Sustainable Satellite Communications in the 6G Era: A European View for Multi-Layer Systems and Space Safety

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Abstract—During the New Space era small countries are also becoming more important players in the space business. While the space activities are rapidly increasing, it is important to make operations in a sustainable and safe way in order to preserve satellite services for future generations. In this survey paper, we discuss the multi-layer networking approaches in the 6G era specifically from the sustainability perspective. We review the most important regulations and international guidelines and revisit a three-dimensional architecture vision to support the sustainability target for a variety of application areas. We then classify and discuss space safety paradigms that are important sustainability enablers of future satellite communications. These include space traffic management, debris detection, environmental impacts, spectrum sharing, and cyber security aspects. The paper discusses also advances towards a planned European connectivity constellation that could become a third flagship infrastructure along with Galileo and Copernicus systems. Finally, we define potential research directions towards the 2030s.

Index terms - Low earth orbit satellites, Radio spectrum management, Aerospace engineering, Spaceborne radar

I. INTRODUCTION

The two main disruptions driving the development and rapid growth of satellite communications (SatCom) are increasing satellite constellations sizes and integration of satellite and terrestrial networks. The former also aims to provide broadband services to currently underserved areas with improved performance. The latter is related to the evolution of mobile networks where different wireless and wired technologies converge together. This creates vast amount of new opportunities in different application fields such as public safety, digital health, logistics and Internet services in developing countries. The annual space business related to 5th generation (5G) and 6th generation (6G) of communication systems is expected to grow to more than €500B during the next two decades [1]–[3]. This is more than the whole space business currently including scientific missions, earth observation (EO) and navigations.

At the same time the whole space sector is in the transformation phase due to so called New Space Economy. Significant reduction of launch costs and easy and affordable access to space have attracted new innovative players to space business [4], [5]. Especially Low Earth Orbit (LEO) systems and small satellites are increasing rapidly. The most typical orbit heights are above 500 km but there are significant efforts to use also very low Earth orbits (vLEO) to provide sensing and communications services. The so called Karman line, defining where atmosphere ends and space begins, is above 80 km and orbiting objects can survive multiple perigees passages at altitudes around 80–90 km [6]. Small satellites in the range of 80-220 kg can be seen as a sweet spot [5] since they are large enough for payloads to support e.g. broadband communications [7]–[9] or synthetic aperture radar (SAR) imaging [10], [11].

A. Multi-Layer Networks

6G systems will be used to provide pervasive services worldwide in order to support both dense and less dense areas. To achieve this goal, 6G systems will need to integrate terrestrial, airborne (drones, high-altitude platforms (HAPs)) and satellite communications at different orbits [12], [13]. This means that in contrast to traditional research and development (R&D) work, network analysis, planning and optimization will be updated from two dimensions to three dimensions (3D), where also the heights of communications nodes are taken into consideration [12]–[15]. In this way, 6G networks will be able to provide drastically higher performance to support e.g., passengers in ships and airplanes.

The initiatives spawned recently range from very high throughput geostationary orbit (GEO) systems to unmanned aerial vehicles (UAVs) [16]–[18] and small satellite systems dedicated to machine-to-machine (M2M) and Internet-of-things (IoT) services [19]–[21]. Especially interesting are mega-constellations consisting of hundreds to thousands of small and medium size satellites like those proprietary ones envisaged by OneWeb, Starlink, Orbcomm and Telesat to mention but a few. There is also ongoing active work in the 3rd Generation Partnership Project (3GPP) standardization to define non-terrestrial networks (NTN) with interoperable interfaces in order to have truly seamless connectivity in the future, described in detail in Section V.B.

B. Space Safety and Sustainability

There are not only technical drivers in the development of the multi-layer 6G networks. It is essential to develop services and technologies in a sustainable way in order to ensure high quality services also to coming generations. To mention a few examples: 1) According to International Telecommunication Union (ITU) only half of the world’s population has access to broadband services above 256 kbit/s currently [22]. 2) The COVID-19 pandemic has shown that video communications provide means for people and businesses, including medical
professionals, and their patients to remain in virtual contact, avoiding the need for travel while remaining socially, professionally, and commercially active [23].

A comprehensive analysis to linkage between 6G and the United Nations Sustainable Development Goals (UN SDGs) from technological, business and regulation perspectives has been provided in [24], [25]. A very good overview on how European Space Agency (ESA) programs support SDGs is given in [26]. For instance, satellite communication technologies provide e-learning in Congo, tools for telemedicine and transmission of key medical data to and from remote locations, and means to gather and share data on arctic sea and climate conditions. Thus, it supports multitude of SDGs including good health and wellbeing, climate action, quality education, sustainable cities and communities, reduced inequalities, and life on land by helping to protect terrestrial ecosystems.

Therefore, modern communication networks will be purposefully designed to be socially, economically and environmentally sustainable, and they will provide means to support equality globally. The main sustainability aspects are visualized in Figure 1. In the following, we list a couple of key points from the SatCom point of view.

- Satellites provide cost-efficient and environmentally sustainable platform compared to building terrestrial infrastructure especially in remote areas such as the Arctic.
- The number of satellites is increasing especially at LEO orbits. Sustainable use of space [27] ensures flight safety and mitigation of debris and creates means to detect the debris to avoid collisions and enable space cleaning.

| Topic of the article | Ref. | Contributions given in the article |
|----------------------|------|------------------------------------|
| Review of small satellites | [7], [8] | Survey on small satellites and their capabilities and related transformation of the space business. |
| Unmanned aerial vehicle based communications | [16] | Comprehensive review on the use of airborne platforms to support wireless services. |
| Satellite communications in the New Space era | [28] | Comprehensive overview covering technical topics and development environments. |
| 5G and 6G satellite communications | [29], [30], [31], [34] | Reviews describing 5G use cases, technologies, and standardization activities related to non-terrestrial networking. |
| 6G wireless systems visions | [12], [24], [25], [28], [39] | Survey papers and white papers on 6G connectivity regarding main drivers, sustainability, requirements, technical building blocks and architecture visions. Focus on terrestrial aspects but also remote connectivity. |
| Dynamic spectrum sharing | [32], [33] | How to share spectrum between different networks such as satellite and terrestrial. Focus on database-assisted technology. |
| Sustainability and threats caused by constellations | [27], [40], [42] | Overview of sustainable space operations and emerging threats |
| Sustainable satellite communications in the 6G era | Novelty in this article: Sustainability and space safety aspects in multi-layer networks |

Figure 1. Sustainable 6G SatCom aspects.

- Spectrum must be allocated and used in a way that does not endanger existing services. For example, some frequencies are actively used to gather information about space environment and should not be interfered by communications signals.
- Integrated systems need to be designed from the beginning as cyber secure ones in order to ensure reliable services and prevent data and systems to be accessed by unauthorized users.

C. Background and Contributions of This Paper

This paper has been prepared as an outcome of a project that aimed at creating a national roadmap towards 6G systems. In the project we have interviewed more than 20 mostly national organizations including companies, ministries, and funding entities operating on SatCom aspects. In addition, during the roadmap work we have been collaborating with ESA. Finland is an example of a relatively small country that has significantly increased space activities during the New Space era, and chose to strongly focus on sustainability in the development. Part of the material presented in this paper originates from the interviewed organizations. Insights and findings can be generalized to other countries as well.

Many recent survey and vision papers discuss technology developments related to integrated satellite-terrestrial networks [13], [28]–[34] and 6G topics [35]–[39]. In addition, there are papers discussing space sustainability and threats related to emerging constellations [27], [40]–[43]. We address these together with a special focus on national activities. The novelty of our paper, that is elaborated in Table I, is three-fold:

1. We revisit a multi-layered architecture from a sustainability perspective and extend our previous work presented in [13] to a survey with up-to-date information from extensive interviews and the latest 6G literature.
2. We discuss national and European level developments related to a planned flagship connectivity initiative [44] that could complement Copernicus and Galileo programs and support European sovereignty.
3. We examine 6G SatCom systems from the sustainability perspective focusing on space safety aspects. We classify the space safety related development into seven subtopics and discuss related regulatory issues.

The organization of the paper is described in Figure 2. First we will discuss regulations and international guidelines related to sustainable communications in Section II. Then, we define use cases and the multi-layer architecture in Sections III and IV. We discuss 6G related developments including large constellations in Section V before taking a deeper look at the space safety in Section VI. We review recent results related to multi-layer networks in Section VII, focusing specifically activities in Finland. Finally, potential research directions towards sustainable 6G SatCom are given in Section VIII before concluding the paper.

II. REGULATIONS AND INTERNATIONAL GUIDELINES

Regulations can be seen as one of the most important, or maybe even the most important aspect in order to ensure sustainable operations. They provide an international framework to be followed by space nations and ways to control and monitor the actual operations.

A. Frequency Management and Licenses to Operate.

Currently different frequency bands are assigned to different users and service providers and licenses are required to operate within those bands. Cellular communication systems, broadcasting services, satellites, etc., all have dedicated bands on which they may operate. These licensed systems possess characteristics that are distinctively different from each other and thus require dedicated bands for interference-free operation. In addition, there are unlicensed bands where several systems such as Wi-Fi, Bluetooth and other short range communication systems may operate according to given rules without any regulatory protection against interference.

Operators, both in terrestrial and satellites networks, need a license from a regulator to be able to provide wireless services. Regarding the space segment, the license also specifies allowed orbital positions in order to avoid interference with other satellites in the same frequency band as well as physical collisions. The ITU Radiocommunication sector (ITU-R) is the international organization that defines the high-level regulatory framework through World Radio Conferences (WRC). Spectrum resources are allocated to radio services based on analysis and compatibility studies which are carried out by
Member States of the ITU. This high-level regulatory framework is then detailed at regional and further detailed at national level with the definition of technical parameters to operate an application in a frequency band. Furthermore, as appropriate, the necessary coordination procedures to be applied at the borders of countries are defined to ensure acceptable level of interference for an application.

In Europe, the Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administration (CEPT) is responsible for the compatibility and sharing studies and is the entity which details the technical parameters and coordination procedures which may be applicable at regional level. Each country has also its own regulatory organization. For instance, Finnish Transport and Communication Agency (Traficom) is responsible for frequency regulations in Finland.

**B. Space Debris Related Aspects**

Space debris, also called orbital debris, are non-functional man-made objects orbiting the Earth or re-entering the atmosphere [45]. Space debris is an important aspect of space sustainability [27]. Most international guidelines are non-legally binding. Such guidelines include the Inter-Agency Space Debris Coordination Committee (IADC) space debris mitigation guidelines, the UN Committee on the Peaceful Uses of Outer Space (COPUOS) space debris mitigation guidelines, and the UN COPUOS Guidelines for the Long-term Sustainability of Outer Space Activities (LTS Guidelines). The EU has also included space situational awareness (SSA) in its space program for 2021-2027. SSA includes space surveillance and tracking (SST), which tracks resident space objects (RSOs), including both active and inactive satellites and space debris. In addition to SSA, a more comprehensive target is prompt space traffic management capability similar to air traffic management. However, as things are more complicated in space, we are still quite far from an effective space traffic management system [46].

Companies have also realized the important economic aspects of space sustainability and debris mitigation. The space safety coalition is an ad-hoc coalition of companies, organizations, and other government and industry stakeholders that have endorsed a set of best practices for the sustainability of space operations to address gaps in current space legislations [47]. They promote the exchange of information between all actors, the careful selection of launch providers, the prioritization of space safety in the design and operation, design best practices, and sustainability enhancing operations. Additionally, the World Economic Forum’s Global Future Council on Space Technologies has developed, together with stakeholders, the concept of Space Sustainability Rating (SSR) [48]. The SSR will score space missions based on markers such as evidenced-based debris mitigation and alignment with international guidelines. The sustainability certifications to mission operators will start in early 2022.

The importance of space debris mitigation has led many countries to incorporate some of the guidelines into legally binding national instruments. “Today, many national space acts include appropriate space debris mitigation measures as an element of the licensing requirements to their nongovernmental space actors” [27]. In Finland, the ministry of Economic Affairs and Employment takes care of the national space legislation and authorizes and registers any space activities [49]. The Finnish act on space activities of 2018 includes a section on environmental protection and space debris. The operator of the space activity “shall assess the environmental impacts of the activities on the earth, in the atmosphere and in outer space, and present a plan for measures to counter and reduce adverse environmental impacts.” Additionally, “the operator shall seek to ensure that the space activities do not generate space debris. In particular, the operator shall restrict the generation of space debris during the normal operations of the space object, reduce the risks of in-orbit break-ups and in-orbit collisions and, after the space object has completed its mission, seek to move it into a less used orbit or into the atmosphere.”

**C. Territorial Aspects Related to 5G and 6G Networks**

SatCom operation and communication service from high altitude platforms (HAPs) can easily cross borders i.e., cover areas in more than one country. In addition, there are also international water and land areas without territorial claims such as the Antarctic where service from satellites is provided. An example of extraterritorial access is where a mobile network identifier (ID) is used for a local network on e.g., a ship or plane travelling in/over international waters and then satellites are used to connect to outside world [50]. The IDs are authorized by one administration in one country, but they could also be transmitted by a radio access network (RAN) in another country. 3GPP is currently developing guidelines for regulatory aspects related to regional operation including e.g., how to enable routing to a core network in a specific country. Regulations may, for example, require that the satellite ground station and/or base station and the core network all have to be in the same country as the user equipment (UE), unless countries have made specific agreements [50]. Finally, international regulations ensure safe and efficient maritime traffic management and air traffic management and other safety-critical applications. On the other hand, passenger communications must comply with regulations of the territory with sovereignty over the location they are in.

**D. UAV Regulations**

Airborne platforms differ from satellites in a sense that they operate in the air space of different countries whereas space is international. UAV regulations include not only connectivity but also operational limitations on different locations and ethical constraints related to privacy protection [51]. When the UAV is small enough, its use is regulated by national aviation authorities but when they are larger than 150 kg they are usually regulated similarly to manned aircrafts. Typically, there are also no-fly zones defined e.g. to minimize risks to manned air flights and the UAVs can only be operated with line-of-sight conditions.

**E. Ground Stations and Data**

An important item in the regulatory domain is work related
to ground stations and data aspects. This work is actively ongoing in Finland in order to support practical ground station operators in their work. There are new operators willing to start operations to support both Earth observation and communications systems. Nordic locations are favorable compared to Southern Europe locations due to longer visibility times for satellites using polar orbits and consequently better data downlinks. However, there are regulatory aspects that need to be clear for commercial operators willing to support number of operators from different countries. For example, the data that goes through the ground station is not necessarily visible at all to the operator. With whom in this case can the Finnish operator collaborate?

F. Cyber Security Requirements and Guidelines

Cyber security is not meant to be a legal concept. However, regulators, such as Traficom’s National Cyber Security Centre Finland, develop and monitor networks and services and provide also guidelines nationally. It is well stated in [52] as “Ensuring the security of society is a key task of the government authorities and the vital functions of our society must be secured in all situations.” The main cyber aspects for multi-layer 6G networks include three attributes: a) Availability i.e., communication services must be available for legitimate users to access at any time. Radio frequency interference can be seen as denial-of-service attack when it is intentional. b) Confidentiality, which is maintaining the secrecy of information by preventing access to systems and data from unauthorized users. The platforms, interfaces and end-to-end connections should be well protected so that “hostile quarters cannot obtain the control of the constellations” as one interviewee put this. c) Integrity, i.e., protecting data from unauthorized alteration such as modification, deletion, or injection of wrong data. It is good to protect the system also against unintentional alteration such as data loss caused by system malfunction.

III. IDENTIFIED USE CASES: NORDIC PERSPECTIVE

There are numerous papers discussing 6G related use cases. Our objective is to provide a consolidated Nordic view based on interviews with Finnish industry actors and administrations. Obviously, some use cases are also of high interest in other regions outside the Nordic countries. Here we list the findings that are depicted also in Figure 3. The list is not meant to be exhaustive but rather it indicates potential application areas and shows where needs from the Nordic perspective are.

The views are also in line with the Finnish recovery and resilience plan, part of Finland’s sustainable growth program, where Pillar 2 focuses on digitalization and the data economy [53]. This pillar is further divided into three component areas: digital infrastructure, accelerating the data economy and digitalization, and digital security. The aim of the digital infrastructure is to have a high-speed reliable network and nation-wide coverage. Another target is to promote digitalization of traffic, which will further support attainment of transport emission reduction targets.

A. Autonomous and Remote-controlled Systems and Communications on the Move

Communications on the move is a natural use case for future satellite-terrestrial systems. 6G technologies will need to provide robust high-capacity connections to the airplanes, trains, cars, working machines, and maritime users across the globe. Satellites support operations by providing connections and enhancing situational awareness via remote sensing and navigation capabilities. Satellites can provide complementary redundant connection for railways, e.g., thinking about the future of GSM-Railway services. Latency is still seen as a challenge for remote-controlled and autonomous systems such as cars, but upcoming LEO solutions are expected to provide significant improvement for latency reduction.

B. Digitalization of Maritime

The satellite connections and integrated systems are inherently needed in maritime domain. Digitalization of maritime requires development that is described e.g., in [55], [56]. The 3GPP standardization forum identifies the following main services for maritime communications (MarCom), covering both needs of humans as well as maritime systems: 1) Mobile broadband services for users at sea; 2) Machine type communication services inside a vessel, between vessels and between UEs at sea; 3) Maritime communication services between authorities and users at sea; 4) Interworking and harmonization (with very high frequency (VHF) and satellite systems). Additionally, other services specified for other verticals by 3GPP are applicable to MarCom as well. Moreover, MarCom can be used to monitor marine aids to navigation (AtoN) from a wide range of peripherals and their supporting sub-systems as well as the collection and dissemination of sensors data e.g., meteorological and hydrographic data. Based on the conducted interviews of related MarCom end users it is essential to have integrated systems that can provide services globally also in areas where mobile cellular networks do not provide coverage. It is also observed that now there is quite a good connection using e.g., the Finnish public safety network (VIRVE) towards Tallinn but commercial networks are not so good far from the shore.

C. Arctic Areas and Sustainable Development

The Arctic area is very relevant for many Finnish stakeholders since solutions that generally work in the Arctic work also in Finland. One of the main SDGs is to provide coverage to poorly connected areas. The developed solution should not only be technically capable, but it should also be easy to use and adaptable to different cultures. Also, ESA promotes sustainable use of space for all services in 6G in a sense that supports SDGs via telecom, EO, and navigation. Trustworthy and reliable SatCom is seen as an essential part of sharing EO and navigation data. One company pointed out that in general they are looking for use cases that promise sustainable development from climate point of view. It is also good to develop situational awareness solutions that can be used to detect environmental impacts.
Although EO can be considered a separate business area from communications, the amount of EO data transmitted to dedicated ground stations is significant. Collected sensor data at the satellites may be so large, that some pre-processing is required before downlink transmission. In such a case, the data links form the limiting factor of the system. The situation arises especially with LEO satellites, which are visible to ground stations only a short period of time during which the download of data must be performed. Inter-satellite links (ISLs) to GEO, highly elliptical orbit (HEO) or other LEO satellites solve the problem, but then the EO satellites become a part of a satellite communication networks and justify the inclusion in the communications business area. The number of EO satellites is constantly increasing due to increased need to monitor the changing environment and resources of Earth.

D. Space Safety

One part of the sustainable development is to take care of space safety related aspects. Space weather services provide information to the space infrastructure and helps in defining required protection for the coming satellites and their electronics. One of the interviewed organizations pointed out that space safety has to be taken care first and only after that you can think about services provided on Earth.

The number of satellites is increasing rapidly in New Space era and both avoidance and detection of space debris is very important. Both ground-borne radars and space-borne radars can help in space debris management. It was found in a recent paper [57] that “While high-density constellations intrinsically increase the risk of satellite collisions, a key observation is that they can also be used to mitigate the debris problem. It is evident that to maximize the physical safety of upcoming high-density satellite constellations, a tight integration between space-based and ground-based radars is crucial to provide a more versatile contingency if some part of the detection system fails for some reason.”

E. Public Safety

Public safety authorities are increasingly using broadband services, new multimedia applications, and smart devices. Many new critical user sectors are emerging, including live broadcasting, critical business, security, remote control, and value transportation. The resulted connectivity needs cannot be supported by traditional narrowband systems. Instead, broadband mobile networks and satellites connections are needed as enabling technologies. For example, border guards and military personnel need rapidly deployable networks, or so called “tactical bubbles” [58] in remote locations. Coverage and capacity for integrated networks and easy to use solutions are mentioned in interviews as goals for adopting satellite systems for operational use. Satellites could become part of the future VIRVE network in Finland. The use of NTN for public safety applications in Finland was studied in [59]. It was concluded that “Satellites could be used as backup connections especially in locations where terrestrial network is not available. This will create resiliency to the operations.”

F. GovSatCom and Secure Connectivity

Secure and resilient connectivity solution with sovereignty also during crisis times is an essential part of future development in Europe. There are plans in developing governmental SatCom (GovSatCom) solutions that can support broadband needs and provide services to governmental users in any location over the continent. GovSatCom is defined in [60] as a new service class between fully commercial and military applications, providing highly available secure connections. The air interface of the system could be based on 5G and later 6G in order to create a standardized system on top of which security functions are built. From the cybersecurity viewpoint, quantum solutions are foreseen.
G. Military Use

Usually, the military has the satellite system under their own control. Also in Finland, ground stations, terminals, and personnel are internally managed, only satellites are not controlled by them. In addition to mentioned tactical bubbles, military users need satellites as redundant connections that can provide services anywhere. Satellites can, e.g., connect hierarchically different parts during the operations. For example, the facility area that handles the main resources can be connected to the battle zone where satellites and drone swarms provide redundant performance to the troops.

H. Direct Handheld Connections from Satellites

Direct 5G and 6G handheld connections could make emerging satellite services widely used by consumers and enable seamless integration with mobile cellular networks. The ability to connect without separate satellite equipment is definitely of high interest both to entertainment and authoritative applications. 3GPP is working on a global new radio (NR) based solution enabling hand-held devices to be used both in terrestrial and non-terrestrial networks as well as mobility in between. This is a promising business opportunity to the mobile phone manufacturers.

I. IoT Services over Satellite

Internet of Things (IoT) and machine-type communication services include cheap, low complexity sensors, and actuators that are able to generate and exchange data. Due to a large number of devices, the traffic generated by them will have a significant impact on the network load. Satellites can help to offload the terrestrial IoT network traffic through backhauling or provide service continuity in cases where a terrestrial network cannot be reached. Several interviewed companies thought that this is an important future use case and said that IoT does not require so many satellites in a constellation in order to have reasonable business cases available. However, there are many old and new players and the IoT area is competitive. NTN-IoT interconnecting every point on Earth to service centers is interesting for many industries. There is ongoing development for narrowband IoT (NB-IoT) services over satellites in 3GPP standardization.

J. Broadcasting Services

Satellite broadcasting i.e., transmission of television and radio programs directly from a satellite to the large number of receivers in homes has been a significant part of space business and is still interesting for some Finnish companies. They would like to understand where it is going and how broadcasting in the future will be provided by satellite and terrestrial infrastructure. Broadcasting capability of satellites could be used also e.g., in sending software updates to devices over a large area.

K. Broadband Connections and Internet

Roughly half of the population globally cannot access Internet via broadband connections [61]. In addition, Internet services are very limited e.g., in Arctic areas. Building terrestrial infrastructure in remote locations and in the developing countries is not economically feasible. Thus, this is a good opportunity and driver for the development of satellite services since they can provide truly global connectivity. In more populated places satellites will most probably only complement terrestrial systems, not replace them. Satellites can still provide backhaul services to the mobile networks, playing an important role in their development.

L. Satellites as a Service and Programmable Satellites

As future needs and technology developments cannot be predicted accurately there is a need to develop programmable satellites [62] and concepts such as satellite-as-a-service or payload-as-a-service. The former concept refers to providing the satellite capability to a customer whereas in the latter a single satellite may carry several payloads for different customers. Still the development of the platform and operation of the satellite is done by the satellite operator, easing the customer access to the satellite data.

The envisioned development requires use of software-defined radio technology and software-defined satellite platforms. Then, the satellite or its payload could be reconfigured over the air to the needs that are not even known yet to improve its longevity and sustainability. In addition, this could make also updates of technology releases possible so that e.g., regular updates of 3GPP releases would not mean launching new satellites to orbit. Satellite-as-a-service and payload-as-a-service reduce needs for large technical teams in different organizations, they can pay for the service only when needed and the satellites can be used by multiple customers for multiple missions. A recent example is the Lockheed Martin’s SmartSat concept that allows satellite operators to quickly change missions while in orbit with the simplicity of starting, stopping or uploading new applications [63].

IV. 6G Multi-Layer Architecture

Architecture of a future multi-layer system is depicted in Figure 4. It is a 3D network consisting of terrestrial communications, aerial platforms, and satellites at different orbits interconnected via high throughput inter-satellite links (ISLs), which can directly route data packets through space [13], [64]. The architecture has to accommodate requirements of the targeted vertical industries and to utilize the assets and infrastructure owned by multiple stakeholders. The user segment includes user terminals that may be fixed, or mobile ones deployed on platforms such as trains or airplanes i.e., located in multiple layers. The layers are discussed in more detail in the following subsections.

A. Terrestrial Network Layer: Ground segment

The terrestrial layer includes several radio access technologies such as cellular radios, WiFi, and IoT solutions to support fixed and mobile users. Car-to-car and ship-to-ship communications are enabled also by radios specifically developed for those purposes. The ground segment consists of a gateway and a core network operated by the network operator. System control, network access, and backhauling are done at the ground segment. A satellite operator uses telemetry, tracking & control (TT&C) stations to monitor the status of
satellites and their subsystems, run updates, and update the configurations. These can be used to keep the satellites at the desired orbits, to update camera parameters, etc.

Small user terminals are handheld devices with small antennas and very small aperture terminals (VSATs) with dish or flat antennas are installed e.g., on a ship deck. The UE of a future system will be a multi-radio terminal (any type of integrated communication device) including the satellite access. The RAN is assumed to be software-defined networking (SDN) capable with multi-tenancy support. That is essential because in practice, different RANs and transport networks are often managed by separate network operators. Network virtualization and slicing techniques enable different operators to share network resources with other (virtual) operators and to provide end-to-end connectivity across operator boundaries. The whole 3D network could be controlled by a centralized entity, an SDN controller, which has the control over the network devices and global knowledge about the network state within an administrative region. The core network in the 6G architecture supports seamless cooperation between the terrestrial and non-terrestrial segments and enables QoS management of data transmission e.g., by dedicating part of the resources to applications with higher priority.

Furthermore, multi-access edge computing (MEC) provides localized computing and storage resources for applications as well as real-time information of local network conditions. The satellite can provide a reliable backhaul link for edge computing. Together, software networks permitting flexible control of network traffic with fine granularity and MEC enabling the provision of scalable distributed services and network functions create a highly elastic integrated satellite-airborne-terrestrial system. This means that the whole system can be tailored during the operation of the network to support different kind of services.

B. Airborne Network Layer

The airborne layer comprises of UAVs that can be classified based on their altitude. Low altitude platforms (LAPs) characterized with an altitude laying within the troposphere [65] and HAPs between 10 km and 50 km, mostly concentrated around 20 km altitude [18]. UAV types include 1) balloons, 2) fixed-wing aircraft, and 3) rotary-wing aircraft. There can be WiFi, 5G and 6G type of payloads providing connectivity to terrestrial users, and Earth observation sensors for remote sensing purposes. Due to the short distance, there is no need to use different radio equipment and standardized cellular
equipment can be used to provide services from HAPs to cellular users. HAPs are used for various use cases and their implementation scenarios include dedicated, shared, and neutral hosts.

A major challenge for many operations is the ability of a HAP to maintain stationary position due to windy conditions at high altitudes. An operating altitude between 17 and 22 km is often chosen for platforms because in most regions of the world this represents a layer of relatively mild wind and turbulence above the jet stream. This altitude (> 17 km) is also above commercial air-traffic heights, which would otherwise prove a potentially prohibitive constraint.

Tethered aerostations, drones and unmanned balloons are density neutral, floating at the desired altitude [66]. Propulsion is only used to maintain the position. Tethered balloons are generally LAPs, operated with a few hundred of meters altitudes. Although tether limits the achievable height of the aerial systems, it also offers means to feeding electric power and communications cable to the platform. Thus, they can be used for long-duration missions.

The majority of drones or UAVs operate at the low altitude. They are versatile and easily deployable aerial platforms that are increasingly used for different applications and purposes. According to [67] the following attributes makes drones desirable candidate to substitute or complement terrestrial networks: 1) higher probability for line-of-sight (LoS) links to connect users in the ground and ability to adjust locations to maintain high quality links; 2) dynamic deployment capability according to needs. No needs for site rental costs; 3) UAV-based swarm networks for ubiquitous connectivity to recover and expand communications in fast and effective ways.

C. Space Network Layer

The space layer comprises of satellite constellations and large satellites operating at different orbits - and links between them. The satellite payloads can be transparent or regenerative. In the latter case part of the base station functionalities are performed by the satellite (e.g., demodulating and re-modulating the signal) whereas in the traditional transparent case the satellite acts as a simple repeater that amplifies the signal and makes frequency conversion between uplink (UL) and downlink (DL) frequencies.

| Table II. Comparison of Satellite Orbits. |
|------------------------------------------|
| Orbit         | (v)LEO | MEO | GEO    |
|----------------|-------|-----|--------|
| Typical orbit height (km)                | 160 – 1400 | 10000 – 20000 | 35786 |
| Path loss at 17.7 GHz (dB)               | 161 – 180 | 197 – 203 | 208 |
| Number of satellites for global coverage | 40 – 200 | 10 – 30 | 3 |
| Orbital period (h)                       | 1.5 – 2 | 6 – 12 | 24 |
| Pass time (min)                          | 6 – 22 | 130 – 300 | - |
| 1-way latency, Zenith (ms)               | 0.5 – 5 | 33 – 67 | 119 |

There are satellites in LEO, vLEO, medium Earth orbit (MEO), GEO and even HEO. Large satellites at high orbits are mostly built, launched, and operated with established companies within the space industry. GEO satellites are used for providing broadband access especially to remote areas, which otherwise cannot be served – either by technical or economic reasons. Modern high-throughput satellites (HTS) are able to provide sufficient data rates to most consumers. However, availability of GEO broadband services becomes limited in polar areas with higher than 60° latitude. Thus, satellite constellations at lower orbits are developed to also support Arctic environments.

Small satellite R&D efforts are growing rapidly with new players that focus on non-geostationary (NGSO) orbits and integrate products and services of different technology providers. Major parts of the planned small satellite missions globally consider communications, also using very small platforms such as CubeSats. In addition to providing coverage for remote areas, it is also required that the space segment is able to support low-latency services and that is only possible from lower orbits. Satellites in the future system can be tailored on-the-fly with on-board processing capabilities. For example, space-hardened software-defined radios can enable on-board waveform-specific processing which can be upgraded during the satellite lifetime [28].

The main orbits are depicted in Figure 5 showing footprints and the distance from the orbit to Earth. A comparison summary is given in Table II. The number of satellites is related to coverage of the entire globe. However, more satellites might be needed to fulfill capacity requirements. Orbital period can be calculated with Kepler’s third law in seconds as [9]

\[ T = 2\pi\sqrt{\frac{(R_e+h)^3}{µ}} \]

where \( µ = 398600.5 \text{ km}^3/\text{hs}^2 \) is the Earth’s geocentric gravitational constant, \( R_e \approx 6378 \text{ km} \) is the Earth radius, and \( h \) is the orbit height defining the distance between the ground station and the satellite. Pass time or possible connection time from a specific location on the ground to a passing satellite from horizon to horizon is then

\[ T_p = \frac{T}{\pi}\arccos\left(\frac{R_e}{R_e+h}\right). \]

The pass time also defines the maximum handover time from a satellite to another. Usually, the time is somewhat less than that since a safety margin is needed to guarantee connectivity.
D. Development Paths

When we look specifically from the SatCom point of view, the following development paths can be seen when we move towards 6G [1], [13], [34].

1) The networks will become multi-layered ones; the role of small satellites at LEO orbits are essential.

2) The on-board computer (OBC), the brain of the satellite, is evolving and its computing power increasing. This allows for the softwareization of the payload, which brings flexibility to the system and renders possible the dynamic adaptation of beams, power and frequency allocations, as well as reconfigurability of the payload itself. Reconfigurability improves the longevity and sustainability of the satellites. On the software side, isolation using partitioning, virtualization, or containers, can prevent the on-board data processing to interfere with the basic operations of the satellite.

3) From the spectrum point of view, millimeter wave and terahertz technologies and optical links allow very high rate data links, and spectrum sharing techniques are used to reduce interference in the future.

4) Reconfigurable phase array antennas and multi-beam architectures are used to reduce power consumption and to improve spectrum efficiency.

5) End-to-end cybersecurity is to be taken into account early in the design phase (security-by-design) to cover all interfaces, handovers, and the whole platform. Quantum technologies including post-quantum cryptography will be used for secure connectivity.

V. 6G SATCOM SYSTEMS DEVELOPMENT

A. Brief History of Developments

Satellites have been studied and developed in parallel to mobile cellular networks during all generations. During 1G and 2G the satellite networks were separate, proprietary systems providing services e.g., to remote areas [30]. During 3G the first step towards convergence of satellite and terrestrial systems was made and the satellite air interface was made compatible with the terrestrial universal mobile telecommunication system (UMTS) infrastructure [68]. In addition to satellites, also HAPs were considered [69]. Satellites became more important again in 4G and the satellite systems were considered an essential part for achieving e.g., global roaming in places where terrestrial 4G network is impossible to be installed or too expensive [70]– [72]. 5G is making the progress further and there are real promises of having wide-scale use of integrated systems in the future. In 5G, service continuity ensures smooth handover e.g., from terrestrial to NTN interface.

The timeline for 3GPP development since 3G and some milestones related to LEO constellations are shown in Figure 6. The first Finnish satellite was launched in 2017 [73] and the first telecommunications satellite was launched in summer 2021. The W-cube mission aims at modeling 75 GHz channels and their suitability for future satellite systems [74]. In addition to 3GPP, also other standards such as the enhanced version of the second generation of Digital Video Broadcasting standard for satellites (DVB-S2X) is still very relevant for HTS satellites [75], [76]. It is forming the basis for digital satellite transmission across the globe.

Figure 6. Timeline for 3GPP development and small satellites by 2030.

B. Standardization in 5G and Beyond

3GPP is the main standardization body for mobile networks. During the 5G standardization, an important action item has been to include non-terrestrial networks to support 5G use cases such as public safety and mobile autonomous systems. The consensus and general agreement on what satellite brings to achieving 5G requirements are [13], [77]:

- **Ubiquity**: Satellite provides high-speed capacity across the globe using the following enablers: capacity in-fill inside geographic gaps; overspill to satellite when terrestrial links are over capacity; global coverage; and backup for network fallback.

- **Mobility**: Satellite is the only technology capable of providing connectivity anywhere at sea, on land or in the air for moving platforms, aircraft, ships and trains, while requiring a minimal terrestrial infrastructure for support.

- **Broadcast (Simultaneity)**: Satellite can efficiently deliver rich multimedia and other content across
Table III: 3GPP NTN Standardization as of Dec. 2021.

| Technical spec. group | Release | Feature and study item | Objectives | Technical report / year |
|-----------------------|---------|-------------------------|------------|-------------------------|
| Radio Access Network (RAN) | Rel. 15 | Study on NR to support non-terrestrial networks | Channel model, deployment scenarios | TR 38.817 / 2018 |
|                        | Rel. 16 | Study on solutions for NR to support non-terrestrial networks | Necessary features | TR 38.821 / 2019 |
|                        | Rel. 17 | Solutions for NR to support non-terrestrial networks | Enhancements for LEO, GEO | n/a, completed 2021 |
|                        | Rel. 17 | Study on NB-IoT/eMTC support for NTN | Scenarios and changes to support IoT | TR 36.763 / 2021 |
| Service & System aspects (SA) | Rel. 16 | Study on using satellite access in 5G | Use cases and requirements | TR 22.822 / 2018 |
|                        | Rel. 17 | Integration of satellite access in 5G | Stage 1 requirements | n/a, requirements defined in 2018 |
|                        | Rel. 17 | Study on architecture aspects for using satellite access in 5G | Key issues for integrating satellite in 5G architecture | TR 23.737 / 2020 |
|                        | Rel. 17 | Integration of satellite systems in the 5G architecture | Normative specifications | n/a, completed 2020 |
|                        | Rel. 17 | Management and orchestration aspects with integrated satellite components in a 5G network | Business roles, service management and orchestration | TR 28.808 / 2020 |
|                        | Rel. 18 | Guidelines for extra-territorial 5G systems | Use cases, relevant features, operation over borders | TR 22.926, 1.0.0 draft in Sept. 2021 |
| Core network and terminals (CT) | Rel. 17 | CT aspects of 5GC architecture for satellite networks | Issues related to PLMN selection | TR 24.821 / 2021 |

![Diagram showing direct and indirect (backhaul) access with some tentative technologies.](image)

Figure 7. Direct and indirect (backhaul) access with some tentative technologies.

- **Security/resilience**: Satellite networks can provide secure, highly reliable, rapid, and resilient deployment in challenging communication scenarios, such as in emergency responses.

The same topics are still very relevant when going towards 6G. Excellent research papers have been published recently, covering NTN related activities such as [29]–[31]. The standardization status is summarized in Table III and documents therein including [50], [78]–[84]. It is expected that the Rel. 17 will be finalized during the first quarter of 2022 and the first NTN chips might become available within two years from that.

Note that From Rel. 18 on, 3GPP is calling the technology 5G Advanced. The study items currently include public land mobile networks (PLMN) related topics where new deployment scenarios are studied: 1) Terrestrial access and satellite access in the same PLMN, 2) PLMNs with shared satellite access networks, and 3) Mobility between PLMNs with terrestrial-only and satellite-only access. In addition, regulatory guidelines for extra-territorial operations discussed in Section III. D are prepared.

Considering the architecture options for network integration, there are two main ways to it as depicted in Figure 7. First, in direct access mode the end user is directly connected to the satellite as well as to the terrestrial base station. This enables accessing satellite services anywhere with the typical mobile phone. Secondly, indirect access is basically the backhaul case where the end user terminal is connected to the radio network using 3GPP or non-3GPP technology. The RAN is connected to the 5G core network via a satellite. The indirect use enables connecting local private networks on ground, on ships or in aircraft to the outside world. In the backhaul case, the gNB could be located in the airborne platform such as a HAP.

C. **Performance Indicators**

The basic requirements of the 6G connectivity as given in Table IV, with comparison to 4G and 5G. In general, 6G systems [35]–[39] aim to offer:

- Extremely high data rates per device,
- Extremely low latency,
- Ultra-high reliable connectivity,
- Very large number of connected devices,
- Very low energy consumption with IoT devices,
- Global connectivity, and
- Connected intelligence with machine learning capability.
situational awareness, advanced services to end users, including localized services, navigation satellites may all be integrated in order to provide advanced services to end users, including localized services, situational awareness and Internet connectivity anywhere.

It should be however noted that not all these happen simultaneously. Performance can be tailored according to application requirements. 6G networks will fuse digital, physical, and virtual worlds together and consequently increase the range of applications and services. Compared to previous generations, 6G will increase the capacity and mobility support and aim for extremely low latencies. However, what is clearly evident is that the integration of networks and operations from the beginning, leading to the 3D architecture. Therefore, 6G systems can support connectivity and positioning needs of future users and applications accurately and efficiently.

During the discussions with ESA and the industry, it has become evident that in the 6G era researchers should not focus solely on the connectivity part of the space systems. Instead, telecommunication satellites, earth imaging satellites, and navigation satellites may all be integrated in order to provide advanced services to end users, including localized services, situational awareness and Internet connectivity anywhere.

D. Proprietary LEO Megaconstellations and Multi-layer Connectivity

A major part of the planned small satellite missions globally considers communications, encouraged by the business visions presented earlier. There are many initiatives aiming to launch communications satellites to LEO orbits including megastarlink is already by far the largest satellite constellation ever built with over 1500 satellites in orbit. A good state-of-the art analysis of the current situation is given in [85]. Figure 8 shows that the number of satellites launched to LEO has exploded and most of the launches include small communications satellites with 100+ kg mass. One thousand SatCom satellites were launched during 2020 alone. These launches are related to building the mega-constellations. There are also a rapidly increasing number of nanosatellites with less than 10 kg mass in orbit.

| TABLE IV. PERFORMANCE INDICATORS OF THE MOBILE SYSTEMS. |
|--------------------|--------|--------|--------|
| Parameter           | 4G     | 5G     | 6G     |
| Peak data rate      | 1 Gbps | 10 Gbps| 1 Tbps |
| Max spectral        | 15 bps/Hz| 30 bps/Hz| 100 bps/Hz|
| efficiency          |       |       |       |
| Mobility support    | up to 350 km/h| up to 500 km/h| up to 1000 km/h|
| End-to-end latency  | 100 ms | 10 ms  | 1 ms  |
| Network architecture| Horizontal| Horizontal + NTN component studied| Three-dimensional (3D) with vertical|
| Positioning accuracy| Tens of meters in 2D| 10 cm on 2D| 1 cm with 3D|

Figure 8. Evolution of launch traffic per mission type (left) and LEO launches categorized based on the launch mass (right) [85]. Reprinted with permission.

D. Proprietary LEO Megaconstellations and Multi-layer Connectivity

A major part of the planned small satellite missions globally considers communications, encouraged by the business visions presented earlier. There are many initiatives aiming to launch communications satellites to LEO orbits including mega-constellation initiatives from the USA, Asia, and Europe. For example, Starlink is already by far the largest satellite constellation ever built with over 1500 satellites in orbit.

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There are also a rapidly increasing number of nanosatellites with less than 10 kg mass in orbit.

TABLE V compares existing and planned LEO satellite constellations, including Iridium and Viasat-2 information as reference examples of traditional LEO and GEO systems. The information is gathered mostly from public webpages. In addition to Starlink, OneWeb is also already providing initial services and both systems plan to provide Arctic coverage, including Finland, in 2022. Other notable LEO constellation initiatives include Kuiper Systems, Telesat Lightspeed, AST Space Mobile, Lynk, and Chinese plans on their 13 000-satellite constellation. More information on initiatives on LEO orbits can be found e.g., from [86]–[89].

In addition to LEO, there are system developments related to other orbits and multi-layer systems including Inmarsat Orchestra [90], [91] and O3B [92]. Finally, there has been some failed attempts to build a constellation such as LeoSat even though it first raised a good amount of funding. Also OneWeb was very close to go bankrupt before the British government and an Indian investor supported the work. Already more than 350 satellites have been launched to orbit and the company seems commercially competitive.
| Constellation        | Frequency band          | Altitude       | Number launched/authorised | Mass     | User data rate/total capacity | Terminal type               | Status                                    |
|----------------------|-------------------------|----------------|-----------------------------|----------|------------------------------|------------------------------|-------------------------------------------|
| SpaceX Starlink      | Ku-band DL: 12 GHz UL: 14 GHz + Ka-band | 550-570 km     | 1791/4408                   | 227 kg   | 1/20 Gbps roughly 100 Mbps DL for users | VSAT, ESIM                 | > 100 000 users commercial in Arctic 2022 |
| OneWeb               | Ku-band DL: 12 GHz UL: 14 GHz + Ka | 1200 km        | 358/648                     | 150 kg   | 10 Gbps per satellite         | VSAT, ESIM                 | Arctic area coverage in 2022             |
| Telesat Lightspeed   | Ka-band DL: 20 GHz UL: 29 GHz | 1015 km / 78 satellites 1325 km / 220 satellites 2/292 both test satellites deorbited | 700 kg | up to 7.5 Gbps for a single terminal, 20 Gbps for hotspot | VSAT, ESIM               | Plan to have commercial service 2023    |
| Kuiper Systems       | Ka-band DL: 20 GHz UL: 29 GHz | 590-630 km     | -/3236                      | -        | 400 Mbps user data rates in terminal tests | VSAT, ESIM                 | Half to be launched by 2026              |
| China SatNet         | Ka/Ku bands             | 1145 km / 508-600 km | 1/12992 test satellite in 2018 | -        | -                            | VSAT, ESIM                 | Plan to have 60 satellites in 2022       |
| AST Space Mobile     | Terrestrial frequencies < 2 GHz | 700 km         | 168                          | 1500 kg  | Initially 120 Mbit/s peak data rate for a cell | Commercial cellular handheld | Aiming 20 satellites to be launched in 2022 |
| Lynk                 | Terrestrial frequencies < 2 GHz | 500 km         | Plan up to 5000             | 25 kg    | Narrowband transmission such as text messages | Commercial cellular handheld | FCC license files for up to 10 small satellites in May 2021 |
| European Constellation plan | Not defined yet | Multiorbital LEO+MEO +GEO | -                          | -        | Broadband services targeted | -                           | Feasibility study ongoing, to be finished by end of 2021. Potential new EU flagship |
| Inmarsat Orchestra   | L-band S-band Ka-band   | Multiorbital, GEO, LEO, and terrestrial 5G 14 GEOs in orbit, 5 GEOs scheduled | 2000-6500 kg | L-band BGAN high data rate 600-700 kbps/user EAN up to 100 Mbps/aircraft | VSAT, ESIM               | 2 6th generation GEO to be launched in 2021-2022 Planning for 150-175 LEO satellites |
| Iridium Next         | 1.6 GHz (TDD)          | 780 km         | 75/66                        | 680 kg   | Call 2400 bits/s. Up to 1100 simultaneous calls per satellite. | Proprietary handheld       | Operational, 9 in-orbit spare satellites |
| Viasat-2             | Ka                      | GEO            | 1                           | 6400 kg  | 260 Gbps total, up to 100 Mbps for user | VSAT, ESIM                 | Operational since 2017                  |
| Sateliot             | Terrestrial frequencies > 2 GHz | LEO, ~550 km | 1/100                       | 3U nanosat test, final satellites not confirmed | IoT                   | Cellular handheld, sensors | Plan to launch whole constellation in 2022 |
| Swarm Technologies   | 137-138 MHz 400-401 MHz | 300-585 km     | 121/150                     | 0.4 kg   | (smallest commercial satellites in space) | IoT                         | Proprietary system | SpaceX acquired Swarm in 2021, full constellation in 2022 |
| SES 03b mPOWER       | Ka band                 | 8000 km + vLEO | 20/70                       | 1700 kg (MEO) | max user rate 10 Gbps / total capacity of a satellite hundreds of Gbps | VSAT, ESIM                 | MEO satellites operational, plan to include 36 vLEO satellites |
Costs of the proposed constellations are quite high and there is clearly strong belief in the business models. SpaceX Starlink, OneWeb, Telesat and Kuiper projects have estimated total costs ranging from $5B to $30B. AST SpaceMobile has slightly lower price around $2B but e.g. economical information regarding the Chinese state-sponsored ChinaSat plans are missing. Comparing the proposed systems, we can highlight e.g. the following findings:

- Iridium works with handhelds and low data rates, providing e.g. voice services.
- Lynk and SpaceMobile also aim for handhelds, even commercial mobile phones. Lynk has successfully demonstrated the ability for two-way communications between a satellite and a handheld for a limited data rate applications such as text messaging.
- Many initiatives consider VSAT and “cellular Internet” type of performance. Both fixed and mobile user terminals will be supported.
- Viasat-2 has a higher total capacity for a GEO satellite, but the total system capacity and maximum user throughput is clearly higher in megaconstellations.

Table V provides an overview of the situation. However, there is a number of initiatives not presented in the table such as the IoT satellite constellation being built by Kepler Communications [93]. Finally, there are also LEO constellations for Earth observation including Spire Global, Planet Labs, and Iceye.

### E. European Flagship Constellation Plan

The European Commission is funding an ongoing feasibility study on a secure space-based connectivity system, fulfilling Europe’s needs to rapidly develop a space-based connectivity initiative [94], [95]. This could potentially become a third flagship space infrastructure besides Galileo and Copernicus. The initiative aims at implementing the most advanced satellite infrastructure for connectivity, providing first broadband coverage to areas where terrestrial infrastructure cannot reach and later supporting services such as autonomous transport. The consortium doing the study includes European satellite manufacturers, operators and service providers, telco operators and launch service providers. The final report of the study is expected to become public in 2022.

The Directorate-General for Defence Industry and Space (DG DEFIS) has created a high-level figure of the system, depicted in Figure 9. The planned system includes traditional large satellites at higher orbits as well as a LEO constellation and the 5G terrestrial infrastructure. The system would support European sovereignty, providing secure services to governmental users as well as broadband connection to consumers. The main objective is to create broadband service for the whole of Europe so that the continent will have an ultra-secure connectivity system to guarantee operations also during times of crisis. EuroQCI, a secure quantum communication infrastructure, and standardized 5G technology are key components of the initiative.

There are ambitious goals for the system set since the initial service should be provided already in 2024 and the multi-layer network should be fully operational in 2027. To enable this, the European commission and ESA are expected to fund several technology development projects in coming years. The development is partly funded by the ESA’s 4S program (Space Systems for Safety and Security) that works on secure space systems to integrate them into seamless operations on Earth. Quoting the program webpage [96]: “There’s no safety on Earth without safety in space.”

### VI. SPACE SAFETY

The described development is both enabling sustainable growth globally but inevitably creating challenges related to space congestion. The risks associated with space systems originate from hazardous characteristics of the system design.
and its operating environment, and from hazardous effects from the system failures [97]. The space system itself comprises of hardware, software, and the human operator. ESA defines a "hazard" as a source of threat to safety. A hazard is therefore not an event but a characteristic of a system or its potentially dangerous environment. We adopt the same view and look at the situation from the SatCom perspective. Thus, we do not consider e.g., manned flights and related risks to humans on-board. Those topics are well covered in [98]. The topic of space safety has been visibly raised to the agenda in many countries. For example, in [99] the UK Space Agency is raising the following points in order to preserve the space environment to future generations:

“a) We welcome the United Nation’s Long Term Sustainability Guidelines and call on others to join us in implementing these guidelines. b) We welcome all efforts, public and commercial, in debris removal and on-orbit servicing activities and undertake to encourage further institutional or industrial research and development of these services. c) We recognize the importance of developing common standards, best practices and guidelines related to sustainable space operations alongside the need for a collaborative approach for space traffic management and co-ordination.”

A. Classification of SatCom Related Aspects

Emergence of large amount of small satellite systems at LEO orbits including the flagship initiative is creating challenges in keeping the systems safe and reliable. There should be no physical collisions to prevent totally losing the services and creation of space debris. On the other hand, there is a need to
manage the radio system interference both between satellite and terrestrial services and between different satellite systems. Current space safety procedures including debris mitigation and collision avoidance are designed with lower traffic densities and the New Space era is causing clear challenges. We classify the space safety aspects related to SatCom to seven different themes depicted in Figure 10. Even though the main focus is on the communication systems the classification and discussion can be easily generalized to any space-based activities. Each topic is covered in detail in TABLE VI and following subsections.

B. Space Traffic Management

Space traffic is increasing rapidly including both launchers and the number of satellites in orbit. According to the European Space Agency, there are currently 7550 satellites in space of which 4700 are still functioning [100]. Due to the miniaturization of thrusters in the satellites, also small satellites are capable to maneuver themselves. NewSpace operators are making extensive use of low-thrust systems for both transit and station-keeping. One approach is to launch to low LEO orbit, transition to the higher operational altitude via low-thrust, and at end-of-life, deorbit the same way [101].

Space surveillance networks are keeping their catalogs of space objects including satellites and tracked debris up-to-date and also aim at predicting where they are going in order to prevent collisions. However, existing catalog and collision avoidance processes have no effective way of dealing with frequent or continuous maneuvers, since they are based on predictions generated days in advance, with no assumption of maneuvers. Thus, if an existing satellite constellation is operating in proximity to one of the SatCom constellations that is using automated maneuvering frequently, its current collision avoidance process breaks down. The automated maneuvers may move one vehicle in the constellation out of a conjunction, or it could create a new problematic conjunction [101]. This concerns especially SatCom constellations due to their high number of satellites.

C. Space Debris Detection and Avoidance

Thousands of satellites and rocket bodies especially at LEO orbits can break into debris upon collisions, explosions, or degradation in the harsh space environment [42]. These fragmentations increase the collision probability per time and in the worst case these collisions could dominate on-orbit evolution, leading to a situation called the Kessler Syndrome [102]. There are approximately 29,000 catalogued space debris objects, and it is estimated that there are 1,000,000 objects larger than 1 cm in diameter [100]. Debris is travelling in space with very high velocity where relative speed of debris objects compared to satellites can be in the level of 15 km/s. Thus, even small pieces can destroy satellites and it is important to develop means to manage a situation that is becoming more and more complex. The evolving situation is both putting space-based services in danger and challenging space traffic in total, and could even prevent people to leave Earth in the distant future in order to look for other inhabitable planets.

The main mitigation approaches of space debris include debris creation avoidance, debris collision avoidance, debris removal, and debris shielding [103]. Provided that the debris is already existing in the space, a key enabler in defending the satellites is the ability to detect the time-varying positions of the debris. Several approaches have been developed in the past for debris detection including ground-based radars (GBRs) and space-based radars (SBRs) using either radio frequencies or optical measurement techniques [104]. While the former remains the basis technology for larger objects, say larger than 10 cm, the latter approach is often preferred for smaller objects. A separate stand-alone space-borne debris detection system would not, however, be a cost- or spectral-efficient solution. To overcome this, complimentary space-borne radar systems that would be more deeply integrated in the emerging satellite communication infrastructure have been recently proposed [57]. Smaller satellites are being launched to the lower orbits by several satellite operators, e.g. SpaceX, and therefore this solution is now timelier than ever before. Next, we look at this option more carefully.

1) Space-Borne Radar and Communication Concept

A simplified illustration of the 5G space-borne radar and communication (5G-SBRC) concept is shown in Figure 11. The space debris is detected over signals that are designed solely for communication purposes between satellites. Specifically, while the communication incentive is to exchange information between two collaborating entities, the radar incentive is to extract information by sensing radio signals reflected from a non-collaborating target. In general, there are several alternate strategies to develop an SBRC system with different trade-offs regarding the achievable integration gain and compatibility with existing legacy systems. These strategies include: i) independent signals of communication and radar subsystems operated in a single platform, ii) communication over existing radar signals, iii) radar sensing over existing communication signals, and iv) jointly optimized waveforms by redesigning both domains. Clearly, the first option represents the least efforts for integration with least integration gains while the last option provides the most advanced integration solutions maximizing benefits jointly for both communications and radar tasks at the cost of higher integration efforts as both domains must be redesigned. The two options in the middle represent design approaches where some compromises are made between achievable gain and compatibility.

The main benefits of the approach are that a separate space-borne radar infrastructure would not be needed, the payload of a satellite can be reduced, and the spectrum efficiency is improved. However, also the transmission power and antenna size of satellites must be reduced compared to that of the GBRs. In practice, the satellites cannot be brought arbitrarily close to each other due to cost, safety, and interference regulations. To enable a reliable detection of very small objects less than few cm, the detection distance should be reduced to less than few km when using smaller satellites. To obtain some rough understanding on the required constellation complexity, we plot the ISL distance versus constellation inter-plane density in
Figure 11. Illustration of the SBRC concept. Figure created with the STK software.

Figure 12. ISL distance versus constellation inter-plane density for different orbits.

Figure 13. Advantage of the 400 MHz 5G on velocity estimation accuracy of debris objects.

other signal characteristics, the 5G bandwidth (BW) has an important role in radar estimation accuracy of the mm-size debris objects. Using our velocity estimation techniques and parameters proposed in [57], we newly show the processing gain advantage of increasing the BW from 100 MHz to 400 MHz in Figure 13. In space, high velocities also cause integer frequency offset (IFO) in addition to fractional frequency offset (FFO). With the IFO compensation up to the signal-to-noise ratio (SNR) threshold, root mean square error (RMSE) performance is comparable to the case where there is only FFO distortion.

3) Future Outlook

There are several directions for the future work under space debris mitigation. Clearly, the signals that optimize jointly the different objectives of communications and debris detection would provide some interesting opportunities for both satellite communications and space debris detection. Furthermore, a tighter integration between space-based and ground-based radars could boost the overall detection reliability. Obviously, it is not enough to aim at merely improving debris detection approaches. To this end, different types of active space debris removal methods are being proposed including lasers, tethers, sails, and satellites, see a survey from [106]. Commercial debris removal technologies are being developed, e.g., by Astroscale [107].

D. Environmental Impacts

A very positive development towards more sustainable space operations have included smaller launchers and reusable rockets that can carry satellites to orbit multiple times, such as the ones used by SpaceX. However, also in their rockets the second stages are usually controlled through re-entry and deposited in remote areas of ocean [42]. Cumulative impact of the rocket bodies can cause environmental damages to the fragile ocean environment. In addition, a high number of launches produces black carbon to the atmosphere. If the number of launches per year is above 1000 it can lead to a
persistent layer of black carbon particles in the northern stratosphere [108]. That could potentially cause changes in the global atmospheric circulation and distributions of ozone and temperature. Over years of active launching this may lead to radiative forcing comparable to the effects of current subsonic aviation.

Another significant effect from the launches required to keep the megaconstellations functional is that the satellites have limited lifecycle and over the update cycle there can be several tonnes of satellites re-entering Earth’s atmosphere daily. As explained in [42], satellites include aluminum and re-entry will create fine particles that could greatly exceed natural forms of high-altitude atmospheric aluminum deposition.

Sustainable use of space has led to inventions related to satellite structures as well. A recent Finnish initiative called WISA WoodSat is developing the world’s first wooden satellite that uses plywood panels in its structure [109], [110]. One of the aims of the mission is to understand how well the wooden structure can be applied to the spacecraft including long-term radiation and harsh space conditions. An interesting feature of this design is that during re-entry to the atmosphere the satellite will burn more rapidly, causing less risk to humans on ground and less aluminum particles in the atmosphere. The satellite has passed vibrations tests in the premises of ESA and is scheduled to be launched in the first half of 2022. The first stratospheric test flight up to 30 km to test its communication capabilities, command response, and selfie stick camera was successful. The satellite is depicted in Figure 14 showing the wooden panels in the exterior. The satellite is also equipped with a selfie stick that enables inspection of the satellite condition in orbit. In addition to materials research, the mission initially aimed to provide IoT connections using LoRa technology from space, and to support amateur radio communications via space. However, this was not supported by International Radio Amateur Union. Therefore, there is a requirement to build, test and license a different radio system before the launch can be made.

On-orbit servicing is another solution to extend the life of satellites. There have been few human-assisted on-orbit servicing missions and few others for testing autonomous servicing, like the DARPA Phoenix program. Commercial satellite service models are still not fully developed. One company, SpaceLogistics [111], successfully docked its mission extension vehicle-1 (MEV-1) to a client satellite in February 2020, making it the first commercial on-orbit servicing operation. Other companies working towards on-orbit servicing include Altius Space Machines and Orbit Fab. The Consortium for Execution of Rendezvous and Servicing Operations (CONFERS), a satellite servicing industry group, is working on satellite services standards, ranging from sets of principle and best practices, to fiducials and refuelling interfaces on spacecraft.

E. Space Weather

Space weather describes phenomena that can cause significant impacts to systems and technologies both in orbit and on Earth [112], [113]. It is caused by solar wind and solar flares in the near-Earth space and the upper part of the Earth's atmosphere. Currently, the baseline approach is to collect as much of the required measurement data as possible using ground-based instruments, because they are usually less expensive and easier to maintain and upgrade than space borne instruments on board satellites. For example, the Finnish Meteorological Institute provides space weather data using automatic magnetometer stations located in Finland.

Space weather affects 6G services via their impact on systems such as global navigation satellite systems (GNSS) signals [114], [115] and electronics on satellites. Ionospheric scintillations are one of the earliest known effects of space weather, causing interruptions and degradations to the GNSS receivers. The effects of space weather on signal propagation can be mitigated through engineering design solutions. However, space weather can lead to a total loss of communication due to attenuation and/or severe scintillation when the broadcast signals in certain frequencies cross the ionosphere. Thus, in order to make the future system resilient, one has to take space weather effects into account.

In order to make electronics and shielding of satellite stand against harsh space weather, standardized quality procedures and tests defined by the European Cooperation for Space Standardization (ECSS) must be met. This means that the New Space players should not rush too quickly to the orbit but rather ensure that even the smallest and cheapest satellites are engineered in a sustainable and reliable way. This is a good action towards debris creation avoidance.

F. Near Earth Objects and Deep Space Communications

A near earth object (NEO) is an asteroid or comet that passes close to the Earth’s orbit, more accurately comes within 45 million kilometers from it. They are classified based on their size and the NEO with more than 140 meters in diameter is considered potentially hazardous since they can create significant damage on the Earth’s surface. There are many powerful radars on Earth to detect NEOs and also space-borne missions are used to complement the information to create a catalog of NEOs and help preparing counteractions to ease and even avoid hazardous effects. So how does this relate to SatCom and New Space developments?
As an example, the planned HERA mission depicted in Figure 15 will use deep-space cubesats launched by the larger satellite when in the vicinity of the Didymos asteroid, which is to be studied in detail [116]. Also, deep-space intersatellite links will be tested between the large and small satellites. HERA will also demonstrate autonomous navigation around the asteroid similar to modern autonomous cars or ships on Earth, and gather crucial scientific data, to help scientists and future mission planners better understand asteroid compositions and structures. In addition, jointly with the DART mission [117], the aim is to study planetary defense mechanisms and possibility to shift the asteroid orbit with a kinetic impact.

In addition, there is active research ongoing towards deep space communication networks in order to provide connectivity anywhere in the solar system and to support exploration of the universe. It is described in [118] as “The deep space exploration missions require high quality of communication performance between the Earth stations and various deep space explorers, such as Mars orbiters and rovers.” The paper describes a structured solar system satellite constellation network where several relays are used to create a topology that can support deep space operations and connect objects from the deep space to each other and to the Earth.

Many innovative missions are developed annually and it is foreseen that the development of a visionary 3D network around the globe and a deep space communication network would enable unforeseen growth in New Space missions. When the connectivity is robust and working anywhere also innovative missions for science and remote sensing can be served at an unprecedented level.

G. Cybersecurity

There are many emerging cybersecurity challenges due to development of complex multi-layer systems [119] and the rapid increase of platforms and interfaces. The infrastructure both in space and on the ground must be protected. In addition, application areas such as autonomous and remote-controlled shipping means opening up the previously closed systems due to external control interfaces [55]. Therefore, before the design phase for the whole architecture can begin, it is important to first define relevant threats and assess impacts of those threats to the system. Secondly, map out risk scenarios and finally, understand the trade-offs between acceptable and unacceptable risks. After this evaluation, it is possible to proceed to define the architecture i.e., using security by design principle. Thus, fine-tuning the multi-layer architecture for future networks requires a new type of approach. In order to make this happen across different countries and stakeholders, effective coordination of actions and organizing training for space actors is required. Space agencies such as ESA and NASA will play an important role in coordinating the activities [120], [121].

Both payload and control communication need to be tested before launching the satellites to orbit. It is important to cover the whole end-to-end path when creating reliable, secure communications. Cybersecurity issues have been recently studied from different viewpoints including general issues in space networks [122], 5G and beyond networks [123], looking at the effects of machine learning on security [124], and ensuring secure telemetry and command links [125].

An example of a security challenge is the handover situation that can happen quite frequently in dynamic 3D networks [122]. The situation is depicted in Figure 16. Key management during the handover situations is challenging. For example, when a police officer is changing his connection from the terrestrial 5G to a LEO satellite, handover information includes both previously accessed networks and newly accessed satellites. Signaling is exchanged between different entities and might be eavesdropped, falsified, or fabricated.

Finally, it should be ensured that the system to use for critical communications is available. For Europe and Finland, it is good to have systems that are under their own control. This was described by a Finnish organization as: “Can we trust systems outside Europe during the time of crisis? It is much better to have a European constellation.”

H. Spectrum Management

Enabling services: The number of satellites increases but the spectrum resource is naturally limited [126]. We covered some regulatory aspects related to spectrum allocations already in Section II. The potential for new allocations is shrinking because the expansion of wireless communications is continuing and new systems are emerging faster than the ageing systems currently in use are becoming extinct. There are two main ways to cope with the spectrum scarcity problem [32]. 1) To use higher frequencies that are not yet allocated (or optical
links [127]) and 2) Use currently allocated frequencies more efficiently. The latter leads to the concepts of dynamic spectrum sharing and spectrum coexistence.

Spectrum sharing means that two or more systems are operating in the same frequency band. In the 6G SatCom this may include spectrum coexistence a) between different satellite systems, b) between satellite and terrestrial systems and c) between systems in different layers of the multi-layer network. This is a very challenging field and leads to the use of techniques such as spectrum sensing [128], [129], adaptive beam control and multi-beam satellites [130], [131], predictive frequency allocations [132], and licensed spectrum management [33]. The latter includes database-assisted techniques [32] that enable controlled spectrum sharing with guaranteed QoS for sharing parties. The basic principle of a spectrum database approach is that the secondary user of the spectrum is not allowed to access the band until it has successfully received information from the database that the channel it intends to operate on is free at the location of the device for the time period needed.

Astronomy: It is important to use spectrum efficiently to enable interference free environment and reliable delivery of wireless services to end users. Another crucial point is to allocate and use frequencies so that this does not endanger other space safety services including astronomy [133], [134]. The astronomical radio signals arriving on Earth are extremely weak compared to signals from communication systems and require large radio antennas called radio telescopes to detect them. Even a cellular phone on the Moon would produce a signal on Earth that radio astronomers consider quite strong. Thus, cosmic radio sources are easily masked if this is not taken carefully into account. Regulations are done to set the power and frequency limits in order to keep services operational. Technical studies on aggregate interference effects from new wireless services have to be done in order to support the regulatory activities.

Radio astronomy is used to increase our knowledge on space, particularly deep space topics such as pulsars, black holes, radio galaxies and cosmic microwave background radiation. Thus, it helps to answer questions such as how the universe and planets are born or trying to find extra-terrestrial intelligence [135]. In addition, radio astronomy provides useful information on sun and solar activities and thus, we can learn about stars in general. Astronomy uses a wide range of frequency bands from a few kHz to tens of GHz and there have been many interference incidents caused from ground-based broadcast systems, GNSS signals or cellular phones. New allocations in any layer of the 6G system should not produce harmful interference in co-channel or in the adjacent bands. In addition, large constellations are challenging optical astronomy since satellites can reflect sunlight and appear as bright streaks in telescopes [136].

In Finland, the Sodankylä Geophysical Observatory has already been operating for more than 100 years. For example, they will be using the European Incoherent Scatter Scientific Association (EISCAT) 3D research infrastructure, consisting of thousands of phased array antenna elements operating in 233 MHz band [137]. It uses radar observations and the incoherent scatter technique to cover the near-Earth space environment for space weather forecasts and space debris detection.

VII. RECENT RESULTS WITH FOCUS ON FINNISH R&D ACTIVITIES

A. Constellation Design and Simulations

Satellite constellation design is a complex task that needs to take into account service requirements, coverage areas, and also sustainability aspects. Traditionally, the constellation has been optimized for global coverage [138]–[141] or for regional coverage especially for EO constellations [142] using a single layer system. There is no specific unified design approach for a local continuous coverage or surveillance mission over a region [143], and the design can aim at maximizing coverage while minimizing revisit time or achieving revisit time target. Also, EO satellites need to download their measurement data to ground stations. Depending on the number of satellites in the constellation and the locations of ground stations it is also necessary to design proper datalinks and scheduling algorithms. Data downlink scheduling is part of a much wider problem that involves also scheduling the sensing and managing on-board and terrestrial system limitations [144]. Finally, the described 3D architecture requires multi-layer constellation design that has been considered e.g., in [145], [146].

Typically, constellation designs are made using advanced simulators and various constellation creation methods, such as the Walker constellation, which is a globally symmetrical configuration, or streets-of-coverage. The latter refers to the swath on ground with continuous coverage. Deterministic and location-based models that have been applied to analyze satellite systems are typically restricted to support simulations. Recently, also stochastic geometry analysis that abstracts the generic networks into uniform binomial point processes have been developed to support constellation design and analysis [147], [148]. Analytical methods can lead to very fast results. Since numerical models can lead to more accurate outcomes than analytical, they are still favored in the constellation and orbit designs. There are also semi-analytic approaches proposed for lowering computational burden related to satellite propagation [143] or probability of detection calculations [57] in case of joint communication and sensing constellations.

Regarding the SatCom applications, it is not enough to be able to create a constellation that provides the required coverage globally or for the area of interest. The design needs to consider also detailed physical layer protocols, network traffic characteristics such as end-to-end delays, throughput requirements, routing, and interference. In Finland, Magister Solutions Ltd has developed the Satellite Network Simulator 3 (SNS3) [149] as part of an ESA ARTES project to support network simulations. Magister has also created a system simulator for 5G NTN evaluations [150] to support 3GPP-based SatCom development. In addition, there are studies e.g., from University of Oulu regarding the use of 5G NR over SatCom links [151].

There is no single simulation tool currently available on the
market that can cover holistically all the needs. Traditional simulation tools handle either orbital or network aspects, with limited interfacing and coupling between the two. Thus, one approach is to combine different simulation tools intelligently together e.g., by using Systems Tool Kit (STK) to create a constellation and then using MATLAB for detailed link level analysis in the designed constellation [152]. Another recent example of this approach is the Satellite Constellation Network Emulator (SCNE) project [153] that is done in collaboration between Airbus, Magister and VTT. The project has developed a novel co-simulation approach that enables the modelling of complete satellite constellations including orbital and network aspects. The objective of the project has been to enable to study and assess protocol performances used in large LEO constellations. The tool is particularly helpful in the study of routing protocols and consequently end-to-end quality of service aspects.

The high-level architecture of the tool is presented in Figure 17. It includes the following components. First, the human computer interface (HCI) provides means for a user to define a wanted constellation and load the orbital and network scenarios. The HCI includes STK Graphical User Interface (GUI), to define the constellations using a GUI or the scripting approach. Second, there is an orchestrator that is a plugin developed specifically for interwork between STK and ns-3. The orchestrator calculates the link characteristics of all the possible links based on STK accesses-defined restrictions between satellites, users, and gateways. Finally, the orchestrator transfers the link information to the ns-3, where the L2 and upper layer protocols are added and the end-to-end link performance is assessed.

Figure 17. The SCNE simulator architecture.

B. Integration of Satellites into 5G/6G Test Networks

5G Test Network Finland is a multisite test environment and co-operation network [154]. Test networks provide infrastructure to support 5G and 6G technology development, service research, and large-scale field trials. The majority of the projects have focused on terrestrial technology developments to support various verticals such as port automation and ultra-reliable low latency aspects [155], [156]. However, there are also drones and real satellite equipment (both LEO and GEO) included in the test network to support 3D network studies. The GEO connection in VTT’s test network includes two different types of terminals that support high throughput broadband connections. The fixed terminal is located in Espoo and the nomadic one has been used at various locations. In addition, the LEO connection with lower latency supports 700 kbps DL and 300 kbps UL connections. We also plan to use megaconstellation-based connections in the near future when they become commercially available in Finland.

Part of the work has been developing concepts and conducting analysis and simulation studies e.g., for IoT satellites [157]. Some areas such as autonomous shipping [158], or connected driving and road safety [159], [160] can be greatly enhanced with the integrated satellite-terrestrial networks. Satellites can provide both connectivity and positioning services. A practical connectivity solution of an autonomous ship includes both satellite and terrestrial communication systems. It may include also HAPs e.g., along the shipping routes in the Arctic.

Implementation activities in the test network have first focused on measuring the performance of the available solutions and then building proof-of-concepts for selected application areas. Regarding the public safety networks, we implemented a private network or “tactical bubble” to provide local connection to authorities and used the GEO connection as backhaul towards the core network [161].

C. Spectrum Sharing and the World’s First LSA trial in Integrated Satellite-Terrestrial Networks

Adaptive communications research, that started in the sixties [162], led over years to cognitive radio (CR) studies aiming to share and use spectrum efficiently [163]. Spectrum coexistence studies in satellite communications were done at the same time [164] and the first ESA funded activity considering application of CR techniques to SatCom provided results regarding the suitable scenarios and frequency bands in [165]. In parallel, Business Finland funded test network projects started to develop practical solutions for licensed spectrum sharing starting from licensed shared access (LSA). In this approach the incumbent operators are required to provide a priori information about their spectrum use over the area of interest to this database, telling where, when, and which parts of the frequency bands are available. A limited number of users obtain the right to use the band while the LSA controller, using the information from the database called LSA repository, ensures predictable QoS for all spectrum rights of use holders with proper power and frequency allocations.

The timeline for spectrum sharing developments from the database-assisted system point of view is given in Figure 18. The world’s first LSA trial was done in 2013 in the CORE+ (cognitive radio trial environment) project at the 2.3 GHz band showing the applicability of the system in practice [166]. Multiple enhancements were done during the following years adding more base stations and advanced technologies to the setup. Another spectrum sharing approach proposed in the 3.5 GHz band called spectrum access system (SAS) for citizens broadband radio service (CBRS) emerged in the USA [167]. While LSA is a two-tier model with primary and secondary users, the SAS model includes a third tier called general
authorized access (GAA) to facilitate opportunistic spectrum use. In order to protect FSS earth stations, the Federal Communications Commission (FCC) has adopted a rule that requires satellite operators to register their stations annually. The SAS obtains this information from the FCC database and uses the data when it grants or denies access to users willing to operate in the same band. The world’s first CBRS trials were conducted in the CORE++ project [168].

The use of database-assisted technologies to SatCom continued in the ESA Freestone project [32]. Findings from the project provided technical and economic analysis for several frequency bands and application scenarios. Controlled sharing was shown to be an attractive option since in some cases it can ensure the status of the satellite operator in the band instead of losing it totally to some other systems via new spectrum allocations. Applicability of LSA for public safety and to support local networks via the use of distributed architecture was studied in [169]. Finally, the recent ESA ASCENT project created a testbed and conducted field trials using real base stations and up to 1000 virtual base stations [170]. Trials considered spectrum sharing scenarios between satellite and cellular systems at the 5G pioneer bands at 3.4–3.8 GHz and 24.25–27.5 GHz where a satellite system is operating in the downlink direction and a cellular system is accessing the same band.

As described in [171], spectrum discussions for 6G networks are currently at their infancy. Database-assisted technologies [172] can support local networks that will be more and more important in the future, and those networks can use satellite connections from any location to connect to the outside world. In addition, the development of joint communication and sensing especially at higher frequencies opens up further possibilities for 6G networks to sense and adapt their operations in real-time.

D. Millimeter Wave Satellite in Orbit: W-Cube

In order to maximize data rates for multilayer systems, millimeter wave technologies need to be applied in terrestrial and satellite links [173]–[175]. Frequency bands clearly above 10 GHz can provide larger bandwidths compared to conventionally used frequencies and enable the use of highly directional antennas. However, those frequencies are heavily attenuated due to effects such as atmospheric absorption and tropospheric scintillation. Thus, successful application of those frequencies requires development of RF and antenna technology as well as channel modelling missions to really be able to evaluate performance over satellite links.

The ESA ARTES activity called W-Cube is using a 3U (where 1U is 10 cm x 10 cm x 11.35 cm) nanosatellite equipped with a beacon transmitter to measure and characterize wireless channel in the 75 GHz band [176]. This opens possibilities for the use of the high millimeter wave frequency range in communications satellites in the future. The first-ever W band satellite that was launched to orbit in June 2021 is depicted in Figure 19. The payload design includes an innovative concentric ring antenna for signal transmission. In addition to the main payload, the satellite broadcasts a Q band signal at 37.5 GHz to compare the information on measurements with previous models at lower frequencies. The satellite platform was designed, developed, and tested by the Kuva Space company, and the payload was developed by VTT.

The aim of the mission is to understand e.g., how weather phenomena affects signal propagation and polarization. To save battery power, the beacon signals are only switched on when they can be detected by measuring stations located in Austria and Finland. At other times, the satellite charges its batteries using the craft’s solar panels. The satellite orbits the Earth approximately once every 1.5 hours and is visible to the ground station for about 10 minutes at a time. The signals from space have been successfully received at the ground station and the actual channel modelling work that is led by Joanneum Research from Austria is now ongoing.

E. Towards Terahertz and Optical Communications

The quest for ever higher frequencies is actively continuing especially in terrestrial short-range communications. For example, D-band (above 100 GHz) active electronically
steerable antennas have been developed recently [177]. There are studies on terahertz technology such as [178] in which the authors show that the capacity of the satellite-to-airplane THz link may reach speeds ranging from 50–150 Gbps, thus enabling cellular-equivalent data rates to the passengers and staff during the entire flight.

In small satellites the cost and power consumption are clearly limiting factors. Ground stations will use electronically steerable multi-beam antennas, able to communicate with multiple LEO satellites simultaneously. Miniaturization and creation of efficient antennas for small satellites is an important topic and e.g., planar patch antennas are being developed actively. It is essential to develop antenna systems that can sustain wireless links or remote sensing requirements in a small, stowable package [179].

Optical communication is a disruptive technology that will enable ISLs and satellite formations and can lead to significant power savings compared to RF communications. According to [180] it can provide safe and cyber secure way to serve scalable 3D networks, enabling the shift from partitioned ground and space segments into a fully integrated system. Optical communications are limited in many areas due to clouds. There is actually an “optical belt” across Sahara and middle East where satellite-to-ground connections are possible due to cloud-free availability [181].

VIII. POTENTIAL RESEARCH TOPICS

In this section we identify a few promising research directions with focus on sustainability and space safety. In addition to the mentioned technical topics we foresee a plethora of new application areas that can be supported and enabled by multi-layer networks in the future. These include so called metaverse i.e., virtual environment that blends physical and digital world, facilitated by the convergence between the Internet and extended reality (XR) technologies [182]. Another example is telemedicine [183] and advanced global Internet-based services including the least developed countries.

A. Multi-Layer Constellation Design

Traditional constellation designs have considered satellites at a single orbit and updating the designs to multiple layers is not a simple task. There is need to develop new design methodologies and simulation tools for flexible operations and capacity estimations across layers. Future designs might require the use of machine learning frameworks such as the reinforcement learning based capacity estimation derived in [184]. Also, stochastic geometry analysis [147], [148] can provide tools for capacity optimization with a minimum number of satellites at different orbits. In addition to the space layers, new designs are needed for the ground segment.

Thousands of SatCom and EO satellites will provide tremendous amount of data in the future. To access the data, the customers need either to build their own ground stations and antennas or lease them from ground station providers [28]. It would be useful to create a ground station network that can be shared among constellations. For example, in the Amazon AWS initiative [185], the data can be collected from the numerous satellites orbiting the Earth and stored in a central cloud. In such a case, the interested customers will only need to access the cloud without the need to invest in their own infrastructure. Another recent example is the NorthBase in Finland providing secure ground station services to satellite operators [186]. The remaining challenges for the operation are where to locate ground stations to support real-time requirements, how to connect them to the national networks, and setting clear regulatory foundations for the use.

B. Efficient Spectrum Use in 3D networks

Dynamic spectrum management needs to be updated to the 6G era. There are many topics to be addressed to make this successfully. First, defining the most suitable frequency bands for systems and links. Second, developing spectrum sharing mechanisms to manage the complexity of a dynamic and mobile 3D network. Most probably, AI-based solutions are required [187]. When a massive number of devices are involved in 6G networks and require spectrum assignment, AI-enabled spectrum management is capable of intelligently supporting a massive number of connections and diverse services. It is good to note that the inclusion of non-terrestrial base stations (BSs) brings new challenges to the network controller design because in fact, both the serving and interfering BSs can move at the same time in the 3D plane [15].
A concept for spectrum sharing in a multi-layer satellite system is seen in Figure 20. There are GSO and NGSO satellites operating in the same frequency bands. In order to coordinate the spectrum use and enable predictable QoS for all users, information must be shared between the entities controlling the involved layers or towards a third-party entity controlling the spectrum use. The system could use AI-based optimized spot beam allocation and resource management for aggressive frequency reuse and beamforming/precoding techniques [188] to cover the needs of mobile and fixed users. Thus, spot beam settings are dynamically adjusted to support capacity needs and to avoid interference. Suitable database approaches and AI technologies are to be developed to realize the approach.

New types of antenna solutions are being developed including holographic radio where electronically active surfaces are designed and utilized to receive, transmit, and reflect arbitrary waveforms [189], [190]. This can potentially lead to energy savings, especially in aerial and terrestrial layers. 5G and 6G SatCom with multibeam technology will enable even more advanced services [191] and possibilities for a more efficient use of spectrum in time, frequency, and spatial domains.

C. Cyber Security in the Quantum Era

In 6G communications, post-quantum cryptography will be essential to secure information [39], [192]. We can assume that in the near future an adversary may have access to quantum algorithms that will break the commonly used cryptosystems. Therefore, 6G systems should be quantum proof or at least prepared for a fast transition to post-quantum encryption.

Quantum key distribution (QKD) with an elegant practical solution has already been demonstrated by the Chinese Academy of Sciences and their Micius satellite at the LEO orbit [193]. The experiment used the satellite to establish a secure key between itself and a location in Xinglong, China, and another key between itself and Graz, Austria. The secured connection was used for a video conference. The secure connection worked as follows. After Micius distributed a key with Graz (Key1) and Xinglong (Key2), it performs a bitwise exclusive OR between those keys (Key1 ⊕ Key2) and sends this combined key via a classical channel towards Xinglong station. Combining the XORed key at Xinglong with Key1 leads to the same key (Key2) on both sides.

European plans related to secure space-based connectivity include QKD transmission in order to connect securely ministries and other organizations across the continent. However, there are also challenges related to the use of optical connections, especially in Northern Europe during winter times due to cloudy weather. Thus, it is not yet clear how suitable the concept is e.g., for connecting Helsinki to Brussels. Therefore, careful analysis for the availability and reliability of the concept for local conditions are required before its wide-scale use.

D. AI-Enabled Flexible Networking

6G will enable innovative services with different capacity and latency requirements, and AI technologies can be used to tailor the network and its functionalities on-the-fly to support those services in the best way [194]. Deep learning can be used to optimize the 3D networks from configuration, routing, and computation viewpoints [195]. Machine learning provides e.g., means to identify and exploit repetitive patterns in the constellation geometry and minimize routing computations [196]. This could finally lead to a dynamic network architecture and management with different optimization goals.

Satellite operators aim to reduce costs of future satellite connectivity by using software-defined satellites that enable radio updates with the latest standard features, such as on-the-fly and 3D layered architecture control and management based on extensions of software-defined network concepts that are already used for the terrestrial components [197]–[199]. The ability to change coverage areas, power and frequency allocations, and architecture on-demand would mean that a satellite can be manufactured first and tailored to the operator needs later. AI-empowered SDN technology and MEC paradigms enable anytime anywhere communications.

Dynamic network slicing provides means to support a variety of services [169]. Already, a static network slice enables reserving the resources ahead of time in a coarse-grained manner for end-to-end services instead of per session. Since static slicing consumes resources, dynamic slicing techniques will be needed in future multi-layer networks to quickly create, adapt, and manage slices according to the needs of users and applications while taking into account dynamically varying network architectures. These technologies will not only facilitate the automated network management and increase network flexibility without human interventions, but also provide improved QoS for global multimedia services. This will also improve the longevity and sustainability of the satellites.

E. Deep Space Operations and Autonomous Satellites

Autonomous satellites can use deep learning, expert systems, and intelligent agents to process spacecraft data (telemetry, payload) and to take decisions autonomously during the mission. Artificial intelligence enables autonomous re-planning, detection of internal and external events, and reaction accordingly, ensuring fulfilment of mission objectives without the delays introduced by the decision-making loops on ground [200]. However, increase in the autonomy creates challenges for space traffic management as described in Section VI and thus, new approaches for collision avoidance and information sharing need to be developed.

There are ambitious plans for the humanity in order to see us multi-planetary species in the future. Countries such as the USA, China and the UAE have their own plans related to settlement of Mars during the next century, see e.g. [201]. In order to make this a reality, one needs to create also a supporting infrastructure that includes food and water supply and production, mining, construction, and connectivity. Thus, studies aiming at adding even more layers to the network to also support inter-planetary connections are ongoing. A practical example is the NASA’s Mars Cube One (MarCo) mission – relaying data from the lander to Earth with 6U CubeSats [202]. Another recent example is Nokia’s plan to create a cellular network in Moon [203]. The network will
TABLE VII. SUMMARY TABLE OF FUTURE RESEARCH DIRECTIONS

| Technology topics                             | Challenges and research directions                                                                                                                                                                                                                                                                                                                                                               | References |
|------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Multi-layer constellation design              | 3D network architecture will include satellites at different orbits. There will be small and large satellites simultaneously used, each having different capabilities. How to optimize the number of satellites at different orbits and their inter-connections? New type of simulation tools to support design and operations are needed.                                                                                     | [145],[153],[146],[184] |
| Spectrum use over horizontal and vertical dimensions | Dynamic spectrum management need to be updated to the 6G era, taking into account use of very high frequencies such as terahertz communications. What frequencies can be used for dynamic links and how to utilize AI technologies for flexible operations? Development should cover joint communication and sensing approaches and multi-purpose payloads. | [32],[171],[178],[187] |
| Cyber security in the quantum era             | Quantum computing can break current cryptosystems and therefore fast transition for post-quantum encryption might be required in near future. In addition, secure links e.g. in governmental communications will use QKD technology. What is required to ensure protection of space and ground infrastructure internationally and what will be the role of optical satellite communications? | [43],[180],[192],[193] |
| Flexible satellite architectures and networking | In contrast to traditional satellite systems, the future multi-layer systems are designed to be operated in a dynamic, flexible way. Machine learning and software-defined technology will enable automated operations and update of operations on-the-fly. How to create sustainable business models for “payload-as-a-service” type of operations while simultaneously ensuring predictable service quality? | [195],[196],[199] |
| Space operations and people as multi-planetary species | Future space operations has to create improved means for space debris detection and removal while enabling reliable space traffic management and autonomous collision avoidance procedures. In addition to providing services to Earth we have to develop deep space communications networks using optical and RF technologies to support space missions across the solar system. | [200],[204] |

provide critical communication capabilities for applications such as vital command and control functions, remote control of lunar rovers, real-time navigation and streaming of high definition video. The mentioned applications and connectivity capabilities are vital for long-term human presence on the lunar and Mars surfaces. The key challenge related to deep space operations is crystallized in [204] as “Determining the most cost-effective combination of RF and optical assets for communicating with the postulated human Mars assets while still providing for the needs of all the other missions across the solar system.”

We have summarized the research directions in TABLE VII, complementing the space safety specific table presented in Section VI. Thus, there are definitely interesting times ahead and a lot of challenges for researchers and industries to tackle.

IX. CONCLUSIONS

The world is currently experiencing strong developments in satellite communications and the integration of 5G/6G technology to satellite systems. This is leading to a major turning point globally in the satellite-enabled service business. In this paper we have looked at the development of 6G networks and satellite megaconstellations. Unlike other related review papers, we address the importance of sustainability, highlighting importance of space safety related aspects in the development. We provide a systematic classification of space safety topics related to SatCom development and define promising research directions. As a specific example, we investigate joint communication and sensing related to space debris development, showing how satellite constellations can also help in debris detection and management.

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REFERENCES

[1] European Space Agency, “From 5G to 6G: Space connecting planet Earth for a sustainable future,” White Paper, 2021.
[2] P. Haines, “Overview of satcom market evolution,” presentation [restricted access], ESA ICB meeting, 9 Sept. 2020.
[3] Morgan Stanley, “New Space Economy,” [Online]. Available: https://www.morganstanley.com/Themes/global-space-economy.
[4] C. Pomeroy, A. C.-Diaz, and D. Bielicki, “Fund me to the Moon: Crowdfunding and the New Space Economy,” Space Policy, vol. 47, pp. 44-50, Feb. 2019.
[5] G. Denis et al., “From new space to big space: How commercial space dream is becoming a reality,” Acta Astronautica, vol. 166, pp. 431–443, Jan. 2020.
[6] J. C. McDowell, “The edge of space: Revisiting the Karman line,” Acta Astronautica, vol. 151, pp. 668–677, Oct. 2018.
[7] M. N. Sweeting, “Modern small satellites - Changing the economics of space,” Proc. IEEE, vol. 106, pp. 343-361, Mar. 2018.
[8] N. Saeed, A. Elzanaty, H. Almorad, H. Dahrouj, T. Y. Al-Naffouri, and M.-S. Alouini, “CubeSat Communications: Recent advances and future challenges,” IEEE Commun. Surveys Tuts, vol. 22, pp. 1839–1862, Third Quarter 2020.
[9] D. Roddy, *Satellite Communications*, 4th edition, McGraw-Hill, 2006.
[10] V. Ignatenko, P. Laurila, A. Radiu, L. Lamentowski, O. Anttropov and D. Muff, “ICYE Microsatellite SAR Constellation Status Update: Evaluation of First Commercial Imaging Modes,” in *Proc. IGARSS*, Sept.-Oct. 2020.
[11] IeCyE SAR satellite constellation, [Online]. Available: https://www.iecye.com/sar-data/satellitecapabilities.
[12] S. Dang, O. Amin, B. Shihada, and M.-S. Alouini, “What should 6G be,” *Nature Electronics*, vol. 3, pp. 20–29, Jan. 2020.
[13] M. Höhytýä, M. Corici, M. Covacci, and M. Guta, “5G and beyond for New Space: Vision and research challenges,” in *Proc. IJCSST*, Oct. 2019.
[14] J. Lia, Y. Shi, Z. M. Fadullah and N. Kato, “Space-air-ground integrated networks: A survey,” *IEEE Commun. Surveys Tuts.*, vol. 20, pp. 2714–2741, Fourthquarter 2018.
[15] E. C. Strinati et al., “6G in the sky: On-demand intelligence at the edge of 3D networks,” *ETRI Journal*, vol. 42, pp. 643–657, Oct. 2020.
[16] M. Mozaffari, W. Saad, M. Bennis, Y.-H. Nam, and M. Debbah, “A tutorial on UAVs for wireless networks: Applications, challenges, and open problems,” *IEEE Commun. Surveys Tuts*, vol. 21, pp. 2334–2360, Thirdquarter 2019.
[17] Y. Hua, et al., “Distributed and multi-layer UAV network for the next-generation wireless communication and power transfer,” *IEEE Internet Things J.*, vol. 6, pp. 7103–7115, Aug. 2019.
[18] GSMA White Paper, “High altitude platform systems: Towers in the skies,” June 2021. [Online]. Available: https://www.gsma.com/futurenetworks/wp-content/uploads/2021/06/GSMA-HAPS-Towers-in-the-sky:Whitewaper-2021.pdf.
[19] Alén Space, “Successful launch of the first satellite of the Sateliot constellation,” news announcement, March 2021. [Online]. Available: https://alen.space/successful-launch-of-the-first-satellite-of-the-sateliot-constellation.
[20] B. Soret, I. Leyva-Marga, S. Cioni, and P. Popovski, “5G satellite networks for Internet of Things: Offloading and backhauling,” *Int. J. Satell. Commun. Netw.*, vol. 39, pp. 431–444, July/Aug. 2021.
[21] D. Palmia and R. Birkeland, “Enabling the Internet of Arctic things with freely-drifting small-satellite swarms,” *IEEE Access*, vol. 6, pp. 71435–71443, Nov. 2018.
[22] ITU Broadband Commission, “The state of broadband: Tackling digital inequalities, A decade of action,” September 2020. [Online]. Available: https://www.broadbandcommission.org/publication/the-state-of-broadband-2020/.
[23] International Labour Organisation, “Teleworking during the Covid-19 pandemic and beyond: A practical guide,” [Online]. Available: https://www.ilo.org/wcmsp5/groups/public/---ed_protect/---pravati/---travail/documents/instructonalmaterial/wcms_751322.pdf.
[24] H. Saarimaa, S. Dixit, M.-S. Alouini, A. Chaouab, M. Giordani, A. Kliks, M. Matinmikko-Blue, and N. Zhang (Eds.), “6G white paper: Connectivity for remote areas,” white paper, 6G Research Nos, 5, University of Oulu, 2020. [Online]. Available: http://urn.fi/uri:isbn:9780526226750.
[25] M. Matinmikko-Blue et al., “White paper on 6G drivers and the UN SDGs,” arXiv preprint arXiv:2004.14695, April 2020.
[26] European Space Agency, “ESA and the sustainable development goals,” [Online]. Available: https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Space_for_Earth/ESA_and_the_Sustainable_Development_Goals.
[27] M. Palmroth et al., “Toward sustainable use of space: Economic, technological, and legal perspectives,” *Space Policy*, vol. 49, pp. 12, pp. Aug. 2021.
[28] O. Kodheli et al., “Satellite communications in the New Space era: A survey and future challenges,” *IEEE Commun. Surveys Tuts*, vol. 23, pp. 70–109, Firstquarter 2021.
[29] K. Liolis et al., “Use cases and scenarios of 5G integrated satellite-terrestrial networks for enhanced mobile broadband: The SaT5G approach,” *Int. J. Satell. Commun. Netw.*, vol. 37, pp. 91–112, Mar. 2019.
[30] F. Rinaldi et al., “Non-terrestrial networks in 5G & beyond: A survey,” *IEEE Access*, vol. 8, pp. 165178–165200, Sep. 2020.
[31] X. Lin et al., “On the path to 6G: Embracing the next wave of low Earth orbit satellite access,” [Online]. Available: https://arxiv.org/ftp/arxiv/papers/2104/2104.10533.pdf.
[32] M. Höhytýä et al., “Database-assisted spectrum sharing in satellite communications: A survey,” *IEEE Access*, vol. 5, pp. 25322–25341, Dec. 2017.
[33] R. H. Tehrani, S. Vahid, D. Triantafyllopoulo, H. Lee, and K. Moessner, “Licensed Spectrum Sharing Schemes for Mobile Operators: A Survey and Outlook,” *IEEE Commun. Surveys Tuts*, vol. 18, pp. 2591–2623, Fourth Quarter 2016.
[34] M. Giordani and M. Zorzi, “Non-terrestrial networks in the 6G Era: Challenges and opportunities,” *IEEE Network*, vol. 35 pp. 244-251, March/april 2021.
[35] F. Tariq et al., “A speculative study on 6G,” *IEEE Wireless Commun.*, vol 27, pp. 118–125, Aug. 2020.
[36] A. Yastrebova, R. Kirichek, Y. Koucheryavy, A. Borodin and A. Koucheryavy, “Future networks 2030: Architecture & requirements,” *Proc. ICUMT*, pp. 1-8, Nov. 2018.
[37] T. Huang et al., “A survey on green 6N networks: Architecture and technologies,” *IEEE Access*, vol. 7, pp. 175758–175768, Dec. 2019.
[38] IMT-2030 2021. IMT-2030 (6G) Promotion Group, “White paper on 6G vision and candidate technologies,” June 2021.
[39] P. Raatikainen et al., “Holistic approach to 6G networks,” *VTT White Paper*, Sept. 2021. [Online]. Available: https://info.vttresearch.com/download-beyond-5g.
[40] J. Radtke, C. Kebuschl and E. Stoll, “Interactions of the space debris environment with mega constellations—Using the example of the OneWeb constellation,” *Acta Astronautica*, vol. 131, pp. 55–68, Feb. 2017.
[41] A. H. Sanchez, T. Soares, and A. Wolahan, “Reliability aspects of mega-constellation satellites and their impact on the space debris environment,” in *Proc. RAMS*, Jan. 2017.
[42] A. C. Boley and M. Byers, “Satellite mega-constellations create risks in Low Earth Orbit, the atmosphere and on Earth,” *Nature Sci. Rep.*, Vol. 11, May 2021.
[43] D. Housen-Couriel, “Cybersecurity threats to satellite communications: Towards a typology of state actor responses,” *Acta Astronautica*, vol. 128, pp. 409–415, Nov./Dec. 2016.
[44] T. Breton, Speech at the workshop on space based secure connectivity project, [Online]. Available: https://ec.europa.eu/commission/ commissioners/2019-2024/breton/announcements/workshop-space-based-secure-connectivity-project_en.
[45] Space Safety Coalition, “Best practices for the sustainability of space operations,” Sep. 2019. [Online]. Available: https://spacesafety.org/best-practices/.
[46] SpaceNews, “From space traffic awareness to space traffic management,” [Online]. Available: https://spacenews.com/from-space-traffic-awareness-to-space-traffic-management.
[47] Space Safety Coalition website. Available: https://spacesafety.org/.
[48] World Economic Forum, “Space Sustainability Rating.” [Online]. Available: https://www.weforum.org/projects/space-sustainability-rating.
[49] Ministry of Economic Affairs and Employment, Finland, “Act on Space Activities,” 2018 [Online]. Available: https://tem.fi/documents/1410877/3227301/Act+on+Space+Activities/a396c9-18fd-4504-Rea0-bf1f1986df28/Act+on+Space+Activities.pdf?151730381000.
[50] 3GPP, “Technical Specification Group Services and System Aspects: Guidelines for Extraterrestrial 5G Systems,” TR 22.926 V1.0.0, Technical Report, Sept. 2021.
[51] C. Stöcker, R. Bennett, F. Nex, M. Gerke and J. Zevenbergen, “Review of the current state of UAV regulations”, *Remote Sens.*, vol. 9, no. 5, pp. 459, 2017.
[52] Ministry of Defence, Finland’s Cyber Security Strategy”, [Online]. Available: https://www.defmin.fi/files/2378/Finland_s_Cyber_Security_Strategy.pdf.
[53] Ministry of Finance, Finland, “Sustainable growth programme for Finland,” 2021. [Online]. Available:...
[148] A. Yastrebova et al., “Theoretical and simulation-based analysis of terrestrial interference to LEO satellite uplinks,” in Proc. GLOBECOM, Dec. 2020.

[149] Satellite Network Simulator 3 (SNS3), [Online]. Available: https://www.sns3.org/content/home.php.

[150] J. S. Rappaport et al., “Millimeter wave mobile communications for 5G cellular: It will work!”, IEEE Access, vol. 1, pp. 335–349, May 2013.

[151] G. Andrews et al., “Modeling and analyzing millimeter wave cellular systems,” IEEE Trans. Commun., vol. 65, pp. 403–430, Jan. 2017.

[152] M. Giordani and M. Zorzi, “Satellite Communication at Millimeter Waves: A Key Enabler of the 6G Era,” in Proc. ICNC, pp. 383-388, Feb. 2020.

[153] First W-band transmission from space, [Online]. Available: https://arts.esa.int/news/first-wband-transmission-space

[154] A. Yastrebova, T. Ojanperä, J. Mäkelä and M. Höyhtyä, “Hybrid connectivity for autonomous vehicles: Conceptual view & Initial results,” in Proc. VTC Spring, May 2021.

[155] M. Vehkaperä, M. Hoppari, J. Suomalainen, J. Roivainen, and S. Rantala, “Testbed for local area private network with satellite in orbiting relay,” in Proc. IEECEC, June 2021.

[156] J. F. Hayes, “Adaptive feedback communications,” IEEE Trans. Commun. Technol., vol. CT-16, pp. 29–34, Feb. 1968.

[157] S. Haykin, “Cognitive radio: Brain-empowered wireless communications,” IEEE J. Sel. Areas Commun., vol. 25, pp. 201–220, February 2005.

[158] A. D. Panagopoulos, P.-D. M. Arapoglou, G. E. Chatzarakis, J. D. Kanellopoulos, and P. G. Cottis, “Coexistence of the broadcasting satellite service with fixed service systems in frequency bands above 10GHz,” IEEE Trans. Broadcast., vol. 52, pp. 100–107, Mar. 2006.

[159] M. Höyhtyä, J. Kyröläinen, A. Hulkonen, J. Ylitalo, and A. Roivainen, “Application of cognitive radio techniques to satellite communication,” in Proc. DySPAN, pp. 540–551, Oct. 2012.

[160] M. Matinmikko et al., “Cognitive radio trial environment: First live authorized shared access-based spectrum-sharing demonstration,” IEEE Veh. Tech. Mag., vol. 8, pp. 30–37, Sept. 2013.

[161] M. M. Sohul, Y. Miao, T. Yang, and J. H. Reed, “Spectrum access system for the citizen broadband radio service,” IEEE Commun. Mag., vol. 53, pp. 18–25, Jul. 2015.

[162] M. Palola et al., “Field trial of the 3.5 GHz citizens broadband radio service governed by a spectrum access system (SAS),” in Proc. DySPAN, Mar. 2017.

[163] M. Höyhtyä et al., “Critical communications over mobile operators’ networks: 5G use cases enabled by licensed spectrum sharing, network slicing, and QoS control,” IEEE Access, vol. 6, pp. 73572–73582, December 2018.

[164] M. Höyhtyä et al., “Licensed shared access field trial and a testbed for integrated satellite-terrestrial communications including research directions for 5G and beyond” Int. J. Satell. Commun. Netw., vol. 39, pp. 455–472, July/Aug. 2021.

[165] M. Matinmikko-Blue, S. Yrjölä and P. Ahokangas, “Spectrum management in the 6G era: The role of regulation and spectrum sharing,” in Proc. 6G SUMMIT, Mar. 2020.

[166] M. Höyhtyä, A. Mämmelä, A. Chiumento, S. Pollin, M. Forsell, and D. Cabric, “Database-assisted spectrum prediction in 5G networks and beyond: A review and future challenges,” IEEE Circuits Syst. Mag., vol. 19, pp. 34–45, Third Quarter 2019.

[167] J. Kokkonen, J. M. Jornet, V. Petrov, Y. Koucheryavy and M. Juntti, “Channel modeling and performance analysis of airplane-satellite terahertz band communications,” IEEE Trans. Veh. Tech., vol. 70, pp. 2047–2061, Feb. 2021.

[168] J. Kokkonen, J. M. Jornet, V. Petrov, Y. Koucheryavy and M. Juntti, “Channel modeling and performance analysis of airplane-satellite terahertz band communications,” IEEE Trans. Veh. Tech., vol. 70, pp. 2047–2061, Feb. 2021.
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