ICT now drives how billions of people work, socialize, manage their finances, and take care of their health. However, one drawback of ICT is that it consumes unsustainable levels of energy. In fact, ICT has to evolve in the 21st century to reconcile economic growth with environmental and social objectives. SatCom on the other hand, can enable large reductions in global greenhouse gas emissions. Firstly, because a satellite by design lays on renewable energies during most of its lifetime. Secondly, because SatCom is key in the future IoT services to optimize process and corresponding energy consumption (e.g., smart metering, water management …).

Moreover, in the first strategic plan for Horizon Europe [2], six broad thematic "clusters" of activities have been identified to address the global challenges and European industrial competitiveness: 1) Health; 2) Culture, Creativity and Inclusive Society; 3) Civil Security for Society; 4) Digital, Industry and Space; 5) Climate, Energy and Mobility; 6) Food, Bioeconomy, Natural Resources, Agriculture and Environment. Note that SatCom can have a decisive role not only in 4), but in many others.

3 Challenges and potential solutions

From the vision introduced in previous chapters, the fields of research can be elaborated. Therefore, this section reports the Networld2020 SatCom Working Group perspective regarding the most important challenges to be addressed in the next ten years' time frame.

3.1 Spectrum usage

Rationale and challenges

Radio spectrum is a limited resource and the ability to access spectrum is critical to most commercial and government networked applications relying on wireless connectivity. The never-ending discussion for spectrum allocation for both satellite and terrestrial technologies is particularly motivated nowadays, for terrestrial networks, fed by the current and future needs of 5G network rollouts and, for the space networks, fed by the new contenders in the space sector represented by NewSpace actors and the rise of NGO (Non-Geostationary Orbit) constellations. In the course of identifying new mobile terrestrial allocation, space frequency allocations have been targeted. Discussion started in 2007, when 3,4-3,6 GHz has been identified for IMT (International Mobile Telecommunication) whereas this band was used for satellite operation. The process for repurposing satellite spectrum for 5G terrestrial networks was initiated at this period for this band such a trend has been extended to higher frequency bands following the conclusions of the different successive World Radiocommunication Conferences being held till the last one in 2019. In Europe a regulatory framework has been introduced by the CEPT/ECC to make the 3.4 to 3.8 GHz band available for terrestrial networks few years ago and was enforced in Europe in 2018 (Decision 2008/411/EC), which has already an impact on satellite earth station licensing in some countries.

While spectrum management policies are shifting from traditional "technology per band" approaches in order to leverage technology-neutrality, flexibility and user choice premises, the satellite industry has precious arguments to defend a key role in future spectrum allocation decisions, given its unique advantages to provide ubiquitous services and its indubitable success in managing RF interference in a complex environment for many years. The overall challenge is to develop new technologies and techniques that allow flexible and dynamic spectrum sharing, while ensuring reasonable licensing costs, international/regional harmonization and proper protection levels required due to the very specific nature of satellite's radiocommunication, obviously subject to the laws of physics.

Scope and activities

Cognitive Radio (CR) is a well-known advanced spectrum technique to enable dynamic spectrum management as it could in particular foster maximum spectrum usage in facilitating, for example, the opportunistic use of underutilized licensed bands. Within the satcom context, CR and other sharing mechanisms (ASCENT in [9]) have been considered recently for spectrum sharing in non-exclusive Ka and C-band segments between incumbent terrestrial backhaul links and the non-exclusive satellite links [10-11]. Coordinated spectrum sharing approaches have been considered also for other bands, focusing recently on licensed spectrum sharing mechanisms with the ability to control the number of accessing users and their parameters and to provide guarantees of non-interference for sharing parties. In the coming years, new research is needed to extend these spectrum sharing activities to properly address new frequency bands and new sharing scenarios, covering both uncoordinated and coordinated procedures and different stakeholder combinations, either vertical (e.g. terrestrial-satellite) or horizontal (e.g. between NGSOs). We consider of particular interest spectrum sharing techniques that allow i) seamlessly integrated satellite-terrestrial networks (including backhaul and fronthaul) to achieve optimum joint resources utilization, ii) coexistence among GSO and NGSO systems in high frequency bands (including small and short-lived missions) handling in particular in-line interference, and iii) accessing new available high-frequency bands (e.g. in 6 GHz, 24 GHz and 61 GHz) for satellite communications. New techniques enabling spectrum sharing mechanisms, such as NOMA or non-orthogonal multiple access, smart antennas [12a], interference cancellation, beam hopping, licensed spectrum sharing [12b] or NFV/SDN based negotiation and handling of spectrum resources, will make use at convenience of advanced ground-based and space-based radio access and management techniques to ensure systems coexistence.

Alongside spectrum sharing techniques, new technologies are needed to accurately assess in an independent way overall spectrum use and avoid harmful interference situations according to the increased complexity of the upcoming spectrum picture, characterized by a significantly higher number of actors and inter-dependencies among them. These surveillance and assessment techniques should also be able to support general and global spectrum sharing studies that help to explain the particularities of the satellite networks and the protection levels needed. This class of surveillance technologies could be represented by new capabilities on-board regular missions to monitor spectrum, new dedicated missions for spectrum monitoring and interference detection and geolocation (such as HawkEye), or new signal processing techniques, such as artificial intelligence or machine learning, that allow interference detection and classification, and blind separation of signals of interests and interferers, among others..

Outcome/impacts

The expected outcome is to secure proper spectrum resources for satellite communication missions within the upcoming context of flexible spectrum allocation approach and sharing fostered by international and national administrations. This will have a major impact in managing business risks associated with the large investments needed in the space sector. Furthermore, it will allow the creation of new business models, establishing alliances with terrestrial and/or satellite actors at convenience and improving overall competitiveness in the space industry resulting, ultimately, into significant users benefit.

The new class of spectrum management procedures needed is expected to make extensive use of current and upcoming advances on radio access and management techniques, both space-specific and related to generic 5G technologies. At the same time, it constitutes a cornerstone for the successful deployment of these techniques.

3.2 Radio Access Network: beyond 5G and 6G

Rationale and challenges

In recent years, Radio Access Network aspects have been deeply studied and discussed, in the framework of the NTN integration into the 5G ecosystems. Studies have clearly had an impact in 3GPP and shown the feasibility of such integration and the suitability of the terrestrial solutions to the characteristics of the non-terrestrial scenarios.

It has been shown that, with limited and acceptable modifications, the NR air interface can be adapted to the NTN case, thus introducing a completely new dimension in the overall 5G ecosystem. At the same time, it is also clear that the potentiality of the NTN component, considered in its widest sense as the combination of space-born and air-born platforms interacting in different orbits and with different constellations, can be further empowered by future research and development activities addressing those RAN aspects that can benefit from a design that takes into consideration the NTN strengths and peculiarities, from the very beginning.

In this context, the specific challenges posed by NTNs to the RAN design span all of the system elements, from the ground segment to the payload, from the design of the constellations to the frequency bands and spectrum usage.

Scope and activities

The new multidimensional and multi-layered communication architecture devised for 5G, which will find its full complexity in the Beyond 5G and 6G generations, will call for a drastic change in the air interface design paradigm that will see the flexibility, adaptability, and overall efficiency of the RAN design to become predominant with respect to the classical approach of spectral efficiency maximization.

Notwithstanding the need of exploiting every single hertz at its maximum, the research and development activities related to the Radio Access Network shall focus on the design of techniques able to flexibly and dynamically adapt to different requirements, scenarios, and conditions by maintaining at the same time extremely high spectral and energy efficiencies. In particular, the introduction of GSO and NGSO constellations, active antenna payloads, aggressive frequency reuse call for a RAN design aware of the peculiarities of the NTN component so as to satisfy the overall system KPIs.

Also, for those scenarios where the system requirements call for a shift from a bent pipe to a reconfigurable and regenerative payload approach, it is of a paramount importance to address the design of highly reconfigurable RAN techniques that, thanks to Software Defined Payloads (see the Software defined payloads section), allow the NTN component to adapt to the ever-changing communication scenarios without the need of costly updates of the flying nodes.

The support of multiple logical networks, and even multi radio access, increases the complexity and requires enables as AI/ML in cooperation with data mining solutions (see the Machine Learning for SatCom section).

Expected outcomes or impact

The expected outcome is the design of a unified air-interface that can provide connectivity in an heterogenous environment, where users may access the network through terrestrial and satellite links, and a reconfigurable radio access network that can be dynamically adjusted to changing conditions and requirements and ease the co-existence of different services. The expected outcome related to radio access network opens new research avenues. As it is summarized in [13], the research and development activities addressing the Radio Access Network of the Beyond 5G and 6G future systems shall provide support for:

- Space-borne and air-borne integration;
- GSO and highly NGSO constellations (down to vLEO for the space-borne platforms) ;
- Multilayer integration and handover;
- Multi NTN system integration;
- Highly flexible and adaptable air interface for reconfigurable, regenerative, and software-defined payloads;
- Advanced Radio Resource Management algorithms to allow satellite beams to overlap terrestrial cells and also a seamless terrestrial-satellite integration;

- Interference management techniques for frequency aggressive multibeam and multi-layered systems;
- Suitable non-orthogonal access schemes (e.g. allowing massive IoT access to LEO satellites, requiring low signalling overhead, …)
- Predictive system reconfiguration and resource orchestration for energy-efficient traffic delivery, resilience, and security;
- Centralized and distributed ground system gateways;
- Integrated access and backhauling in the space;
- Intra and inter-system spectrum management.

3.3 Network function virtualization

Rationale and challenges.

To really allow the satellite systems to be a component of the 5G network and to be considered one of the possible solutions to guarantee connectivity and best performance, as well as other technologies, it is strictly mandatory to develop all the functions necessary respecting the NFV paradigm and 5G standard [14].

The adoption of a NFV framework standardizes the reference points along which the components interact among one another. In addition, it natively supports service chains, providing the basis for the decomposition and provisioning of complex network services via a series of interconnected network functions, where each of which could reside in a different, either virtual or physical, machine of the network.

Scope and activities

The scope is to design and implement a number of functions realising also a service chaining which is achieved by constructing a forwarding graph interconnecting network functions in the NFV layer, the so-called Virtual Network Function Forwarding Graph (VNFFG). This concept is analogous to the IETF Service Function Chaining (SFC) standardization effort (several proof-of-concept solutions have been explored in the literature. A detailed, but absolutely non-exhaustive list of virtualised functions to be developed to make the satellite network fully compliant with 5G architectures is the following: Transport Layer Optimization VNF, Deep Packet Inspection as a VNF (DPI-VNF), Adaptive CODEC box, Bonding proxy, Virtual Cache, Virtual PEP. More ambitious virtualisation research could address the SatCom mission segment functionalities enabling higher degrees on automation allowing the instantiation of satellite resources, enabling e.g. multi-tenancy schemes and secure SatCom infrastructure “virtual” fragmentation providing enhanced and more accessible SatCom resource allocation and usage.

Expected outcomes or impact

The outcomes of these activities are expected to be the availability of virtualised functions to be utilised by service providers and virtual telecom operators (agnostic from technological point of view but wishing to achieve the best performance guaranteeing to meet user requirements) installed on servers along the network infrastructure, ready to be instantiated when needed. The impact will be an increased use of the satellite segment because no longer depending on the capability to convince content providers, OTT, telecom operators that they need the satellite but on the optimization of network management algorithms which will actually utilise the satellite when this really improves performance and increases efficiency.

The development and deployment of networks based on virtualised functions which will include the satellite segment among the possible technology to be used to provide efficient services due to the introduced flexibility will also unleash new business cases for virtual operators. In fact, it will be possible to set up complex networks optimised on specific services satisfying the relative requirements and QoS transparently for the final user who may not be aware to use the satellite but will just enjoy the performance improvement.

3.4 Optical based Satellite Communications

Rationale and Challenges

High Throughput Satellite (HTS) systems are necessary to provide 5G data services in geographical areas where terrestrial networks are not available. To achieve aggregate data rates of few Terabit-per-second in future networks, a very large number of spot-beams with aggressive frequency reuse are needed for RF access. In this situation, the feeder link becomes the bottleneck of the HTS system, as it must transport the aggregate data rate of the RF spot-beams. Different solutions have been proposed to address this problem, such as adding new RF spectrum for the feeder link, deploying multiple satellite gateways on different geographical locations, and using optical wireless technology in the feeder link. This section focuses on the latter option, known as Optical Feeder Link, due to the following reasons:

- **Wider EM spectrum.** The achievable data rate in a point-to-point optical wireless link can be few orders of magnitude larger than with an RF wireless link.
- **License-exempt.** Optical wireless systems do not require a license for operation.
- **Interference management.** The propagation conditions of the optical wireless channel, as well as the high directivity gain of the optical wireless transmitter and receiver telescopes, mitigates notably the interference that is generated in ultra-dense deployments.

The design of the optical feeder link depends on the approach that the HTS system uses to forward the information that is received from the gateway. In the *"ideal"* case of a **fully regenerative payload**, the optical feeder link terminates in the satellite; therefore, robust Forward Error Correction (FEC) can be used to correct the long burst of bit errors that the turbulent optical satellite channel introduces. Moreover, this approach enables the implementation of advanced signal processing mechanisms on-board the satellite, such as beam precoding, enabling higher spectral/energy efficiency. In contrast, the fully regenerative payload demands the highest processing power on-board the satellite and gives limited flexibility to adapt to modifications on the communication standard during the lifespan of the HTS system. Therefore, transparent non-regenerative *"bent-pipe"* solutions should be initially implemented regardless if they are analog or digital transparent.

In the **analog transparent** payload, the instantaneous value of the RF signal modulates the Intensity of the feeder link Laser Diode (LD). On the other hand, in the **digital transparent** payload, I/Q components of the baseband radio signal are oversampled and quantized to guarantee an acceptable Signal-to-Distortion Ratio (SDR). After that, the resulting sequence of bits modulates (digitally) the optical carrier of the feeder link. In the digital transparent payload, only limited signal processing capabilities are required on-board the satellite to reconstruct the complex-valued I/Q baseband signal; moreover, Forward Error Correction (FEC) can be used to protect the transmission against the impairments of the optical turbulent channel. Unfortunately, the digital transparent approach limits the aggregate data rate that the HTS system can support, as the digitalization process expands *many times* the original bandwidth of the complex I/Q baseband signal that wants to be transported.

Scope and activities

The most practical approach to implement the analog transparent optical feeder link consists in multiplexing the RF signals intended to the spot-beams of the HTS on a different wavelength in the infrared spectral window (1064/1550 nm). This Wavelength Division Multiplexing (WDM) solution enables high flexibility due to its channel scalability: The denser is the channel spacing of the optical grid, the larger is the number of satellite RF signals that can be accommodated over the same optical feeder link. For example, typical dense WDM systems in the C-band (1525-1565 nm) can accommodate 40 (80) optical channels at 100 (50) GHz spacing. For ultra-dense WDM solutions, 25/12.5 GHz spacing is also possible. The C-band offers a bandwidth of more than 5 THz and, when compared to the 1064 nm window, it has less background light and is more resistance against turbulence.

In the analog transparent optical feeder links, the effect of atmospheric perturbations can only be mitigated at the PHY-layer. The random turbulence that exist in the atmosphere leads to wave-front distortion and scintillation. For the uplink, the smaller aperture size of the receiver telescope leads to deep turbulence-induced fading events. For the downlink, the spatial dissemination of the received beam creates a similar effect after coupling the received optical signal into a Single-Mode Fibre (SMF). Different techniques exist to mitigate the effect of turbulence, such as:

- **Transmit micro-diversity schemes**: Deploy multiple transmitters, carrying the same information, with a separation proportional to the transversal coherence gain of the atmosphere. This way, optical beams are affected by a different turbulent section of the atmosphere, averaging out the effect of deep fading. The total optical power also grows.
- **Adaptive Optics:** Consists of a deformable mirror that compensates the distortion of the received optical wave-front after propagating through the atmosphere. This way, the received optical beam can be better focused into a SMF with a good coupling efficiency.
- **Macro-diversity schemes:** Consist in deploying a network of geographically spread satellite gateways, such that the probability of having at least one satellite gateway that is not covered by clouds is very high (typically, 99.9%).

So far, RF technology has been used to implement an over-dimensioned satellite feeder link, such that the End-to-End (E2E) performance was mainly limited by the RF wireless access. However, if optical wireless technologies are used to implement the feeder link, the effect of the (optical) non-linear distortion and noise that are added should be considered when dimensioning the links of the HTS system. For example, pre-distortion and post-distortion compensation could be applied on the RF signals at both extremes of the satellite link, such that the non-linear distortion and noise that are added by both optical and electrical components of the resulting Optical/RF transmission chain are jointly compensated.

Expected outcomes or impact

The main expected outcome is to identify a unified technology for the implementation of the optical feeder link. So far, mostly theoretical studies have been reported on the literature on the different implementation approaches. Nevertheless, if a common standardized solution is found in a reasonable time window, large-scale experimental trials could be later organized, paving the way to a full implementation of the technology in an operative HTS system. This way, a giant leap will be taken to integrate the satellite segment into the Beyond 5G landscape.

Once the implementation approach of the optical feeder link is defined, different signal processing methods to mitigate the impact of the impairments introduced by the optical components of the feeder link, the electrical components of the access link, and the different effects that the atmosphere creates on the optical signal mainly (*i.e.*, turbulence, particles, etc.), should be also taken into account. For this purpose, a consensus on the requirements and implementation limitations should be clearly defined, including the use-cases in which the HTS systems will be involved and the KPIs that should be maximized.

3.5 Software defined payloads

Rationale and challenges

One of the concepts that is revolutionising the infrastructure of current communication systems is the so-called Software Defined Radio (SDR) technology [15]. In short, SDR refers to a radio communication system where the major part of its functionality is implemented by means of software. The advances in this software disruptive paradigm is currently reinventing future network architectures, accelerating service deployment, and facilitating infrastructure management. Satellite communications are not an exception. The main advantage that SDR brings to the satellite is the capacity of adaptation which has been identified as a crucial characteristic of the future broadband systems. By replacing as much hardware as possible with software, the satellite payload becomes much more flexible and allows to deliver cost-competitive connectivity in response to evolving consumer demand and price expectations.

Scope and activities

SDR-based payloads become more flexible and automatically reactive, able to face the dynamicity envisaged in the forthcoming wireless traffic. Also, this opens the arena to the flying base station concept, where, by exploiting the functional splits of the 5G RAN architecture, parts, or all, of the access stratum protocols can be terminated to reduce the latency and to potentially simplify most of the access layer procedures.

The ability to reprogram beam pattern, frequency and power allocation dynamically at any time during the satellite mission, has made SDR technology very attractive to the satellite community, whose data markets have recently become more uncertain [16-17]. These capabilities open a door to advance resource management strategies for satellite communications [18-19], but at the same time bring new research challenges. In particular, the new on-board processing capabilities combined with the emerging role of active antenna systems, require advanced resource management techniques capable of maximizing the satellite resource utilization while maintaining QoS guarantees, and dynamically matching the distribution of the satellite capacity on ground to the geographic distribution of the traffic demand and following its variations in time.

Different orbits require different flexibility. GEO satellites have to be in operation for several years, thus “softwarization” shall focus on the capacity of adaptation. In lower orbits, much more processing can be applied as those satellites can be more easily updated by adding new satellites to the constellations.

Expected outcomes or impact

SDR-based satellite systems bring important improvements from a network management point of view, by allowing a better orchestration of the satellite resources. Unavoidably, "softwarization" will expand to the whole satellite ecosystem, replacing the custom hardware solutions, resulting in a more flexible and dynamic system with overall better performance and efficiency.

3.6 Machine Learning for SatCom

Rationale and challenges

The NewSpace economy is primarily dominated by the necessity of substantially reducing the operational costs of satellite systems. This fact involves rethinking the entire set of space operations from both ground and space segment. Similarly, to other industries (e.g. automotive), satellite communication stakeholders are targeting a digitalization and automation of many functionalities currently managed by engineering experts. For instance, managing unintentional interferences constitutes one of the major time consuming and; thus, expensive roles of the satellite control centre [20]. Reducing the time-to-react of interference events by automating its detection and classification represents a relevant cost reduction and quality-of-service increase to the satellite customers.

New satellite technologies will also require their proper automation with the aim of being competitive in the global internet access. In particular, the deployment and management of mega-constellations presents a challenging multiagent problem. These systems do not only present issues on the possible collision of different space elements, but also its radiofrequency emissions which may cause interference to other GEO or NGEO systems. In this context, automating system level decisions is a must since human intervention might be very difficult. Artificial intelligence allows fast decision-making even in millisecond timescales in order to meet full potential of integrated systems consisting of space-borne, air-borne and terrestrial components. This could include predictive spectrum allocations, predictive routing, and even autonomous replanning at the satellite without the delays introduced by the decision-making loops on ground.

Considering the above discussion, we think that satellite communication industry is dealing with a short-term automation process of already launched systems and a medium/long term technology development of forthcoming systems based on GEO and NGEO satellites. Although some of the functionalities of the mentioned systems could be tackled by rule-based tools (e.g. if A then do B else do C), other mechanisms would require the use of machine learning techniques. In the following, we provide some examples of potential usages of machine learning in SatCom.

Scope and activities

While spectrum sensing signal processing approaches have been studied and deployed during decades, certain interference detection aspects that appear in satellite operations would require additional approaches. For instance, in band interference or intra-system interference which consists of having the same signal duplicated in the same frequency bin. For these spectrum monitoring scenarios, the use of deep learning could potentially allow the detection of a variety of spectrum events [21]. Once the interference is detected, satellites being launched this year will have the capability of reacting to this situation in order to meet the customer service level agreements. This involves to judiciously change the frequency allocation, transmit power and beamforming of the satellite payload. Although an operator could try to provide a new configuration based on the location of the undesired interference and the affected bands, an automated system able to configure the payload will reduce the time-to-react. This configuration update can be based on genetic algorithms [22] with a potential support of deep learning regression techniques [23].

Finally, mega-constellation systems offering capacity to mobile users such as vessels and airplanes have to tackle a two-level dynamic environment: the satellite and the user terminals. This varying system has to be able to deal with potential hotspots beams (i.e. a coverage area which a high demand) that change over time and satellite. Although a classical data fusion between satellite and user terminals trajectories may help in detecting these hotspots, demands and motion present a stochastic nature which could be tackled via data-driven algorithms. In other words, the past detection of hotspots may support the inference of future ones.

Impact

As a general statement, the adoption of machine learning mechanisms by the SatCom industry aims to increase the efficiency of current systems by reducing the operational costs and the processing time of certain operations. At the same time, in the future systems it is envisioned that some functions, due to its complexity, will not rely on classical operations but on data-driven techniques.

The digital transformation of the satellite industry will allow to discover new potential opportunities. Having an easy access to data sources will promote the creation of innovative SMEs and innovation departments in big companies able to provide data-based solutions to unexplored SatCom aspects.

3.7 New Constellations and system architectures

Rationale and challenges

Microelectronics (MEs) and microsystems technologies (MSTs) contribute to reduce the size of satellite hardware components, both the primary ones, such as engine, attitude control, battery, antennas, and the payload ones, such as sensors. MEs and MSTs allow also decreasing satellite mass, getting power savings, and increasing flexibility as well as robustness. Size and weight of used satellites are much smaller than in the past. In addition to GSO satellites, there are NGSO satellites called micro, nano, and pico satellites whose main advantage lies in the lower cost, low communication latency, low energy consumption, and high fault tolerance, if the employment of tens of small satellites at the same time is considered. These aspects make small satellites appealing for many application scenarios such as Earth monitoring, disaster recovery, remote surveillance, M2M, IoT, especially if the devices are in rural and remote areas (e.g., see the works in [24-29]). The IoT via satellite can enable ubiquitous connectivity platforms with the capability of providing massive connectivity even in the most remote/inaccessible places at the lower costs. In this direction, looking forward a little bit more, Internet of Space Things (IoST) represents a wider-scale cyber-physical system spanning over the air, space and ground. Thanks to technological advances and due to the need of matching a wide variety of application scenarios, also in view of future 5G, next generation SatCom architecture should be capable of supporting GSO and NGSO satellites operating in different constellations but also including other aerial networks such as HAPS and UAVs. Additionally, employing SatCom networks in order to support the terrestrial ones and to overcome their limitations is one of the key solutions to increase the offered coverage and network throughput, both as requirements to match the rapid 5G ecosystem growth. In this view it is important to consider the ground segment as well as including key paradigms such as SDN, network function virtualization and network slicing.

Scope and activities

Cooperative NGSO satellite swarms enabled by intersatellite links

Due to the interest of low latency on some applications, there is a growing trend of deploying very large NGSO constellations such as OneWeb, SpaceX, LeoSat and O3b mPOWER,. Inter-satellite data exchange via inter-satellite links will be implemented soon thanks also to uprising technologies. A laser-connected optical backbone connecting numerous NGSO satellites across different orbits can be considered as a promising future satellite architecture to deliver a highly reliable and secure global SatCom network for various business operations in telecommunications, government, energy, aeronautical and maritime applications.

Hierarchical Aerial Networks (Satellites + HAPS + RPAS)

Remotely Piloted Aircraft Systems (RPAS) and and HAPs provide low-cost support for a large class of applications and can be used both individually or as a swarm. Using multiple UAVs and/or HAPs needs coordination and data exchange services among them, leading to a multi-layer hierarchical infrastructure known as Space Information Network (SIN). SINs are complex network infrastructures relying on heterogeneous network segments implemented by space platforms, such as satellites, UAVs, HAPs, and airships. They can play a key role in many different applications: connectivity for otherwise disconnected areas, emergency communications, environmental monitoring, mMTC (massive machine type communications), IoT, and interplanetary communications, to cite a few. In cooperative distributed SINs, future research directions include the development of novel algorithms/techniques for distributed gateway-selection, cloud-based stability control, mobility modelling, energy-efficient maximization, and security and safety enhancement.

Internet of Space Things / Planetary Communications (Moon Village)

With the recently increasing interest in exploring Moon from NASA and ESA, the concept of Moon Village may become reality in the coming 5-10 years, with the objective of carrying out different projects on the lunar surface including astronomy and mining operations carried out jointly by robots and humans. A stable human presence on the Moon will require a high data-rate link to the Earth that leads to some serious challenges to be solved. An example is related to the routing challenge. Possible routing paths between sources and destinations may include satellite links that are not all active at the same time. This requires the ability to store data onboard satellites for long time periods waiting for the next possibility to forward them. This can be addresses by the Delay and Disruption Tolerant Networking paradigm (DTN). However, different satellite design limitations, especially considering small satellites, such as the limited capacity of energy storage and recharge can hinder the data through long-distance interplanetary satellite links. Smart routing strategies that help reduce data delivery time and take into consideration the strict resource constraints are crucial to allow users to receive data respecting Quality of Service (QoS) requirements.

Push the limits of NGSO and GSO terabit systems to scale according to their terrestrial counterparts (decreasing the cost per bit is more important than ever, to incentivise the integration) also considering the ground segment.

The main challenges faced by today's satellite systems are scaling to VHTS systems (mainly system complexity and cost due to many gateways), the reduction of cost per bits/seconds, and the integration of SatCom systems in the 5G network standards and interfaces. Data exchanges through satellite links should exploit higher frequency bands, such as Q/V frequency bands (33÷75 GHz), even if the attenuation due to rain and clouds is significant at these frequencies. The concept of Smart Gateway Diversity can be employed to overcome this issue. The integration of satellites in the 5G ecosystem will bring opportunities for different use cases including trunking and head-end feed, backhauling and tower feed, communications on the move and hybrid multi-play. In the same time, it makes essential to consider both Gateway and User Terminals, both separately and together as a system, to assure given QoS requirements. Some promising enablers in this regard include smart gateways with the capability of performing virtualization of gateway functions, onboard processing, flexible high throughput payloads, digital twins, machine learning, SDN, network function virtualization, mega-LEO constellations, GaN technology, edge caching, edge computing and cognitive SatCom.

Expected outcomes or impact

The potential impact of satellite networks in this described ecosystem composed of new applications developed in a plethora of scenarios is linked to their intrinsic ubiquity and broadcasting capabilities. Satellites can act as a main single backhaul segment for rural areas, aircraft, vessels, and trains; as additional backhaul means to opportunistically provide additional connectivity/bandwidth resources, also improving service continuity; or as a pure transport subnetwork. Associated outcomes are in the field of Smart Cities, Smart Industry and Smart Farm.

3.8 Antennas technologies

Rationale and challenges

The next generation of satellite communication systems requires a paradigm shift in the field of antenna technologies. Whereas current solutions are mainly based on relatively small reflector antennas with fixed beam patterns, future applications will necessitate the use of larger and/or more flexible antennas. These innovative technologies will especially enable the generation of narrower beams for a more efficient use of power and spectral resources. The steerability of the beams will also play a key role to cope with the dynamicity of the traffic demands and avoid interference between different systems (GEO/non-GEO, satellite/terrestrial).

Scope and activities

Active antenna arrays

Direct radiating arrays (DRAs) and metasurface antennas offer the flexibility required for future systems [30]. Whereas DRAs rely on many low gain active elements (including power amplifiers and phase shifters), metasurface antennas exploit artificial materials whose properties can be modified to produce a desired radiation pattern. An advantage of metasurfaces over typical DRAs is their lower power consumption and cost. It should however be mentioned that advanced approaches for the design of DRAs (e.g. sparse arrays) have been proposed to improve the power efficiency and reduce the costs of DRAs. The reconfigurability of such antennas is advantageous for the ground segment design where the availability of low-cost electronically steerable antennas, instead of complex mechanically steerable reflectors, will be of paramount importance for the economic success of mega-constellations in the next decade. These technologies will also impact fully flexible GEO and non-GEO satellite payloads with the ability to create a given beam response and support null-steering in any direction and at any time. As an example, in place, O3b mPOWER represents a step change in capabilities for satellite-based high-speed low-latency data networking—a shift from the few mechanically steered beams per satellite in previous systems to large phased arrays with thousands of electronically steered beams per satellite. While early-generation HTS satellites have an aggregate capacity of under 20Gbps, each O3b mPOWER satellite has 10 times greater capacity, delivering a terabit-level constellation that scales as more satellites are added. Full use of the Ka band along with tight tracking beam footprints, spectrum reuse and adaptive resource control drive bandwidths to support growth over the next 10 years or more.

Large apertures

Some use cases in next-generation systems will also require the generation of very narrow beams (e.g. to form extremely small mainbeam footprints from a GEO very high throughput satellite). Here, large deployable reflector antennas (~5-30m diameter) represent an appropriate solution [31]. In the coming years, this technology will be mature enough to support frequencies up to the Ka-band. Moreover, the structure of such large antennas will allow a reconfiguration of their shape to adapt the coverage during the operational lifetime of the satellite. However, the maximum diameter of large deployable antennas will be limited by size and weight constraints. If footprints of only a few kilometres must be obtained, a different approach will have to be considered to form a larger effective aperture. Cubesat swarms are in this case a promising approach [32]. They consist in the deployment of a large number (>100) of small spacecrafts flying in formation to obtain a coherent antenna array of up to several kilometres in diameter. A distributed array is also advantageous in terms of maintainability, scalability and flexibility as elements can be independently added or removed without significantly affecting the system operation. The principle of distributed coherent arrays will also be of interest on ground to build feeder link gateway stations with small aperture antennas instead of using an expensive single large aperture. Meanwhile, due to the challenges still encountered in the design of large-scale distributed arrays (e.g. time and phase synchronization,), technological maturity will only be reached within the next decade.

Multiple antenna technology

Finally, since future systems will mainly use spatially separated antenna elements on Earth (gateway stations, users in a multibeam coverage) and in space (antennas on one or several payloads), advanced spatial multiplexing approaches will be used to improve spectral efficiency. The approach which is known as the multiple-input-multiple-output (MIMO) scheme enables to transmit independent signals in the same time and frequency resources [33-34] and is already widely used in terrestrial networks.

Expected outcomes or impact

The development of new antenna designs will be a key enabler for the seamless integration of satellites in existing and future wireless networks. In a digital world where connectivity anytime, anywhere will be required, flexible beam steering will allow the operators to effectively respond to the traffic demands whereas end users will be able to benefit from high speed and lower latency connections with non-GEO satellite constellations. Innovative design methods and mass production are expected to significantly reduce the costs of adaptive antennas.

On the other hand, on-going activities in the domain of large deployable reflector antennas have also brought advances which will impact in the coming years the design of GEO ultra-high throughput satellite systems for which high power density and/or very small beams will be required. To further increase the effective aperture size, cubesat swarms also appear as another promising solution. Their technical maturity will however only be attained on a longer-term perspective.

3.9 Security

Rationale and challenges

There is a potential for running large number to applications and services over a hybrid satellite and mobile networks. Therefore, it is not enough to just provide end-to-end security at the application layer (such as encrypted video stream at the application layer).

Scope and activities

Here some potential security topic for future satellite Communication:

Satellite and future mobile networks security integration

An example of future mobile networks is the 3GPP 5G system. There is a need to address the security interworking between the two systems (satellite and future mobile networks). 3GPP defines three interfaces for native 5G and non 5G access networks:

- 5G native interface with 5G-AKA (Authentication and Key Agreement) procedures: This means tighter satellite integration into the 5G security system.
- Non-3GPP Interworking Unit (N3IWF): Satellite will use a recently defined EAP-AKA procedures. This implies looser security integration than 5G-AKA.
- Trusted non-3GPP gateway function [37], which fits between 1 and 2 and, from the operator perspective, can be very attractive to research for market introduction.

There is a need for detailed security analysis of the two scenarios above, supported by simulation/emulation or real-life demonstrators.

Blockchain Technology (BCT) for secure SatComs

Most of the previous security studies focused on key management authentications and routing protocols. BCT is a decentralized and distributed database invented by Satoshi Nakamoto in 2008 and used widely in digital currency. The main property of BCT is, it provides and authenticated record of history of changes such as configuration and re-configuration history of the satellite and space information network. Therefore, there is need to explore the advantages BCT in future satellite networks such as resilience to DoS, DDoS and insider attacks. Also BCT challenges should be examined as well, such as the BCT database storage and distribution for all satellite nodes in the network.

Quantum Key Distribution (QKD) and key management over satellite

a) Quantum adds to security: Quantum Communication changes the paradigm with respect to current secure communication standards, making the transfer of information secure for long-term requirements and protecting against potential attacks, including those expected from quantum computers [35-36]. QKD consists of the distribution of secret keys in a way that is information theoretically secure. QKD is now a mature quantum communication protocol which allows the verifiably secure sharing of encryption keys between two communicating parties. The “prepare & measure” protocol reached commercial-maturity level on ground fibre links and is currently under development for space channels.

Future more challenging “entanglement based” protocols eliminate the need for secure nodes and pave the way to a more generic communication means, generally called ‘quantum information networks’, that can offer applications beyond quantum cryptography. In other words, the is a need now to expand the QKD key-management aspects such as access control, primary and secondary communication security key derivations and key lifecycle management.

There has been a series of proof-of-principle demonstrations of satellite-based quantum key distribution in 2017. The space segments supporting these QKD system are expected to unlock the implementation of other relevant quantum communications applications beyond quantum cryptography, for instance in distribution of time, metrology and distributed quantum computation, besides fundamental investigations.

b) Security needs certification/accreditation: Standards need to be defined and certification procedures developed by the relevant agencies on both national and international levels. Moreover, quantum and classical security concepts need to be combined and assessed in a single framework.

c) Secure communication needs a system: The design of a secure communication requires a complete system including space and terrestrial components. On ground, fibre-based solutions will offer short-range secure communication. Satellite-based quantum communication will provide the mandatory means for reaching global distances and secure space assets.

The deployment on ground of receiver of keys to be used in pan-European as well as national secure communications will be the most immediate results of such Space QKD system.

d) A roadmap for space-based secure quantum communication: Quantum communication should be implemented on a practical and reliable platform to provide world-wide secure communication for European assets. As time for implementation and service of usual satellite-based systems goes well beyond a decade, and the threat of a future quantum computer has to be taken into account in the same time-frame (even sooner in case of retroactive decryption), the urgency of a QKD solution is striking. The already engaged roadmap for developing space optical communication systems is a solid base enabling space QKD solutions.

Standardisation and certification efforts have to start in parallel to the development of the operational systems. The development of the operational systems serves both as an input to this process as well as later standards and certification requirements will steer the development.

e) R&D on security, quantum concepts, system concepts: In addition to the concrete operational developments, research and development is needed in interdisciplinary topics. These include the development of high-rate QKD payloads, advanced pointing systems, low loss space-to-ground links, also based on adaptive optical systems, and intersatellite links.

Moreover, we aim at the exploitations of quantum functionalities where a provable advantage can be shown and that require current or near-term quantum technology (quantum random number generation, quantum communication complexity protocols, quantum crypto primitives like position verification, oblivious transfer, coin flipping, anonymous message transmission, leader election, and secret sharing, distributed computing tasks like delegated quantum computing).

The exploration of QKD protocols using different photonic degrees-of freedom (frequency, time bins, polarization, orbital angular momentum, ...) will require advanced security analysis and the development of frameworks enabling new, affordable and practical services and highest security applications and a variety of new applications involving time, position, navigation and much more.

Secure multicasting over satellite

Multicasting is an important use case in satellite and future mobile networks such as using Multi-access Edge Computing (MEC) platform for Content Delivery Network (CDN) integration with efficient edge content delivery. Assuming that the current multicasting technical challenges in mobile networks are resolved, then secure multicasting should also be analyzed in details such as group key management and access control. ESA has previous studies on secure IP multicasting over satellites. Therefore, the secure group communications should be re-examined in the context of interworking in hybrid satellite and future mobile networks environment.

Expected outcomes or impact

Secure satellite communications will strengthen the competitiveness of the European space sector on the global market. At the same time it will support the integration of space into European economy and society, and it will increase European autonomy in using space.

The development of a Quantum Communication Infrastructure (QCI) will in a first stage secure government and critical infrastructure communication across the European Union, and in a second stage prepare the connection of quantum computers and sensors in a full Quantum Information Network; namely:

- providing an unprecedented way of securing communications, adding physical security to the current algorithm security).
- contributing to the development of the new ecosystem of quantum technologies, which will be key for the strategic autonomy of our Union).
- being the first step towards a completely new information exchange through Quantum Information Networks, which will enhance the performance of processors and sensors, and will allow creating in the long term a wide range of commercial applications).

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