RESEARCH REPORT

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Emerging 5G satellite-aided networks for mission-critical services

A survey and feasibility study

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Summary

The main goal of this report is to provide a survey and feasibility study on emerging satellite-aided communication networks with respect to target mission critical service (MCS) concepts. While terrestrial VIRVE 2.0 network is now being deployed, a key question is how satellite-aided terrestrial network could further help MCS in future versions of VIRVE network.

A significant boost is expected from recent *3GPP nonterrestrial specification* activities, which are still in early stage, to clue the terrestrial and nonterrestrial communities together more efficiently than in the past. Another boost is coming from *new space economy* and *low-orbit mega-constellation* frameworks. Both of these upswings are expected to realize during the next decade. Nevertheless, small low-orbit satellites will not replace existing large satellites, but complement them, while not being fundamentally that different. Underneath the hype, there are a number of challenges, both business- and technology-wise, still to overcome in the coming years to unleash all the expectations, as summarized in the report.

The performed study is mainly qualitative and based on conducted nonpublic interviews of selected MCS users and publicly available state-of-the-art literature. The report is rather comprehensive with connections to MCS user scenarios, requirements, existing and emerging technologies for terrestrial, airborne, and space, business perspectives, standardization, international and Finnish aspects, etc. However, the satellite technology area is at a turning point in which unpredictable and rapid changes are inherent. Therefore, some items discussed in this report may become quickly outdated, calling for a constant monitoring of the progress of the field.

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Glossary

3GPP	3rd generation partnership project
5G	Fifth generation
5QI	5G quality of service indicator
AES	Advanced encryption standard
AKA	Authentication and key agreement
CMR	Cellular mobile radio
CP	Control plane
DL	Downlink
DRS	Department of Rescue Services
DVB	Digital video broadcasting
E2E	End-to-end
EC	Edge computing
ERVE	Suomen Erillisverkot Oy
ESA	European space agency
ESAF	Emergency Services Academy Finland
ETSI	European telecommunications standards institute
FAA	Federal Aviation Administration
FBG	Finnish Border Guard
FDF	Finnish Defence forces
GEO	Geostationary earth orbit
GMR	Geostationary earth orbit mobile radio
gNB	Next generation node B
HAP	High-altitude platform
HEO	Highly-eccentric orbiting
IoT	Internet of things
IP	Internet protocol
IPsec	Internet protocol security
ITU	International telecommunication union
LAP	Low altitude platform
LEO	Low earth orbit
LTE	Long-term evolution
M2M	Machine to machine
MCData	Mission critical data
MCPTT	Mission critical push to talk
MCS	Mission critical services
MCVideo	Mission critical video
MEO	Medium earth orbit
MTC	Machine-type communications
NASA	National Aeronautics and Space Administration
NB-IoT	Narrowband internet of things
NFV	Network function virtualization
NR	New radio
NSE	New Space Economy
NSI	Network slice instance
NTN	Nonterrestrial network
P25	Project 25
PMR	Professional mobile radio
QCI	Quality of service class identifier
QoS	Quality of service
SatCOLT	Satellites cell on light trucks
satcom	Satellite communication
SDN	Software-defined network
SMEC	Satellite mobile edge computing
TCP	Transmission control protocol
TETRA	Terrestrial trunked radio
TR	Technical report
TS	Technical specification
TLS	Transmission layer security
UAV	Unmanned aerial vehicle
UC	Use case
UCS	Union of Concerned Scientists
UDN	Ultra-dense network
UE	User equipment

UHF	Ultra high frequency
UL	Uplink
UP	User plane
VHF	Very high frequency
VIRVE	Viranomaisverkko

1. Introduction

1.1 Mission critical services

Mission critical service (MCS) is an authoritative service, which must be carried out with a high success probability often in challenging conditions where human life or health is in danger (GSMA 2017). A typical MCS event can be related to a natural disaster, terrorism event, battlefield mission, and missing or injured persons. Both the civil and military authorities can leverage mission critical services. In the civil domain, typical end users are police, fire fighters, rescue personnel, paramedics, civil protection personnel, etc. For the military applications, the end users are land force soldiers, navy soldiers, air force pilots, scouts, etc. Many of the actual military operations can also be related to public safety and disaster relief rather than in waging a war.

Different MCSs have their specific objectives and characteristics. Typically, the management of MCSs is divided into phases to discriminate the events that occur before, during, and after the overall MCS process. The emergency management phases and their specific characteristics can be different for various MCSs. Nevertheless, most of the MCSs can be described via generic MCS cycle as follows (see an illustration from Figure 1):

Preparedness: Monitoring, resourcing, planning, scouting, learning etc. to get ready for possible mission critical events.

Response: Evaluating needs of particular event, alerting interest groups and population, activating control/command centers, conducting intervention of responders, dominating activities.

Recovery: Re-establishing normal conditions, possibly transferring control back to customary authorities.

Mitigation: Prevent other immediate critical events and provide information for the preparedness phase.

Figure 1. Generic MCS cycle.

1.2 Communications as a key MCS enabler

Prompt communication between different interest groups within an MCS is vital to allow successful completion of the mission, see Figure 2. Furthermore, proper communication networks are needed for obtaining sufficient shared situational awareness and alerting the population. The control centre operators make mission coordination decisions based on available information from responders and sensors such as location devices, video clips from surveillance cameras, and emergency communication with other involved parties. The typical communication applications include mission critical push to talk (MCPTT), mission critical data (MCData), and mission critical video (MCVideo). A conventional mission critical communication system is built on a dedicated network infrastructure based on a number of terrestrial professional mobile radio (PMR) technologies (Kumbhar 2017). A more recent trend is to apply publicly available 3GPP specified mobile networks (Choi 2019). One of the main challenges in terrestrial communications is to be able to provide ubiquitous connectivity for diverted and strict MCS needs and requirements. Emerging trend is to apply nonterrestrial networks (NTN) or airborne communications networks to assist reliable and prompt mission critical communications (Berioli 2011).

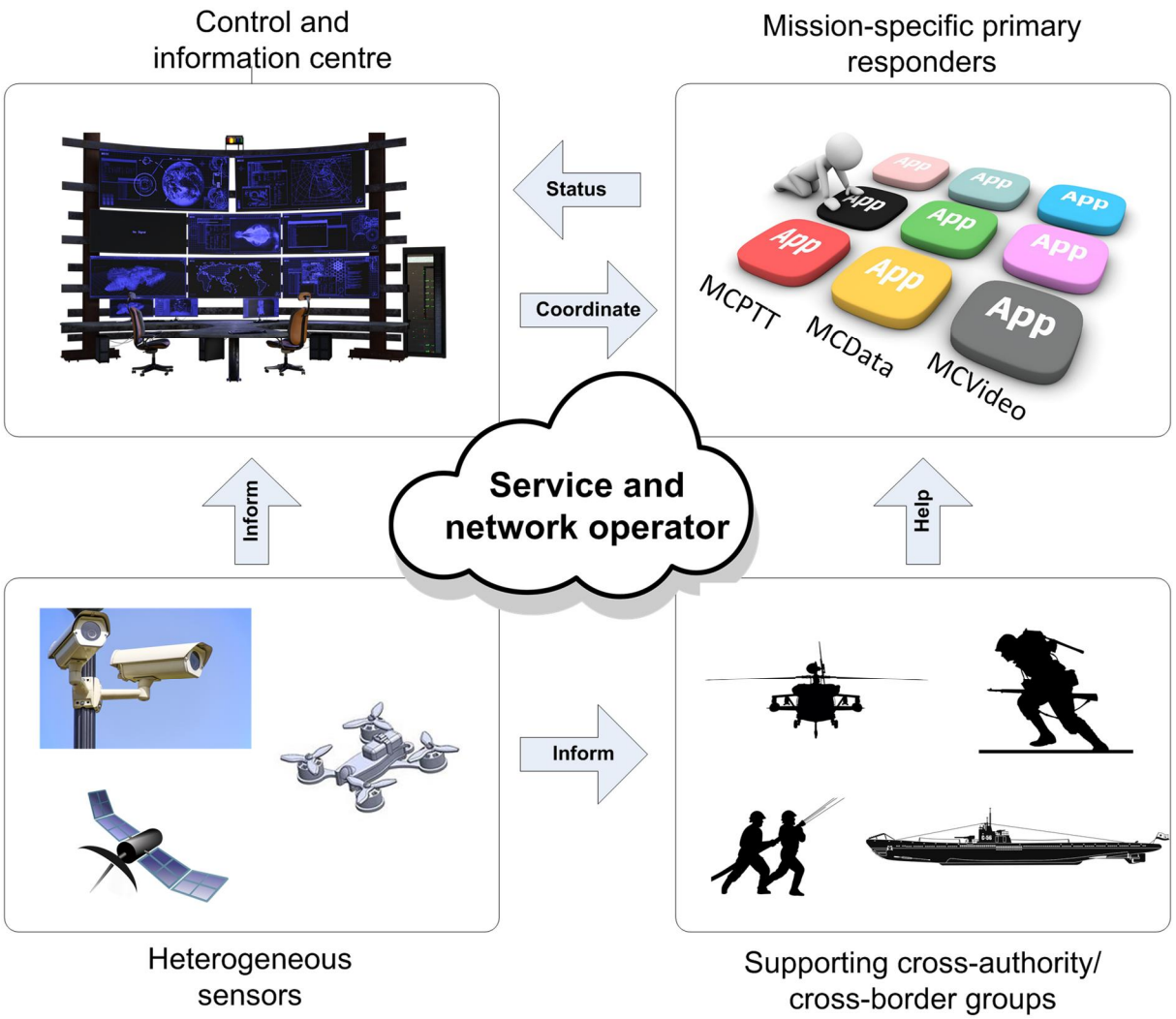

Figure 2. Illustration of a simplified MCS communication architecture.

1.3 Objectives and scope of given assignment

The purpose of this report is three-fold:

i. to present an overview of selected mission critical use cases (UCs) and their requirements that could benefit from NTN communications;
ii. to provide a brief summary of existing and emerging communication technologies;
iii. to present a qualitative analysis on feasibility of NTN communications for the MCS with emphasis on small low-orbit satellites.

The target work flow is given in Figure 3. The service provider is Suomen Erillisverkot (ERVE) and the selected MCS user representatives are Finnish Defence Forces (FDF), Finnish Border Guard (FBG), Department for Rescue Services (DRS), and Emergency Services Academy Finland (ESAF). VTT's background on satellite technologies is briefly described in Appendix 0.

The main driver and perspectives of the report are selected to support the interest of ERVE. ERVE expects to have a useful survey type qualitative analysis on how emerging satellite communication technologies are able to help to maintain reliable communications in their specific authoritative user applications worldwide and in Finland. The material is utilized as background material in ERVE's follow up decisions in using satellite communications in selected use scenarios for the customers of ERVE. The special interest is the usability of small satellites to extend the communication coverage and reliability in Lapland and Arctic areas (satellites as a relay network, "capacity highway"). In essence, ERVE wants to participate in emerging satellite ecosystem in Finland, to understand its capability of surviving in the future, and make the best of it in its central authoritative missions.

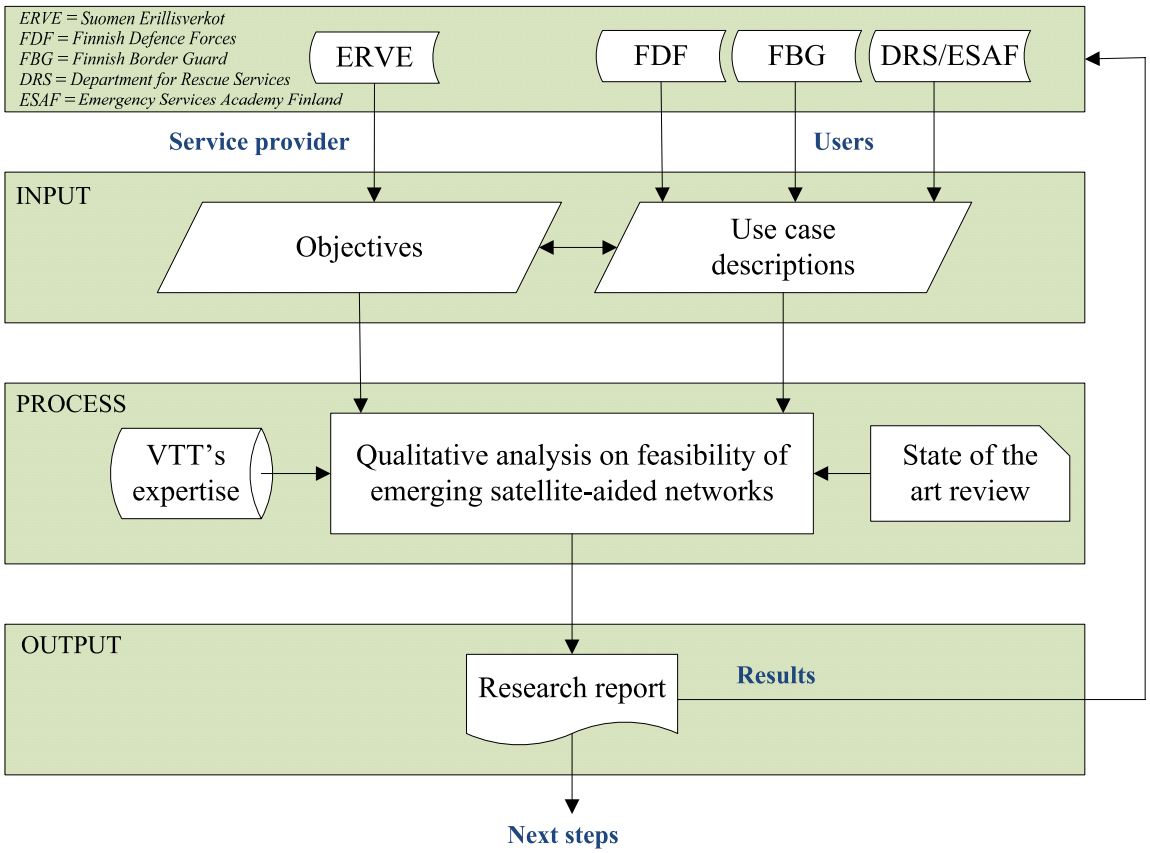

Figure 3. Work flow.

The organization of the report is as follows. In Section 2, the selected use scenarios and their requirements are specified. A brief summary of existing communication technologies is given in Section 3. Emerging 5G integrated communication technologies are treated in more detail in Section 4. Then, business perspectives are provided in Section 5. Finally, discussion and overall assessment are presented in Section 6, followed by our conclusions in Section 7.

2. Mission critical services and requirements

In this section, we provide the selected MCS descriptions and their requirements as received from the invited field experts who have hands-on knowledge on how their specific MCS scenarios are operating today and what are their potential needs now and in the future. We start with an outline of generic MCS characteristics in Section 2.1 to provide a more comprehensive understanding of the global MCS landscape. Next, we provide the received inputs for specific UCs in Section 2.2 which are given in confidential Appendices 1-3. More discussion of the UC inputs is then provided later in confidential Appendix 4.

2.1 Generic MCS types and requirements

The most common MCS types (identified below with Sx) are commonly categorized as (Jarwan 2019):

S1. **Voice services.** Interactive voice services include e.g. regular full-duplex calls (bi-directional simultaneously), regular half-duplex calls (bi-directional in turn), and emergency calls (high priority) between two or more participants. Noninteractive voice services enable ambient listening, sharing caller ID, or exchanging voice alerts.

S2. **Data services.** Interactive data services include e.g. real-time location information and map readings, access to target database servers, and biometric identification with interactive verification. Noninteractive services include text messages and sensor data information related e.g. to environmental features or human vital parameters.

S3. **Video/Multimedia services.** Interactive multimedia services include e.g. one-to-one or group video calls and identifying people based on video monitoring. Noninteractive multimedia services include recording/accessing offline or real-time surveillance video clips and images.

Mission critical users typically require communications that satisfy the following set of essential functional and nonfunctional requirements (identified below with Rx). We propose a requirement classification below where the information is essentially gathered from (Berioli 2011, Budka 2011, Choi 2019, 3GPP 2017, Simsek 2016, ETSI 2012):

R1. **MCS immediacy.** It is important to avoid any extra delays induced from communications in any delay-sensitive MCS. The typical baseline for an acceptable service delay is the human's ability to perceive response time. The response times of human senses are in the order of ~100 ms, ~10 ms, and ~1 ms, respectively, for auditory, visual, and tactile information. For an MCS user, it is important to experience an instantaneous reaction after a service-calling button is pressed in an end user device to avoid any extra delays to conduct a time-critical mission. There are a number of more content-specific delay parameters to specify different parts of the overall delay.

R2. **MCS availability.** In addition to immediacy requirement in R1, MCS availability is an important indicator of the overall system reliability. The availability is defined as the percentage value of the amount of time the end-to-end communication service is delivered according to an agreed quality of service, divided by the amount of time the system is expected to deliver the end-to-end service according to the specification in a specific area. A typical communication service availability target varies between 99 - 99.999 %. E.g. for current satcom of the FirstNet system 99.5% availability is achieved (FirstNet 2019) while 3GPP/R16 specification set the target to be 99.99 % for satcom links (3GPP 2019b). The above availability range can be straightforwardly changed into experienced service downtime per year between 0.08 - 90 hours. It is obvious that for MCS, a high service availability closer to the "five nines" is of

paramount importance, encountering the cases where the primary network infrastructure becomes out of order. Such fault tolerance should be ensured with a possibility to survive with infrastructure-free or network off-mode communications. While the MCS is available to the end user, its communication quality in terms of delay, bit rate, and packet error rate must be satisfactory. Availability measurement may not be trivial as the definition of the state of service unavailability may be diverted. For instance, the period of service unavailability may change from a millisecond (e.g. packet losses) to hours (e.g. base station power outage) and a given period may be significant for the end user to maintain a stable data session but may be unnoticed by the network operator. These all depend on individual user experience. For instance, the voice quality must be good enough so that the received information is not ambiguous in the presence of possible background noise.

R3. **MCS functionality.** MCS has some specific functionalities that are not typically present in normal (non-MCS) applications with such stringent requirements. One main feature is push-to-x property, i.e. a service type (x can denote voice, data, or video) that enables users to reach desired destination(s) with a single button press to ease the information sharing and save energy of the device. Another functionality is group communications where group members are multicasting the same information to each other simultaneously and promptly. The groups can be formed based on certain location or specific connection functionality. The typical MCS operates in phases as shown in Section I. The communications requirements may change in each phase of the operation cycle.

R4. **MCS accessibility.** MCS accessibility refers to ability of the communication network to provide connectivity in critical situations where full operation of the network may be violated. It is highly desirable that MCS operators can dynamically select whether a particular MCS uses on-network infrastructure or off-network infrastructure-less approaches. Infrastructure-less access can be provided via device-to-device proximity based services, local base stations without connection to the core network, or large-distance satellite network. The main objective is to provide seamless radio coverage, mobility support, and service-specific quality provision with a guaranteed bandwidth for emerging multimedia content in MCS. Local and remote access should be provided simultaneously.

R5. **MCS interoperability.** The different technology enablers of MCS must be interoperable. From a communication point of view, the used radio devices must be compatible. There are a number of reasons for potential violation of being interoperable, e.g. group members use different radio standards or cross-border activities lead to incompatibility issues. Moreover, different parties may have different requirements for the performance and security.

R6. **MCS priority and security.** MCS priority mechanisms are important when there are more users than communication resources available and because different MCS can have different levels of urgency. Priority must be handled between MCS users and non-MCS users as well as between users within a single MCS. E.g., dispatchers may need to override responders' connections as they have a broader view of situations at hand. In light of this, a pre-emption mechanism between different connections must be properly established. Efficient encryption for cybersecurity might be essential for some MCS while less important for others. Encryption key management adds extra cost as for group calls group keys are needed. Reliable user authentication is vital.

R7. **MCS usability and profitability**. MCS end device usability may have some specific needs related to device form factors, robustness to accidents, deployment rapidity, operation lifetime, and clarity of user interface. Moreover, feasible service cost models and ecosystem models are needed that include the potential of various hybrids formed via authoritative and commercial systems.

It is important to note that a mission critical operation does not typically require all above requirements to be satisfied at all times. This observation can be utilized to optimize the priority control procedures.

In the following tables, we outline 5G/R16 3GPP requirements for the main MCS applications. 3GPP uses the standardized quality of service class identifier (QCI) to address requirements for different type of payloads (TS 23.203)[1]. 3GPP defines additional set of requirements for 5G networks and call it 5G quality of service indicator (5QI), see more from (TS 23.501). Nevertheless, for the MCS services at hand, the requirements have not changed except for having different priority weights. More MCS-specific requirements can be found separately for MCPTT (TS 22.179), MCData (TS 22.282), and MCVideo (TS 22.281). While some requirements are service specific, some requirements are given for different operating environments (TS 22.261).

Table 1. Standardized 5G/R16 3GPP requirements for MCPTT.

Parameter	Requirement	Comments
Packet delay	75 ms	Link-level IP packet delay between a user and gateway
Access delay	300 ms	Time between connection request and connection availability
End-to-end access time	1000 ms	Time between connection request and connection availability with ack from the receiver
Mouth-to-ear latency	300 ms	Time between generating audio by a transmitting user and hearing the audio by the receiving users
Late call entry time	350 ms	Time between entering the existing group call and receiving audio from a speaker
Packet loss rate	10^{-2}	Link layer rate of lost packets and total number of packets
Priority weight	7	Currently, 5 denotes highest priority and 90 denotes lowest priority

Table 2. Standardized 5G/R16 3GPP requirements for MCData.

Parameter	Requirement	Comments
Packet delay	200 ms	Link-level IP packet delay between a user and gateway
Communication set-up time	1000 ms	
Control delay	50 ms for aerial vehicles 200 ms submarines 400 ms for terrest. vehicles	End-to-end latency between action of controller and movement of robot
Packet loss rate	10^{-6}	Link layer rate of lost packets and total number of packets

[1] All TS xx.xxx and TR xx.xxx references used in this report can be found from https://portal.3gpp.org and are not included in the reference list.

Priority weight	55	Currently, 5 denotes highest priority and 90 denotes lowest priority

Table 3. Standardized 5G/R16 3GPP requirements for MCVideo.

Parameter	Requirement	Comments
Packet delay	100 ms	Link-level IP packet delay between a user and gateway
Start delay	2000 ms	Delay between requesting the MCVideo and actual start of the video transmission
End-to-end delay	1000 ms	Delay between video transmission and reception
Audio synchronization delay	50 ms	Synchronization between video and audio
Packet loss rate	10^{-3}	Link layer rate of lost packets and total number of packets
Priority weight	15	Currently, 5 denotes highest priority and 90 denotes lowest priority

Table 4. Standardized 5G/R16 3GPP requirements for different operating environments.

Environment	Requirement	Comments
Urban macro	Data rate: 50 Mbps (DL), 25 Mbps (UL) Traffic capacity: 100 Gbps/km^2 User density: 10 000/km^2 UE speed: 120 km/h	All values are targeted maximum values for high data rate applications, not strict requirements for all applications. DL = downlink, UL = uplink
Dense urban	Data rate: 300 Mbps (DL), 50 Mbps (UL) Traffic capacity: 750 Gbps/km^2 User density: 25 000//km^2 UE speed: 60 km/h	
Rural	Data rate: 50 Mbps (DL), 25 Mbps (UL) Traffic capacity: 1 Gbps/km^2 User density: 100/km^2 UE speed: 120 km/h	
Indoor	Data rate: 1 Gbps (DL), 500 Mbps (UL) Traffic capacity: 1 Tbps/km^2 User density: 250 000/km^2 UE speed: 3 km/h	
High-speed vehicle	Data rate: 50 Mbps (DL), 25 Mbps (UL) Traffic capacity: 100 Gbps/km^2 User density: 4000/km^2 UE speed: 250 km/h	
Aerial	Data rate: 15 Mbps (DL), 7,5 Mbps (UL) Traffic capacity: 1.2 Gbps/plane User density: 400/plane UE speed: 1 000 km/h	
Satellite	GEO end-to-end delay: 285 ms MEO end-to-end delay: 95 ms LEO end-to-end delay: 35 ms	

2.2 Enquiry responses for specific use cases

In this section, we summarize the responses of the selected interviewees related to use cases of target MCS. Confidential information is left out from the public version of the report. The main objective of the questionnaire was to obtain first-hand information of current challenges of selected MCS and learn the current position of expectations on current and future satcom utilization. The enquiry was implemented in two phases by first providing the answers to the questions off-line in writing and then via supplementary short online oral discussion when it was necessary and possible. The answers were then compiled from these two processes. The goal was to answer in a best-effort fashion, i.e., if the answer was not easily available it was allowed to be ignored.

The questions were divided into the following three color-coded requirement categories (question identification style in parentheses):

1) *Functional requirements, i.e. behavioral description, what the system should do (ID: F.x)*
2) *Nonfunctional requirements, i.e. qualitative description, how well the system should work (ID: NF.x)*
3) *Additional profiling questions treating the target technologies (ID: P.x)*

For each separate set of questionnaire, we start with a very brief background introduction and then end with a short summary of the answers with a rough analysis, written by the authors. The actual interview questions and answers are provided in the nonpublic appendices at the end of the report.

2.2.1 Use Case 1: Military Communications

Background: The communications network of Finnish Defence Forces (FDF) is a large setup composed of core network, access network, and various tactical networks (FDF 2019). The core network is part of national security network called Turvallisuusverkko (TUVE). The construction and maintenance of TUVE is done by Suomen Turvallisuusverkko Ltd and supported by a unit called C5 Agency (Johtamisjärjestelmäosasto) from Defence Command unit of FDF. The tactical networks of land, navy, and air forces are connected via access network whose maintenance is jointly covered by FDF and Suomen Turvallisuusverkko. The support from the public communications network is used where applicable.

Questions and responses for FDF: See (nonpublic) Appendix 1

Obtained inference for FDF: See (nonpublic) Appendix 4

2.2.2 Use Case 2: Border Control

Background*:* The Finnish Border Guard (FBG) is an internal security agency operating under the Ministry of the Interior (FBG 2019). The aim is to maintain peaceful conditions in the border areas of our country. The main tasks are to guard Finland's borders on land and at sea, carry out border checks on persons at land border crossing points, ports and airports, and perform search and rescue operations, particularly at sea. Because Finland is a member of the European Union and a Schengen country, the activities focus on the external border. The FBG coordinates search and rescue at sea activity, performs searches and transports ill or injured persons within the area under its control. The Border Guard also performs police duties and customs controls at border crossing points not covered by the Finnish Customs. At sea areas, FBG cooperates with the Finnish Transport Agency, Finnish Transport Safety Agency Trafi,

Defence Forces, and environmental authorities. The FBG has up-to-date response equipment for oil and chemical pollution incidents.

Questions and responses for FBG: See (nonpublic) Appendix 2

Obtained inference for FBG: See (nonpublic) Appendix 4

2.2.3 Use Case 3: Rescue Services

Background: The activities of rescue services in Finland include a number of sectors of the society (DRS 2019). The department of rescue services (DRS) is focused on accident prevention, rescue operations, preparedness, warning and civil defence in disaster event, firefighting services, paramedics etc. There are 22 different rescue service divisions in Finland. The continuous societal and operational changes constantly challenge the successful mission of rescue services. The rescue service in Finland has been recently undergoing a significant reformation, including ICT activities. Emergency Services Academy Finland (ESAF) is an education institute providing training for rescue services in Finland (ESAF 2019). ESAF is also responsible for coordination of related research activities.

Questions and responses for DRS and ESAF: See (nonpublic) Appendix 3

Obtained inference for DRS and ESAF: See (nonpublic) Appendix 4

3. Summary of existing communication technologies for MCS

In this section, we outline the mainstream communication technologies for MCS. The technologies are classified into terrestrial, aerial, and satellite technologies. We treat the terrestrial and aerial technologies only briefly with references to look for more details, and elaborate satellite technologies more thoroughly.

3.1 Terrestrial technologies

The existing terrestrial wireless communication technologies for MCS can be classified into two mainstream categories: professional mobile radios (PMR) and cellular mobile radios (CMR). Also other less used options exists. In the following, we briefly discuss some main features of these technologies. Good comprehensive surveys with references to find information, that is more detailed, can be found from (Baldini 2014, Kumbhar 2017, Pervez 2018, Jarwan 2019).

3.1.1 Professional mobile radios

PMRs, also called as private mobile radios and land mobile radios, are widely used for various MCS worldwide. Analog PMRs have been largely replaced by digital PMRs for which terrestrial trunked radio (TETRA) and Project 25 (P25) are the most common standards in Europe and USA, respectively (Baldini 2014). TETRA is standardized by European Telecommunications Standards Institute (ETSI) while P25 is a standard from Telecommunications Industry Association (TIA). In the following, we elaborate more on European TETRA standard.

TETRA standard, the first version published in 1995, enables point-to-point calls, point-to-multipoint calls, and broadcast calls. The data rates varies between 2.4 - 28.8 kbit/s using time-division multiple access and differential phase shift keying. TETRA devices can connect directly to the destination that is in coverage or then using TETRA base stations. Interference can be detected and avoided via frequency hopping mechanisms. TETRA has also support for various priority and cybersecurity encryption methods. The second generation is called TETRA enhanced data services (TEDS) increases the data rate up to 473 kbit/s while supporting first generation TETRA features. Another advantage of TETRA includes the scalability of the number simultaneous users, which can range from few users to thousands of users in a number of different groups. The calls are formed quickly supporting the standard 300 ms delay requirement. The main limitation of TETRA is a rather low data rate.

3.1.2 Cellular mobile radios

The older 2G and 3G commercial CMR systems have not been developed to satisfy MCS requirements. However, some organizations, offering MCS, use them if there are no other options for proper communications. The recent development is taking place within 3GPP-specified 4G LTE to be modified towards MCS requirements and first deployments have been made (Jarwan 2019). Essentially, the First Responder Network Authority (FirstNet), operated in USA by AT&T, is one of the most important ones. Currently, it is not intended to replace legacy PMR as it does not possess all the required features and there is need to support the continuing use of the legacy systems. Nevertheless, it provides significant path towards higher data multimedia and sensing applications supporting MCS requirements. New spectrum is taken into use. Nokia and Nordic Telecom reported recently the launch of world's first MCS-ready LTE network in 400 MHz band in Czech Republic (Nokia 2019). Other authoritative cellular networks under development include Emergency Service Network in UK.

It is also expected that LTE technology with substantial market volume will reduce the infrastructure and operating costs for future MCS compared to PMR. The large-scale use of

LTE technology helps further to solve some interoperability issues of PMR. Finally, the recent developments in end-to-end delay performance, device-to-device communications, isolated operation for public safety without backhaul connectivity, priority and quality management, push-to-X functionality, and group communications make LTE an appealing technology for MCS. There is typically a significant delay after which each functionality is actually implemented by vendors. The remaining main challenge involve reaching the ultra-reliable connections closer to 99.999 % availability with guaranteed quality of service. Moreover, the coexistence between legacy PMR and other LTE commercial use must be resolved in different levels.

3.1.3 Other terrestrial radios

If there is no PMR or CMR available in the particular area that MCS is deployed, there are some other terrestrial radio options available. These include wireless local area networks, mobile ad hoc networks, low power wide area networks, short-range radios (near field communication, ZigBee, Bluetooth, radio frequency identification radios), optical radios, personal mobile radios operating on VHF/UHF, and special purpose radios used for avionics and marine communications, see more information from (Baldini 2014, Pervez 2018). They can be also integrated with PMR and CMR to optimize the overall performance. That is, some MCS can benefit from both long- and short-range radios at the same time, sharing information locally and remotely.

3.2 Aerial technologies

Aerial technologies encompass low altitude platforms (LAP) with unmanned aerial vehicles as well as high altitude platforms (HAP). There is no consensus on the threshold where low altitude changes to high altitude but typically low altitude is below few kilometres and high altitude is between few kilometres and few tens of kilometres. For instance, ITU defines HAP to be at an altitude of 20 to 50 km (ITU 2019). In the following, we look at these technologies from a communication point of view when applied to enhance MCS. Good surveys on aerial technologies for MCS is found from (Deaton 2008, Naqvi 2018, Erdelj 2017, Dukowitz 2018).

3.2.1 Low altitude systems

LAP vehicles, such as drones, have been increasingly used for various MCS scenarios. Typically, drones assist the mission by providing visual situational awareness to responders and control centres and today there are number of different sensors that can be mounted to drones. Unmanned vehicles have been used extensively in military applications for surveillance and reconnaissance. Another common MCS example is firefighting where drones can assist in several ways as well as search and rescue. Third significant application, which is more relevant to the scope of this report, is to enhance the communication performance by harnessing drones with base stations utilizing their resulted high mobility capability.

In essence, drones can be used to quickly establish ad hoc networks with line-of-sight links for MCS event areas using embedded base and relay stations. This ability is appealing in situations that the primary infrastructure is out of order or significantly congested. Nevertheless, this scenario has not been used yet that much in actual MCS communications systems. One recent commercialized example is Flying Cells on Wings -concept from AT&T which is operating along with the FirstNet technology (AT&T 2019). The associated drones can see through obstacles, fly through rain, operate in extreme temperatures, and enhance communications coverage up to 40 square miles in disaster areas via LTE or satellite links. After the emergency is over, drones return to closest cell towers and await for their next mission. AT&T used the drones e.g. in Puerto Rico during Hurricane Maria in 2017 where network-assisting drones provided thousands of voice calls and data accesses. Currently, the

drones are operated manually but could be autonomously directed by the network itself in the future.

Currently existing commercial LAP vehicles remain airborne only few tens of minutes without recharging. Energy is consumed by the propulsion system and on-board electronics and radios. Consequently, their missions and flight paths must be carefully designed and optimized given the available on-board energy capacity. Moreover, as LAP vehicle operate airborne, the interference control quickly changing network topologies become even more important as the signals travel with larger distances.

3.2.2 High altitude systems

HAP systems, such as unmanned airships and aircrafts, operate at higher altitudes to increase the communication coverage from that of terrestrial systems as well as LAP systems (Deaton 2008, Mohammed 2011, Oliveira 2016). The suitable altitude is obviously well above clouds and airplane paths where the air resistance and risk of collisions are milder. Mostly used altitudes are between 17 and 22 km due to relatively mild winds and turbulences in that region. It provides further flexibility in the altitudes that are unreachable by LAP or satellites. Larger HAP vehicles typically have also longer operating lifetimes from weeks or even months. The recent interest on HAPs is a combination of many improved factors such as miniaturized avionics, improved solar cells, improved battery densities, miniaturisation of sensors and enhanced communication capabilities (PHYS 2017). As an example, Zephyr developed by Airbus, operates in the stratosphere with maximum lifetime of several months (Airbus 2019). Airbus claims to have the world's first operational HAP site in Australia. It is able to combine parts of the persistence of a satellite and flexibility and reasonable signal delays of LAP systems. In addition, Google has announced several successful HAP field tests with their Loon concept, e.g. for providing Internet connections for disaster relief in Puerto Rico's Hurricane Maria. ITU is actively promoting HAP solutions and new frequency allocations are under discussion (ITU 2019b). The main challenges of HAP are still high costs and disability to maintain its position in windy environments.

3.3 Satellite technologies

As the focus of this report is on satellite communications, we treat the satcom technologies more thoroughly in the following. We start by providing a brief summary of main design elements affecting satcom solutions and their deployment decisions. Next, we elaborate the existing technologies for traditional large GEO satellites and emerging small LEO satellites. Finally, we discuss some features that are specific for MCS.

3.3.1 A brief summary on satellite fundamentals

Satellite systems have a long history from 1940s and 1950s with the well-known landmarks, including ideas from Arthur Clarke and first launched satellites such as Sputnik and Explorer. Satellite systems are quite complex systems, which necessitates understanding the overall system at different levels, see an illustration in Figure 4. The inherent benefits of satellite communications, in comparison to terrestrial and aerial technologies, include global and scalable (broadcasting) radio coverage at sea, land, and air with resilience to local network malfunctions on Earth. The benefits are typically achieved at the cost of higher end-to-end delay and higher deployment costs.

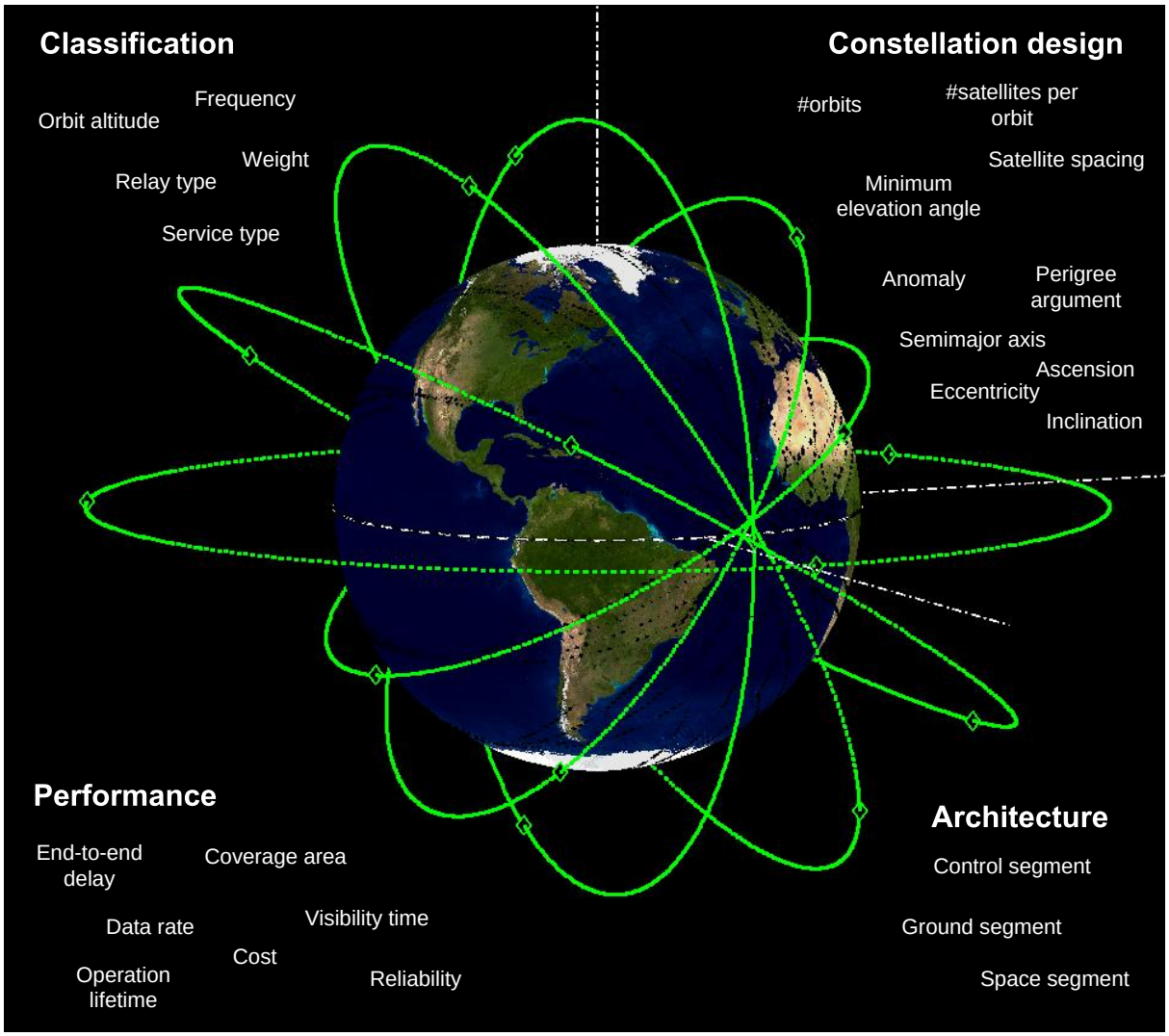

Figure 4. Satellite system design aspects in a nutshell.

The **classification** of satellite communication technologies have been traditionally performed based on a number of things:

- *Orbit altitude*: HEO, (peak altitude >36 000 km), GEO (altitude 36 000 km), MEO (typical altitude 2 000 - 36 000 km), and LEO (500 - 2 000 km). In recent years, altitudes closer to 100 km have been of interest. In these cases, very low Earth orbit or near-space platforms are used. There is no consensus where the atmosphere specifically turns into space but typically, the atmospheric drag becomes significant approximately at 100 km.

- *Weight of the satellite*: Large satellite (>1000 kg), mini satellite (100-1000 kg), micro satellite (10-100 kg), nano satellite (1-10 kg), pico satellite (0.1-1 kg), and femto satellite (<0.1 kg). There is no consensus when satellite should be called small. National aeronautics and space administration (NASA) defines small satellite considered small, if its weight is less than 180 kg while for Federal Aviation Administration (FAA) small satellite is one with less than 1200 kg. In many occasions, 500 kg is also used as a limit.

- *Relay type*: Transparent transponder (bent pipe with simple frequency shifting) and regenerative transponder (more advanced signal formatting).

- *Frequency band*: L (1-2 GHz), S (2-4 GHz), C (4-8 GHz), X (8-12.5 GHz), Ku (12.5-18 GHz), K (18-26.5 GHz), Ka (26.5-40 GHz), V (40-75 GHz), W (75-110 GHz).

- *Service type*: Fixed service satellites (ground stations not moving), broadcast service satellites (one-to-many transmissions), mobile service satellites (terminals moving).

The **constellation design** is of paramount importance for satellite communications (Lo 1999). It involves the system design aspects of the satellite network. It resembles the cell deployment planning of a cellular system and the parameters depends on the target communication objectives. The following parameters are typically emphasised (cf. Maral 2002):

- *Orbit altitude*: Altitude affects the coverage of a single satellite and experienced latency. Typical altitudes are between 500 - 36 000 km.

- *Number of orbit planes*: Satellites can be arranged to follow different orbital trajectories that share common properties so that perturbations affect the satellites and their relative positions are preserved. The optimal number depends on the coverage needs.

- *Number of satellites per orbit and satellite spacing*: Number of satellites per orbit affects coverage and the visibility time of the satellite to a given location on Earth. Satellite spacing affects the collision probability and amount of space debris in particular orbits.

- *Minimum elevation angle*: Defines the allowed elevation angle of the satellite where the communication is still possible. The communication delay and reliability varies with elevation angle. Atmospheric and terrain effects are also more significant at low elevation where signals traverse more into atmosphere and are more inflected by potential terrain blocks.

- *Orbit trajectory parameters*: There are six essential parameters that define the orbit trajectory at any time: Semi-major axis and eccentricity defining the shape (elliptic or circular) of the orbit as well as the velocity of satellite, anomaly parameter defines the position of the satellites in the orbit, and inclination and ascension parameters define the position of the orbital plane. Typical constellations formed via trajectory parameters include Walker constellation and Polar constellation.

The most important **performance metrics** of satellite networks include (cf. Maral 2002, Roy-Chowdhury 2005):

- *End-to-end delay*: There are a number of delay components between the source and destination node of a satellite communication system that contribute to the overall time delay. The most significant ones include i) propagation delay (time for the signal to travel from one node to another inherent to particular transmission media such as radio waves, optical fibre, etc.), ii) transmission delay (time to transmit all the bits of a single data packet), iii) processing delay (time to perform all computation operations of the protocol stack for a single packet), and iv) queueing delay (time to wait at a buffer so that access is granted to use transmission media with scheduled resources). Note that the above components exist for each link between the source and destination, which are typically connected via base stations, gateways, or other relays nodes. In integrated networks, the specific characteristics of terrestrial, aerial, and satellite links must be studied.

- *Coverage area*: The satellite's coverage area identifies the geographic area where communications is possible via a satellite. For a global coverage, minimum of three satellites is required for the constellation at the GEO altitude. For LEO constellations typical global coverage require tens of satellites, as in practise, some overlapping between the adjacent satellites is required to ensure service continuity with practical handover mechanisms. The coverage area can be fractioned into cells (multibeam spots) using antenna arrays similarly to terrestrial systems.

- *Data rate*: The data rate affects the transmission delay and should be sufficient so that the transmission delay is not too much dominating the overall packet delay. The requirement is application dependent where the packet size varies, i.e. the amount of data bits that need to be transmitted during a packet time duration varies. Link budget analysis can be used as a first order to estimate the achievable data rate for given constellation geometry.

- *Visibility time*: The visibility time of the satellite for a given geographical position on Earth is an important factor, if the position of the satellite changes with respect to a given Earth location. For the GEO satellite, this is not an issue as the satellite movement is synchronized with Earth's rotation. However, for LEO satellites the visibility time can be in the order of few minutes that makes the visibility time a fundamentally important factor.

- *Operation lifetime*: Satellites operation lifetime depends essentially on available energy and atmospheric drag and can vary from months (small LEO satellites) to decades (large GEO satellites). The energy availability depends on the available on-board fuel and solar energy capacity for communications and station keeping while the drag depends essentially on the selected orbit altitude and station-keeping capabilities. Solar energy availability is not continuous as satellites are occasionally in the Earth's shadow and solar panels orientation may change. Typically, satellites are launched with their batteries fully charged and solar energy is used to charge the batteries in space.

- *Reliability*: Although satellites do not suffer from local malfunctions of Earth infrastructure due to disasters etc., the reliability of service needs to be addressed carefully. Satellites are vulnerable to space debris and various other perturbations induced from space and atmosphere. Service interruptions are possible also if the handover mechanisms are not working properly. Typically, constellations include inactive spare satellites that can be taken into use on a need bases to increase the reliability of the system. This is important as satellite launching is time-consuming and can experience failures. Especially in the smallest satellites, the available solar energy limits the possibilities for continuous-time transmissions.

- *Mobility support*: The relative orbital movement of satellites causes several challenges that are related to sufficient mobility support of a communication service. Two major mobility measures are handover frequency, connection-dropping probability, and Doppler frequency. In essence, it is desirable to keep the handover frequency and connection dropping probability due to handover low while compensating the frequency shifts caused by the Doppler effect.

- *Security*: Satellites are vulnerable to many attacks, including passive eavesdropping and active cybersecurity attacks. Especially, the satellite handover process can be fragile. Space debris can harm satellites physically.

- *Cost*: Although the cost of launching satellites has reduced significantly in recent years, it is still expensive to deploy satellites. The cost reduction is focused on small satellites operating on LEO altitudes via rideshare (secondary payload) launches. However, the trade-off is that large constellation sizes are required at LEO altitudes to keep the cost level high at service level.

The **architecture** of satellite system is divided into three segments as (cf. Maral 2002, Radhakhrisnan 2016):

- *Space segment*: Consists of one or more satellites organized in different type of formations: a constellation (global coverage), a cluster (a group of closely spaced satellites covering a restricted Earth surface in different orbits), and a trailing (a group

of closely spaced satellites covering a restricted Earth surface in the same orbit). The satellites can be connected via inter-satellite links as well as terrestrial/aerial uplinks (towards satellite) and downlinks (away from satellite). A communication satellite includes a payload (radio transceivers and electronics) and platform subsystems supporting the payload (orbit control, propulsion, power supply, on-board data processing, thermal control).

- *Ground segment*: Includes all earth stations (or aerial stations in case of integration to aerial systems) that encompass interface stations or gateways to terrestrial networks, fixed or mobile user terminals that are directly connected to satellite, and service or hub stations that are used to collect and distribute data.

- *Control segment*: Includes all control and management functionalities with tracking, telemetry and station-keeping commands as well as traffic control and resource management.

3.3.2 Geostationary satcom technologies

The first commercial GEO communication satellite was Intelsat 1 which started its operation in 1965 (Maral 2002, Chini 2010). Equatorial GEO satellites with circular orbits appear stationary to ground observers sharing the same rotation speed with Earth. As with other orbits, the trajectory is affected by the orbit's inclination and eccentricity. Orbits with inclination and an orbital period of one sidereal day are called geosynchronous orbits. Geostationary orbits are always on the top of equator. Moreover, in practise GEO satellites may move away from the orbit due to various perturbations from the space and satellites must be harnessed with station-keeping machines. GEO satellites typically include tens of transponders to support a number of users. The advantages of GEO is high coverage area, stable visibility, and simple satellite tracking as GEO satellites are synchronous to Earth's rotation. The drawbacks are the required high transmit power, nonfunctional areas in polar regions due to fixed position around the equator, and high propagation delay.

UCS satellite database reports 548 operational GEO satellites on various applications on their web page (UCS 2019). Using their publicly available Excel sheet (updated March 2019), we find 315 GEO communications satellites that are still operational. Among others, the well-known GEO communications service providers include Intelsat, Eutelsat, SES, ViaSat, EchoStar, and Inmarsat. The typical GEO communication service include multimedia broadcasting, satellite Internet access, weather, and maritime/aviation communications.

A typical GEO communication standard is DVB-S2 and its variants. It is standardized by ETSI and it describes the physical and link level signalling for satellite television transmissions (ETSI 2014). GEO satellites also interact with terrestrial technologies (Chini 2010). For instance, GEO mobile radio (GMR) air interfaces have been standardized by ETSI and used by Thuraya and ACeS constellations. In essence, GMR allows the user access via satellite to the GSM core network. The user terminals are often dual-mode, allowing the access either to GSM or satellite system. In addition, 3G/UMTS standard has been extended with a satellite component and called as S-UMTS. More recently, Thuraya has provided dual-mode operation with satellites and LTE (Thuraya 2019). It enables auto-network switching function which automatically switch to the network with best coverage. Another solution is the cellular backhauling technology e.g. from Hughes (Hughes 2019) and Gilat (Gilat 2019). Hughes' Jupiter technology replaces the link between an LTE base station and the core network supporting 200 Mbit/s with 600 ms latency. The commonly used transmission control protocol (TCP) is not suitable for satellite links with higher delays and these protocols have been modified for satellite use (Davioli 2018). The lifetime of larger GEO satellites are typically about 15 years.

3.3.3 Nongeostationary satcom technologies

The advantages of smaller MEO and LEO satellites over large GEO satellites are lower latencies, lower costs, and improved frequency reuse due to smaller footprints. The drawbacks are lower visibility times, frequent handovers, and large constellation sizes for global coverage. In the following, we treat the LEO satellites in more detail.

UCS satellite database reports 1338 operational LEO satellites on various applications on their web page (UCS 2019). Using their publicly available Excel sheet (updated March 2019), we find 265 LEO operational communications satellites. Among others, the well-known LEO communications service providers include emerging new players OneWeb, LeoSat, SpaceX, and already existing Iridium, Orbcomm, and Globalstar. The typical LEO communication service includes satellite phones, Web browsing, e-mail access, machine-to-machine communications, and various other monitoring and tracking data services. One of the largest single-rocket launches for small satellites is from Indian polar satellite launch vehicle (PSLV-C37) that simultaneously deployed 104 satellites in sun-synchronous orbits in 2017.

Several companies have started to prepare proprietary IoT LEO satellite systems: SAT4M2M, Kleo, Kepler Communications, Iridium, and Orbcomm. Many start-ups are still in the planning phase. However, for instance, Orbcomm has launched 11 M2M messaging LEO satellites already in 2015. Iridium has now a cloud-based satellite-enabled IoT solution utilizing Amazon web services. Several companies provide automatic identification system services such as exactEarth, Spire Global, and COMSpace (Sweeting 2018).

A number of different communication technologies has been used for LEO satellite systems. The larger Iridium satellite constellation uses mixed time-division and frequency-division multiplexing with L-band channels. The data rates vary from first-generation 2.4 kbit/s to second-generation 512 kbit/s. The latencies vary quite a lot also in LEO systems. For the newest Iridium Certus technology, 40-80 ms latencies are expected although the actual latencies can be currently much greater (Iridium 2019). Another latency test is reported by OneWeb with 32 ms (OneWeb 2019). Traditionally, smaller cubesat-class satellites have used the AX.25 standard to communicate with ground stations (Burleigh 2019). AX.25 protocol is rather reduced, e.g. it allows detecting errors but not correcting them. The currently used nanosatellites typically do not have much processing power and cannot establish complicated intersatellite links. Very low orbit satellites possess a number of challenges as summarized in (Dakka 2018). The operation lifetime of LEO satellites depends on the size of the satellite and selected orbital altitude, and can vary from months to several years, see (UCS 2019).

3.3.4 Satellite networking for MCS

Although satcom technologies possess a long history, there have been some new developments that have increased interest to apply satellite communications for MCS (Pecorella 2015, Berioli 2011, Baldini 2014). In essence, it is believed that space communications can become a good candidate for MCS, provided the performance is sufficient and there is an effective integration solution available.

In addition to voice services, satcom technologies have been used previously for population early warning systems of which COSPAS-SARSAT is a good example. This system is developed specifically for search and rescue operations and locating emergency beacons in maritime scenarios. Many countries have their own emergency population warning systems which are based on satellites such as J-Alert system in Japan. More examples of commercial satellite emergency solutions are Emergesat and Proximity B1 systems, see more from (ETSI 2011). In disaster scenarios, the basic idea is to provide a long-range satellite link between on-disaster segment and disaster-safe segment providing guidance. Previously mentioned Iridium and Globalstar technologies provide warning message services. In addition, push-to-talk services with one-to-many communications are now provided by Iridium (Iridium 2019b, Prn

2019). Many experimental research projects have further studied the applicability of satcom for MCS and a good survey is found from Pervez 2018.

An important example of GEO satcom technology used in MCS is the Inmarsat's solutions for the first Responder Network Authority (FirstNet) service (Inmarsat 2019). The portfolio includes satellite phones and rapidly movable network recovery technologies called satellites cell on light trucks (SatCOLT). The provided service availability reaches 99.5 %. A dedicated FirstNet Core was launched in 2018. A summary of recent activities of FirstNet is given in (FirstNet 2018). Also a rapid deployment kit is being developed with Sonim (Sonim 2019). It is claimed that FirstNet currently performs 25% faster than any other commercial network.

3.4 Technologies used in Finland

The current use of authoritative communication services in Finland are divided into mission noncritical and mission critical communications (HE226 2018). The main users of MCS include Finnish Defence Forces, Police of Finland, Finnish Customs, Finnish Border Guard, and Department of Rescue Services, Emergency Response Centre Finland, Finnish hospital districts, and various security service providers. However, also other parties such as Yleisradio Oy uses VIRVE to coordinate live broadcasting events where reliability and short delays are important. Different actors on critical communications in Finland can be found from (CCF 2019).

The main current MCS communication technology is called VIRVE, which is based on TETRA technology and operated by Suomen Virveverkko Oy which belongs to Suomen Erillisverkot Oy. Suomen Virveverkko was recently merged with Suomen Turvallisuusverkko Oy, also belonging to Suomen Erillisverkot. VIRVE was established in 2002 and it was the World's first nationwide TETRA network (ERVE 2019). Today, VIRVE network consists of 1400 base stations and 41 000 subscribers. The maximum range of a single VIRVE base station is 56 km (ERVE 2018) for frequency ranges around 400 MHz. The reliability is increased against base station malfunctions by overlapping coverage areas. Moreover, it is possible to connect the terminals directly without base stations, provided that the terminals are within the radio coverage area. VIRVE works well for voice communications and short messages but the capacity for high bandwidth multimedia applications and the coverage for some rural areas are not sufficient. The wide coverage is a specific challenge in Finland and in many MCS, there is a need to connect different units nation-wide quickly and reliably. Low bandwidth TETRA solutions are also more vulnerable to possible jamming threats.

To rise to the aforementioned challenges of current VIRVE, VIRVE 2.0 based on commercial cellular networks is being developed (ERVE 2019b). Suomen Erillisverkot acts as a service provider for VIRVE 2.0 and the network provider will be selected during 2019. The first tests on LTE network has been made e.g. from prioritisation perspective (ERVE 2019c). The development of cooperative use of VIRVE with that of Sweden and Norway has been quite active recently which is important in cross-border emergencies. The current coverage areas for different cellular services from Elisa can be evaluated from (ELISA 2019). While 2G-4G networks already cover a large part of Finland, 5G networks are being deployed in Finland, currently initial networks are operating by Elisa in Tampere, Turku, Helsinki, Jyväskylä, and soon in Oulu (10/2019). The delay between the first 5G standard availability (12/2017) and commercial 5G phone availability (07/2019, Yle 2019) in Finland was about 18 months.

Regarding aerial networks, similarly to the worldwide trend, also in Finland the drones have been used in various MCS to improve the situational awareness. Typical examples are firefighting where drones deliver live video on the fire area, rescue missions of lost persons, border control, and police operations (ERVE 2018b). For the border control, Orbiter Mini MUAS technology is in use with monitoring range of 30 km (ERVE 2019d). Therein, it has been recognized that current communication technologies are not sufficient for real-time high quality video transfer. The use of drones must be considered carefully and the airspace safety issues

must be prioritised. There is currently not that much publicly available field test examples in Finland on improving communication network performance via drones similarly to FirstNet technology in the USA, see (AT&T 2019). One of the rare examples is from (Säe 2018). The conclusion made from their tests in several different areas in the South of Finland is that the use of drones can improve the terrestrial radio coverage significantly in state of emergencies, with local signal gains up to 20-30 dB.

Finland has a rather long history on using satellite technologies. A good reference to find general information on Finnish space activities is from (SF 2019). The main use scenarios include location services, weather, communications, and Earth observation. Typically, the services are used via third party satellite technologies. Use case examples include the Finnish Forest Centre and Finnish Meteorological Institute. However, recently Finnish satellites have been launched for commercial Earth observation applications enabled by synthetic aperture radars by Iceye (Iceye 2019). Also Reaktor has launched its own LEO satellite with hyperspectral camera as a payload. There are also some satellite phone products done by Bittium (Bittium 2019). W-Cube satellite project conducted by VTT and Reaktor and funded by ESA is also on-going activity where ESA is ordering millimeter-wave nanosatellite technology from Finland. Satellite communications is in some use by several Finnish emergency authorities. However, often it happens that the satellite communication is used as a backup technology and not in active daily use (ERVE 2019e). Finnish Defense Forces have used communication satellite technologies in crisis management abroad (Norsat 2019). A typical satellite system operating in Finland’s region is the Iridium system. One recent product example is ICOM IC-SAT100 phone which supports the push-to-talk function important for MCS services (ICOM 2019). In Finland, the product is sold by Insalko. From (UCS 2019) we can learn that there are currently (03/2019) about 200 satellites that are following polar orbits, including commercial communication satellites such as Iridium, OneWeb, and Orbcomm. The orbital inclination of the satellite indicates the latitude of which zenith the satellite can reach (Ursa 2019). For instance, a satellite whose inclination is less than 60° cannot be in a zenith over Finland, and a satellite whose inclination is less than 50° cannot be seen even in the horizon.

4. Emerging integrated 5G communication system for MCS

In this section, we outline recent activities related to the integrated terrestrial-aerial-satellite communication network concept. The focus will be on the terrestrial-satellite integration part and other essential functions that affect the operation of MCS.

4.1 Network integration

4.1.1 Generic integration aspects

In the past, satellite and aerial communication systems have been largely disconnected from the development of terrestrial cellular systems. The communication methods for satellite and aerial platforms are traditionally proprietary or based on some unlicensed technology. Only relatively weak connections to cellular systems have been created, e.g., via GMR standards (Ylitalo 2015, Evans 2005). Therein, selected interface handshaking protocols of the satcom are tuned to be compatible with that of the core network of the cellular system. As a result, current integration solutions largely involve satellite support for GSM/UMTS network backhauls with fixed ground segments, vehicles, aircrafts, and ships. Many times integration attempts are simple hybrids where satellites and terrestrial components are interconnected but act independently of each other with separate network management functions and separate frequency ranges. Some early scenarios for network integration were done by ETSI in (TR 103124 2013).

In essence, the current 3GPP-specified 5G system architecture is defined in (TS23.501 2019) and the corresponding radio access network in (TS38.300 2019, TS38.401 2019). The architecture consists of about 20 different functions determining the overall control and user plane operations via standardized interfaces. 5G system has been developed for three main use scenarios, namely enhanced mobile broadband (high data rate), massive machine-type communications (high device density), and ultra-reliable low-latency communications (low latency with high certainty). The standardized 5G network architecture will be further elaborated in the next subsection. In typical network integration objectives, it is highly desirable to minimize the required changes to already specified terrestrial standards.

The 5G ecosystem enables a divergent position to renew the past integration efforts by reconsidering holistically all subnetworks jointly and from the beginning. The collaborative arrangement provides better readiness to tackle the fundamental challenges of different subnetworks, rather than competing with each others. The generic integrated network architecture is shown in Figure 5. The architecture consists of three altitude-specific subnetworks, namely terrestrial, aerial, and satellite networks which can be further divided into different parts. Incorporating terrestrial protocols directly into aerial and space systems may be difficult due to their very different propagation and mobility mechanisms.

Efficient integration requires optimization of communication system at many different levels. This includes two contradictory aspects: i) the protocols and network architectures should converge to simplify implementation and optimization procedures; ii) the protocols and network architectures should diverge to encounter different propagation mechanisms experienced in terrestrial, aerial, and satellite media. In other words, network designers are ultimately searching for an optimal split between subnetwork-dependent and -independent parts.

The integration of different space, aerial, and terrestrial subnetworks into coherent ensemble is currently one of the key 5G objectives. The simple reason for the goal is to maximize the joint advantages of the three networking types. In essence, the unique features include seamless connectivity in sparse environments with satellites at the cost of longer delays, flexible capacity enhancements for harsh environments with aerial technologies at the cost of short operation times, and high capacity for densely deployed environments with terrestrial

networks at the cost of losing global coverage (Cao 2018, Liu 2018). A benefit is also achieved in the overlapping areas, where diversity gain provides increased service reliability, as the same service can be provided via multiple technologies. However, these benefits require sophisticated cooperation mechanisms between different subnetworks. In the following, we outline the main state-of-the-art characteristics of upcoming 5G developments focusing on the network integration aspects and resulting effects on MCS applications.

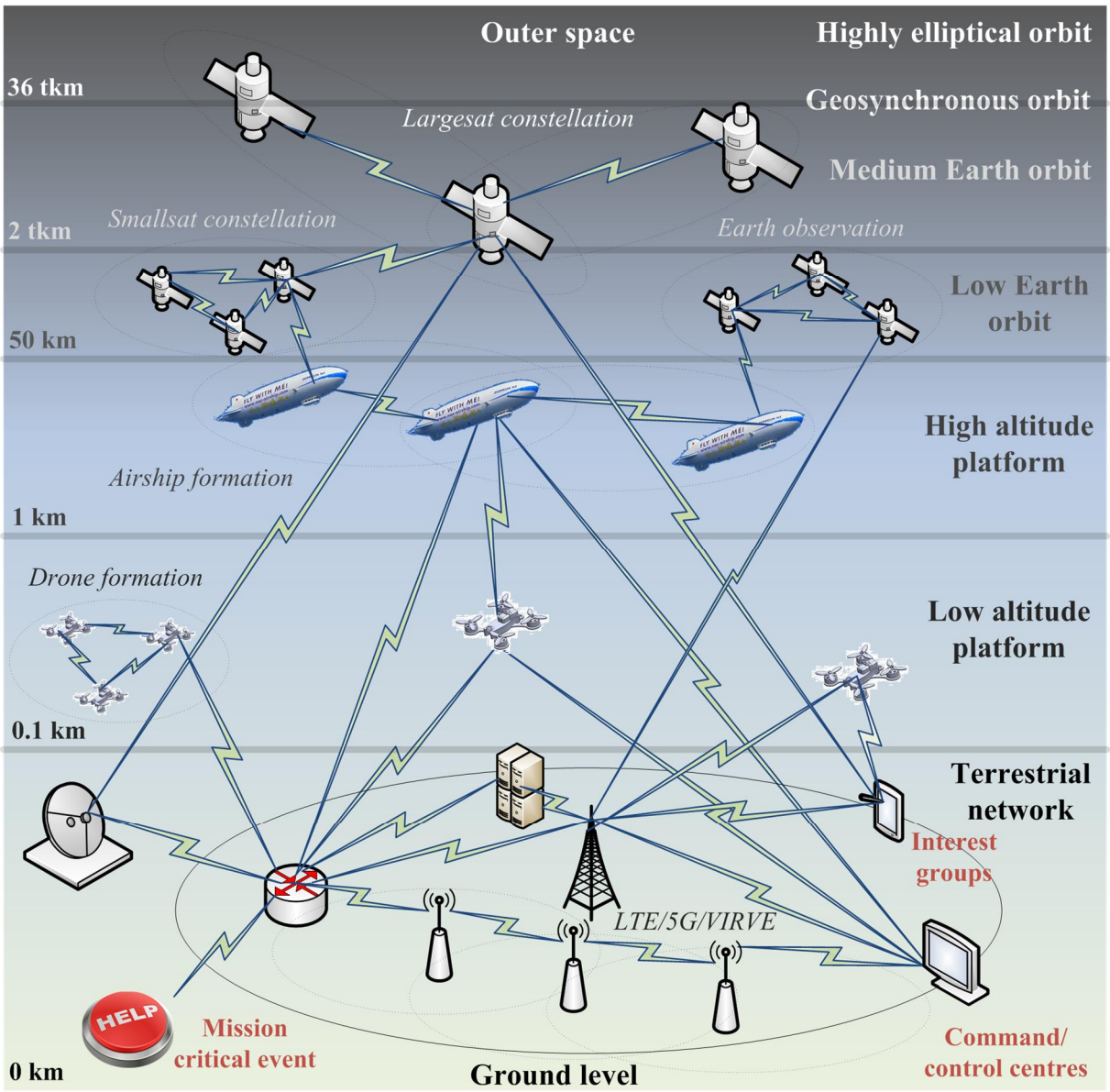

Figure 5. Integrated network architecture vision.

The architectural choices for the network integration may lead to numerous possible combinations of different networking alternatives. A network integrator can try to affect the system efficiency either by substantiating the similarities of different networks (top-down approach) or by exploiting the knowledge of the dissimilarities of the network characteristics (bottom-up approach). That is, in a wider sense, network integration may refer to any attempt to bring two distinctive networks or services closer together. Some important features are highlighted in the following.

- **Transmission path selection.** The transmission of the required data may be conducted via nonsimultaneous or simultaneous use of given networking paths of different technologies. This resembles the traditional network routing task but here the routing decision must infer the distinctive behaviours of the involved networks. The traffic management approach in an integrated system can be asymmetric, i.e, multicast downlink traffic can be routed via satellites while uplink traffic can be routed via terrestrial system. Traffic requirement analysis over heterogeneous links is important for ensuring good service quality.

- **Relay type selection.** To form the E2E path, several relay nodes from different networks may be required. The relay node may be a simple amplifier or a more complicated gateway node that understands a variety of different transmission protocols.

- **Interference management.** Interference management via frequency selection is a fundamental issue in any communication system but is even more aggregated in the concept of network integration. The interference caused by users of different networks can also be addressed in time and spatial domains. Frequency reuse is possible if the network nodes are spatially separated e.g. with smaller cell sizes and multi-spot beams enabled with antenna arrays.

- **Control structure selection.** Each node of the integrated network may take different roles regarding the network management and control. The control can be fully decentralized or fully centralized or, more typically, some form of hybrid of these two extremes. The control plane can be separated from the data plane to increase efficiency.

- **Processing structure selection.** Each node of the integrated network may take different roles regarding the data processing. For instance, in a conventional cloud radio access network, some nodes act as radio remote heads with reduced processing capability while cloud processing nodes use powerful centralized processing capabilities for performing e.g. baseband signal processing tasks. The processing location and functional split can be flexibly selected via network virtualization approaches.

- **E2E transmission protocol adaptation.** In cases where very different systems are combined into a single framework, E2E protocol design is of paramount interest. Typically, the well-established TCP/IP protocol has been the main integrating protocol but it is tedious to make a single protocol that works in all conditions. For instance, in satcom there have been many suggestions how to modify the IP protocol used for terrestrial systems (Wang 2009). The headers of basic IP packets may have to be newly encapsulated to include subnetworking related control data. Traditionally, terrestrial and satellite systems are combined using various interworking units to perform necessary protocol conversion tasks. Adaptations for satcom based IP architecture are proposed e.g. by ETSI in (TS 102292 2015).

- **Resource and quality management.** Any smart network decision must be conducted with some awareness of the consequences on the expected transmission quality. Efficient resource management is a key quality insurer and it requires proper awareness of network status. The network status information obtained from different subnetworks must be sufficiently abstracted and unified for a given functionality. The quality classes must be aligned to take into account the capabilities of particular subnetworks.

- **Hardware integration.** Different system characteristics possess challenges to actual hardware integration especially in small form factor user terminals where different subnetwork requirements, e.g. for antennas, set diverted demands.

- **Cooperation between multiple network operators and backward compatibility.** Roaming and mobility between different operators sharing or nonsharing core networks must be properly organized without adding any significant delays. The integrated network should be compatible with other legacy systems.

4.1.2 Satellite-terrestrial 5G integration

A number of more detailed architectural opportunities for satellite communications are presented in Figure 6. This is based on several 3GPP reports (TR 23.737, TR 38.821, TR 38.811, TS 38.300, TS 23.501, TS 38.401) and it describes the main ways satellite communications could be integrated to terrestrial 5G network architecture. In essence, there are four opportunities: access opportunity to provide direct access to UE that has satellite-capable modem embedded, backhaul opportunity to support 5G backhaul network, core opportunity to support core network functionalities e.g. with distributed mobility management approaches, and transport opportunity to support the transport network between the core network and public Internet. The first two opportunities are the most popular choices whereas there is little information available for the latter two opportunities. Each integration opportunity may incorporate either as a transparent form where satellite link acts as a simple relay link (coverage extender) or as an on-board regenerative link where satellite implements some more involved user plane (e.g. coding) or control plane (e.g. resource management) functionality of different network nodes as well. The satellite interface can be based on 3GPP specified access or non-3GPP proprietary access, e.g. using the well-established DVB interface. The non-3GPP access can be trusted or untrusted and for the latter case, security is ensured via non-3GPP interworking function which is part of the core network.

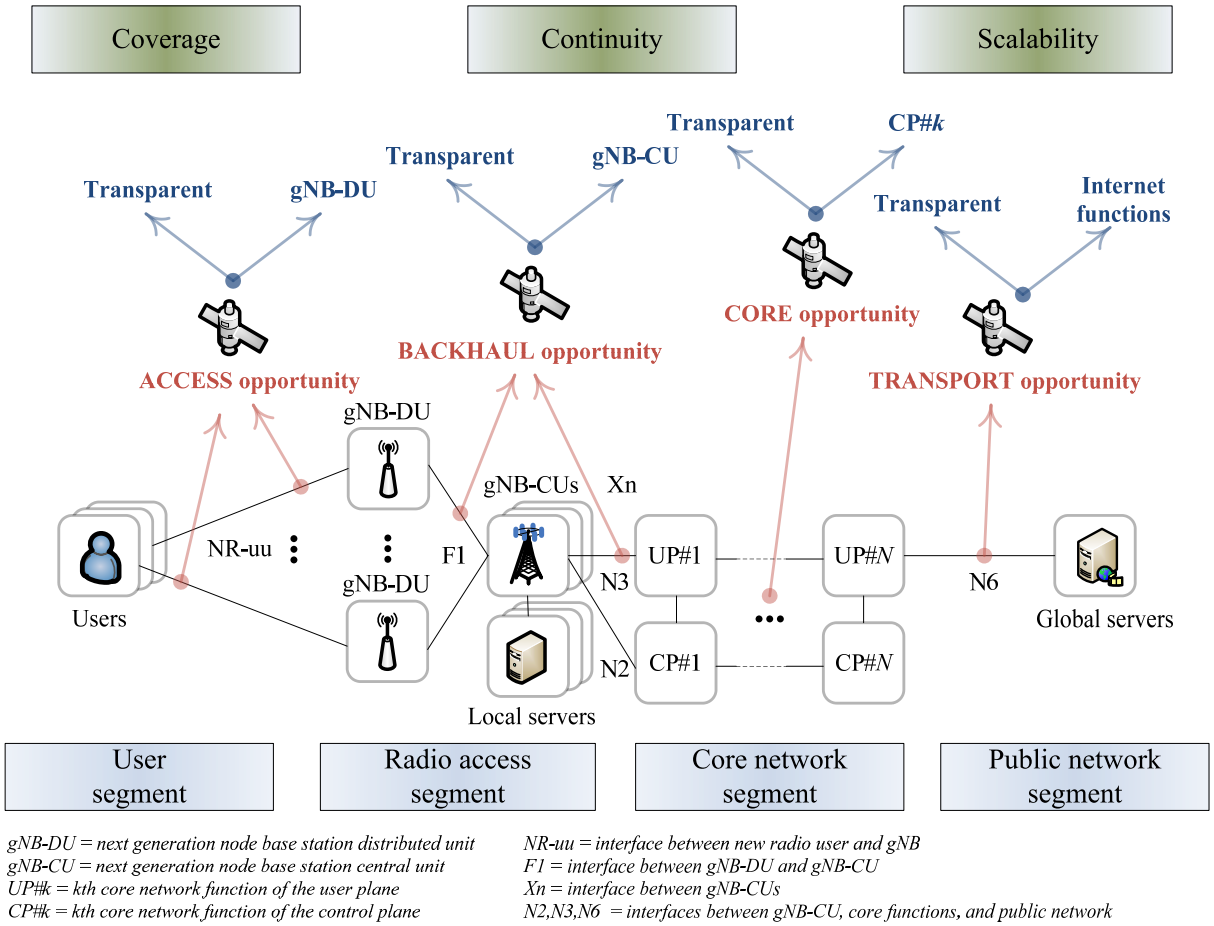

Figure 6. Satellite opportunities for an integrated 5G terrestrial-satellite system.

With the inclusion of satcom into cellular system, there are several detailed adaptations that must be carried out (Bastia 2009, Gopal 2018, TR 38.811, Guidotti 2019, Sequans 2019). The most significant ones are outlined in Table 5.

Table 5. Required changes induced from satellite integration to terrestrial cellular systems.

Design constraint	Delta between terrestrial cellular and satellite multibeam system design
Round-trip delay	Time-dependent closed loop processes, such as TCP, random access, synchronization, scheduling, and automatic repeat request protocols, need to be revised with resilience to longer round-trip times of satellite systems (~100-1000 ms) compared to that of terrestrial systems (~10-50 ms). While roundtrip-delay of GEO satellites is dominated by propagation delay, elevation angles of LEO satellites affect significantly the delay variation. Satellite systems with typical orbital trajectories increases the delay difference between users at the cell centre and cell edge. This will complicate the QoS provision mechanisms to ensure sufficient quality for all cell users. This observation (artifacted performance difference between cell centre and cell edge users) may be true for other link attributes as well. Various buffering schemes can be used to reduce the effects of delay jitter. The loop response time can also be reduced by reducing the transmission time interval. Large delays indicate large transmission buffers to ensure proper retransmission process. The delay affects also the decision of duplex mode: time-division duplex needs a guard time, which increases with delay, to prevent simultaneous transmit and reception.
Link distance	Adaptive algorithms, such as power control and transmission mode selection, need to be revised by adding new power classes and transmission modes due to fact that usual 23 dBm transmission power and standard 10 % transmission block error rate target of terrestrial systems may not be compatible with higher link distances of satellite systems. New survival processes are needed to compensate inefficiency of outdated channel quality information. Obviously, antenna design and some other RF parts are also affected in supporting higher link distances. It is important to set the operation point of power amplifiers close to saturation point which calls for low peak-to-average power ratio mechanisms to minimize nonlinear signal distortion.
Frequency reuse	Dynamic spectrum sharing between subnetworks requires some extra attention to maximize the frequency reuse while avoiding interference compared to spectrum sharing between terrestrial systems. Suitable subnetwork specific margins are required to avoid disturbing interference with simultaneous frequency use. The directional and trajectory restriction of certain orbital constellations as well as elevation angles affect greatly to the interference power that can be utilized in database based spectrum sharing, unlike in terrestrial systems.
Energy availability and form factor	While terrestrial systems are dominated by interference limitation, satellite systems in space are largely more energy limited systems with limited access to solar energy which needs to be taken into account in system design. This is evident especially for small-form factor cube satellites. The trend to use off-grid solutions is also increasing for terrestrial systems to tackle the high energy consumption of cellular networks.
Cell size	Proactive handover algorithms need to be adapted to larger cell sizes compared to terrestrial systems (typical diameter range: ~1-50 km) created by multiple beams of satellite systems (typical diameter range: ~2000-20 000 km). In LEO satellite communications, the cells can be also moving which creates a need to additional cell tracking approaches. Note that moving cells require hand-over processes also for fixed located users.
Doppler effect	Doppler frequency tracking and compensation mechanisms need to be revised to encounter higher satellites speeds of ~7 km/s (25 200 km/h) in comparison with maximum terrestrial speed (~500 km/h). The Doppler shift for a LEO satellite shift can be ~50-700 kHz which is much larger than that of terrestrial systems ranging ~0.1-10 kHz. Subcarrier spacing affects the severity of Doppler effect.
Signal scattering and fading	The performance gains of some important signalling methods, such as multiantenna multiplexing and multiuser diversity methods, are highly dependent on the degree of signal scattering and frequency-selectivity of the channel. While terrestrial systems in urban environments experience non-line-of-sight links, satellite links are typically line-of-sight links with mild signal scattering and frequency-selectivity, leading to low utilization of above signalling methods. Low elevation angles affects significantly to signal attenuation, especially with hilly terrain.
Service continuity	The vertical handover (i.e. handover between subnetworks) algorithm needs to asymmetrically smart in a way that it understands the consequences whether it is about moving from terrestrial system to satellite system or vice versa. It is noted that vertical handover always possesses additional risks to service continuity and should be avoided where possible. Horizontal handover (i.e. handover within subnetwork) is also critical for LEO satellites as typical visibility time of a single satellite beam to stationary user is only

	few minutes. LEO handover includes handover between satellites of LEO constellation and handover between beam of a single multibeam satellite. Currently, there is no one-to-one correspondence between moving beams and fixed tracking areas or registration areas on the ground complicating the paging process.
Mapping of network architecture and interfaces	The mapping of satellite link into terrestrial system needs to be performed. It can also be dynamic via emerging softwarization tools. Three basic mapping options include i) transparent payload, ii) gNB-DU payload, and iii) gBN-CU payload which all have different amount of processing to perform. The different physical links of overall network architectures participate in the mapping process. Mapping includes considerations on separate access and backhaul interfaces or integrated access and backhaul links. Also different flexible functional splits of conventional cloud radio access networks are to be reconsidered in the integrated framework. The combination of interfaces of different subnetworks may require more efficient abstractions of network status information. A lighter version of the integrating mapping procedure is to use available non-3GPP interfaces to utilize existing satellite standards such as DVB to implement the satellite links within 3GPP architecture.
Regulations	Differences in national regulations on spectrum allocation may put challenges in optimal frequency reuse in different subsystems. Moreover, airborne and space regulations affect the usable networking elements in general.

4.2 Emerging 5G architectural functions important for MCS

4.2.1 Network softwarization and slicing

Softwarization (also software defined networking, SDN) and virtualization (also network virtual function, NVF) techniques have been studied extensively for terrestrial communication systems (Kreutz 2015). The increasing need for the service specialization and network integration has led the network design paradigm shift towards more holistic softwarization of network functions as well as network resource slicing to adapt to specific service need e.g. within MCS and different subnetworks (Boero 2018, Petrov 2018, Sharma 2017, Ferrus 2016). The overall network functionality and resource pool is divided into logical subparts that can be flexibly taken into use in on-demand bases. The heart of softwarization/virtualization process is two-fold: to decouple control and data processing actions as well as to decouple network functions from their physical devices allowing virtually any function in any location. Regarding satcom, the functions typically performed in a ground segment could be potentially performed in space, providing more flexibility to network design. The inclusion of softwarization and virtualized functions in satcom is still a rather new study area, and the existing systems are summarized in (Shi 2019).

The benefits of softwarization are typically expected to be (cf. Boero 2018, Ferrus 2016, Kreutz 2015)

- Ø efficient sharing of subnetwork infrastructure and resources between users and operators
- Ø to simplify integration and integrated network management via common interfaces
- Ø to provide predictable performance with isolated resources
- Ø to adapt to local traffic changes promptly and provide agile support for new network services

The remaining issues in optimal integrated network softwarization and virtualization include (cf. Boero 2018, Sharma 2017, Kaleem 2019, Papa 2018, Zaidi 2018):

- Ø ensuring the service continuity at all circumstances when orchestrating the integrated network

- collection of prompt network status information that may be insignificant in a given single subnetwork
- inclusion and maintaining of different delay, power, and processing, and velocity profiles of different network node types (on-grid/off-grid terrestrial, small satellite, aerial) via suitable abstractions
- latency of centralized controllers with highly mobile network topology
- SDN-enabled security risks
- obtained provisions of allocated network slices may become highly time-dependent which needs to be considered carefully

Regarding the quality requirements of MCS, there are two important factors that affect performance of SDN-controlled networks in terms of latency and probability of controller failure. These include controller placement and controller centralization degree (Das 2019, Bannour 2018). The realizable benefits of SDN in practical systems are still under discussion and it is unclear with what scale the SDN will be deployed in 5G (Amin 2018, Zaidi 2018). In fact, it is likely that SDN and NFV will be implemented incrementally rather than holistically. Considering a mix of terrestrial HetNets and large LEO constellations, one static centralized controller may not be enough to satisfy all the management needs promptly with traffic variations. Alternatively, the controller placement can be done dynamically and distributively (Papa 2018, Bannour 2018). The aforementioned discussions are summarized in Figure 7.

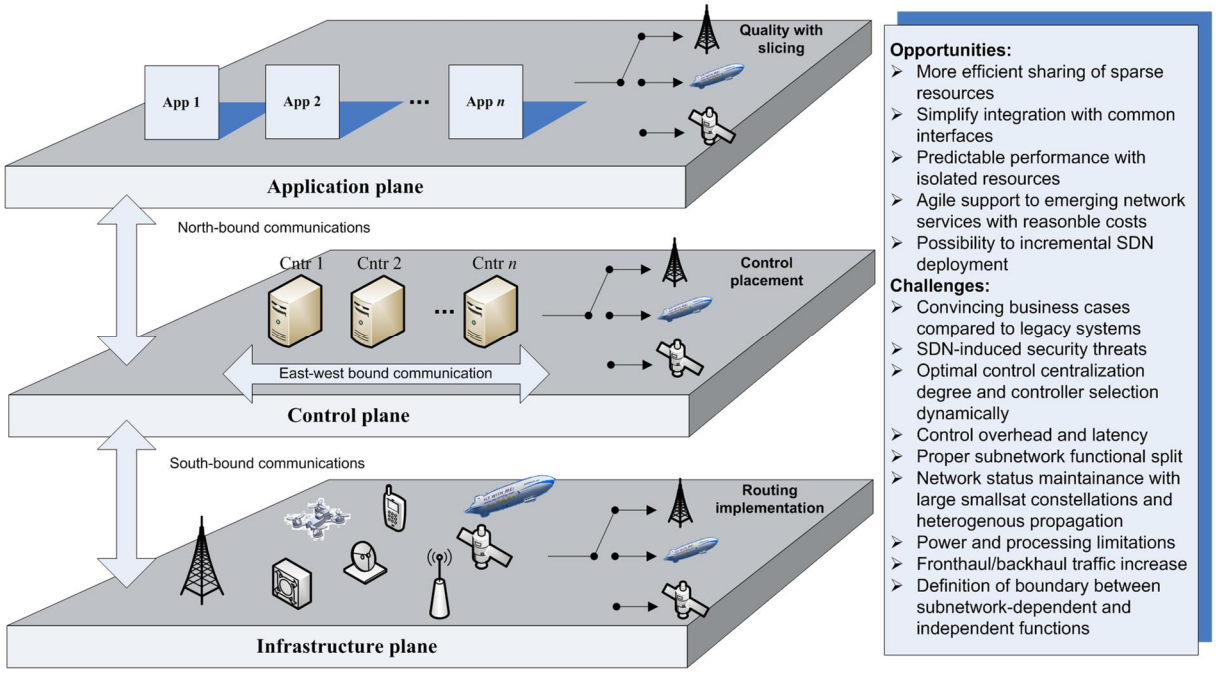

Figure 7. An SDN-enabled integrated network and key issues.

Network slicing is a 5G concept where physical network instances are logically allocated in the virtual network instances (Zhang 2019b). A network slice instance (NSI) can be any combination of network functions and parameter settings either from radio access or core network portions of the overall system. The NSI can be static or changing according to the dynamic needs of the particular application. The 4-phase lifecycle operation is illustrated in Figure 8 where a more detailed explanation of each phase is found from (TS 28.530).

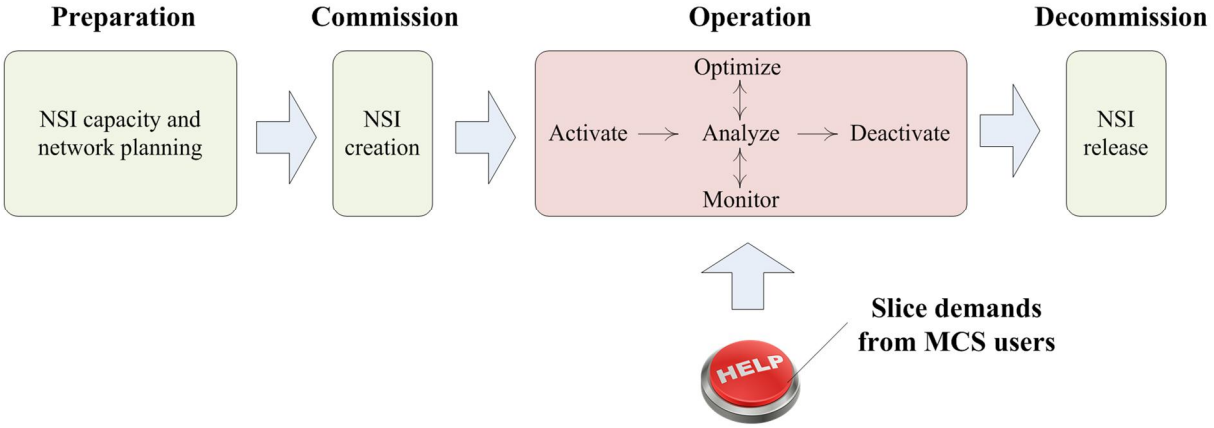

Figure 8. Lifecycle of network slice instances.

4.2.2 Edge computing and caching

Finding the optimal centralization degree for computation tasks is one key objective of modern wireless communications (Mao 2017). While now conventional cloud computing paradigm aims at centralizing computing to reduce the computational burden of portable devices, edge computing (EC) targets at decentralized computing platforms. The main incentive for EC is to reduce the latency, energy consumption, and bandwidth consumption of the core network induced from using the remote cloud servers. The computing tasks can be both content-wise end user services and control-wise network function services. EC has been typically treated separately from network softwarization discussed in the previous section. Given that both EC and SDN have their inherent trade-offs, their combination can be beneficial as suggested in (Baktir 2017). A key issue of this approach is a control mechanism that can orchestrate mixed centralized and distributed environment. Another trend is to make EC smarter via edge intelligence using deep learning methods (Zhou 2019). Moreover, caching or content prefetching at mobile edge networks is important topic for reducing the traffic load (Wang 2017).

EC concept has been already studied extensively in terrestrial systems. Recently, the application of the EC into 5G integrated network paradigm has also emerged (Zhang 2019a, Ge 2019, Sanchoyerto 2019). In particular, satellite mobile EC (SMEC) concept has been proposed by (Zhang 2019a). The provided benefits are largely the same as in terrestrial systems, i.e., computation offloading for users with limited computation power and content caching to reduce the backhaul bandwidth consumption and delay. Different offloading strategies for SMEC are discussed in (Zhang 2019) and illustrated in Figure 9. The SMEC edge server can be located in proximity to terrestrial station or satellite station. Satellite can also act as a relay station to access a remote SMEC server. More advanced offloading can be done cooperatively by combining the resources of above server types and using sophisticated task scheduling algorithms. The EC concept is further studied within an MCS framework in (Sanchoyerto 2019) where it was observed to improve the delay performance significantly in case of MCPTT application.

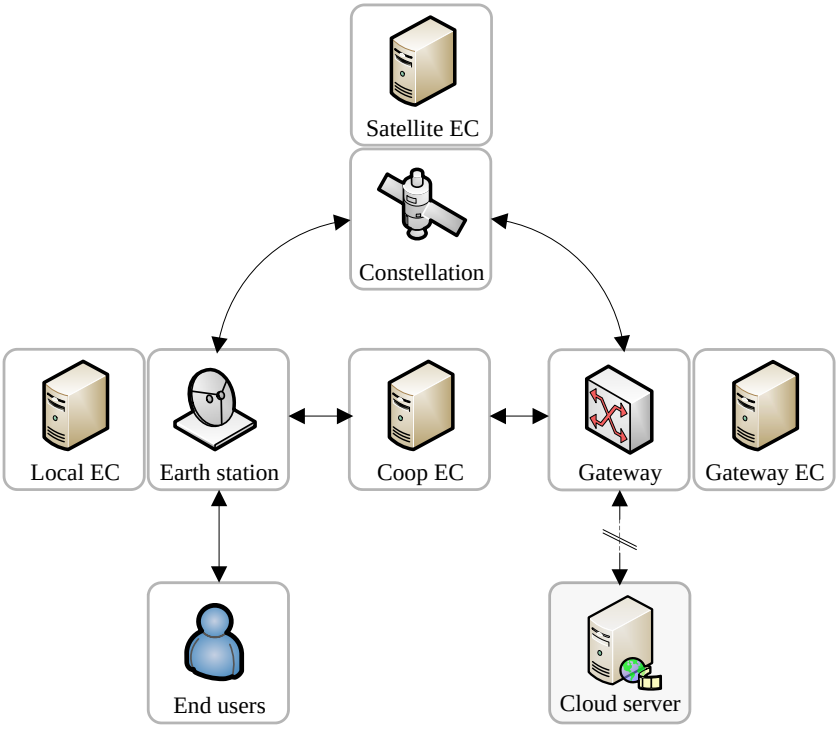

Figure 9. Edge computation scenarios involving integrated network with four different EC mechanisms.

4.2.3 Security and priority

The security aspect (both physical and cyber) has been one dominating challenge in all communications forms in the past. Especially, the security of past satellite phones has been criticised (Driessen 2012). It is not surprise that in MCS, the security is even more emphasised with distribution of critical public safety information.

A good general overview of security aspects in digital communications is given in (Halunen 2018). Security is typically divided into physical security and cyber security where the former is about mitigating threats to physical entities of the communication networks and the latter addresses the passive (e.g. eavesdropping) and active (e.g. jamming) cyber threats. Cybersecurity is provided via encryption with the four-fold aim to provide sufficient authenticity (confirm identity), confidentiality (prevent unauthorized data access), integrity (prevent unauthorized data modification), and availability (prevent denial of service) for all connected terminals. Encryption can be further divided into symmetrical (sender and recipient have the key) and asymmetrical (recipient provides the key) approaches. Commonly used advanced encryption standard (AES) represents the former method. The cybersecurity can be performed at different system layers. The most typical ones are network layer and application layer. Moreover, physical layer security has become a popular research topic both in terrestrial and satellite networks (Hamamreh 2019, Li 2019). Examples of application layer, network layer, and physical layer security approaches include Internet protocol security (IPsec), transmission layer security (TLS), and channel-induced key sharing, respectively. The lower the security layer the better chances there are to achieve perfect secrecy without impractically long keys. The higher the security layer the closer the encryption is to the user, approaching the ultimate end-to-end security objective. More recently, the blockchain concept has been introduced to secure wireless communications.

The increasing number of critical services and devices in 5G has led to new demands for the development of security solutions (Ahmad 2019, Khan 2019). The 5G security architecture is divided into six parts: network access security, network domain security, user domain security,

service domain security, and configurability domain security. While new beneficial 5G functionality, such as softwarization, edge computing, and slicing, are taken into use, they also challenge its security architecture. Therefore, while using partly similar security techniques as in 4G system, new features have been introduced to authentication and key agreement (AKA) protocols and integrity-enabling user plane protection. The primary authentication protocols are access agnostic and can run over non-3GPP technologies.

Regarding integrated networks, the unification of key sharing protocols and layer-specific encryption algorithms among involved subnetworks would be beneficial but often too challenging (Liu 2018, Jiang 2017). Typically, some parameters or headers of IP layer have been changed to better fit into particular subnetwork which introduces new challenges to perform secure e2e communications. Key sharing is difficult to perform via centralized key sharing approaches. Furthermore, frequent handovers in highly mobile LEO satellites and drones produces problems with secure routing approaches, as it entails exchange of sensitive information for the service continuity. The multitude of handover mechanisms (e.g. spotbeam handover, satellite-drone handover, QoS maintainability) magnifies the challenge. It is also recognized that re-programmability introduces new security threats (SpaceNews 2019). Finally, high link delays and line-of-sight airborne leads to inefficient encryption in terms of encryption overhead and jamming vulnerability, respectively. The cybersecurity threats are summarized in Figure 10. More details on specific threats can be found from (Ahmad 2019, Khan 2019, Liu 2018, Jiang 2017, TR 33.899).

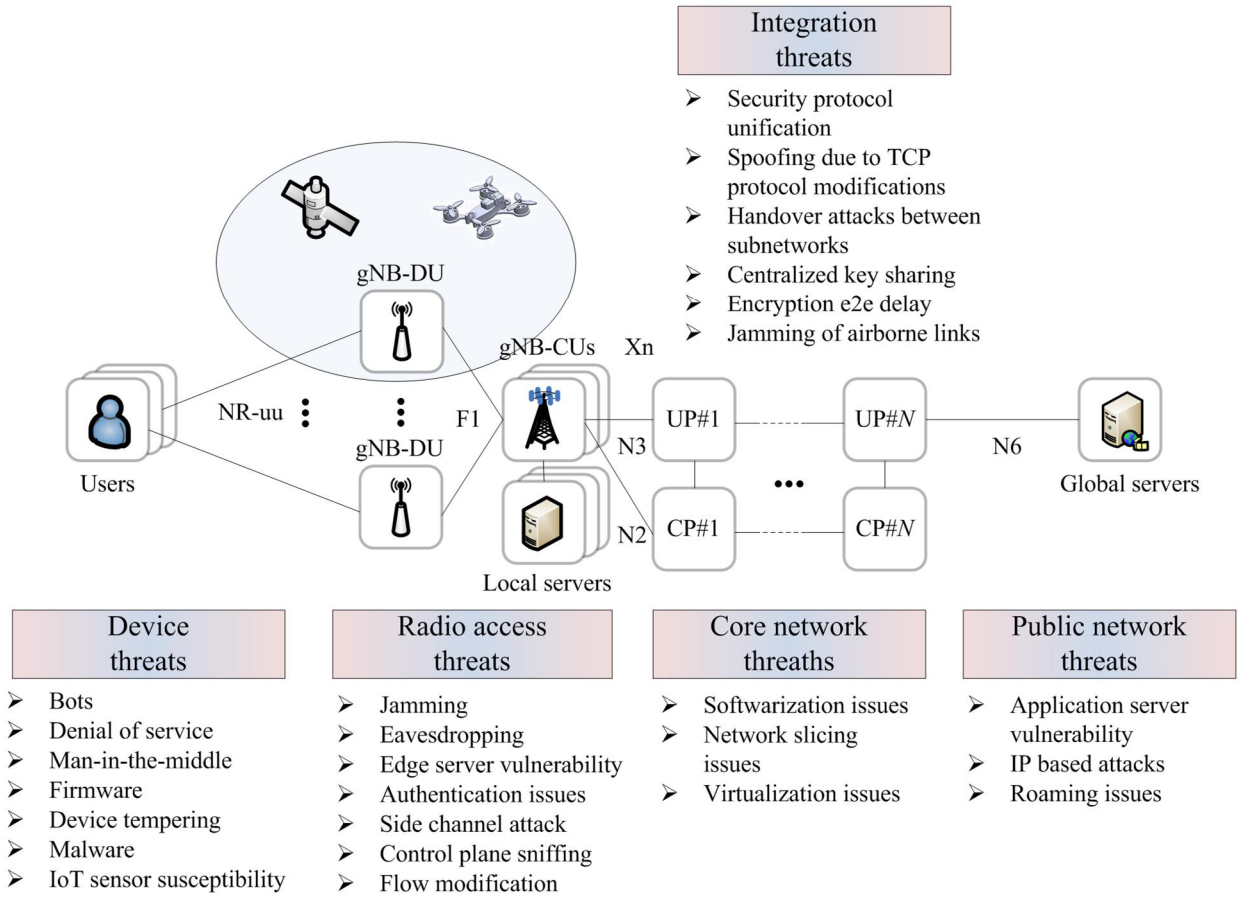

Figure 10. Overview of 5G security threats.

Regarding satellites and drones, physical security is of special interest for obvious reasons. In space, recent estimates suggest that there are one million particles larger than one millimetre and 13 000 particles that are larger than a tennis ball (Torky 2019). Most of the particles move at about 8 km/s with detonating capacity of tens of sticks of dynamite. Debris collisions is

avoided by screening before satellite launching or by removing the debris from space via specific nets (Lamb 2018). In addition, dynamic evasive actions can be performed. However, the smaller particles are obviously more difficult to detect and avoid. LeoLabs has the world's first commercial satellite tracking service and to obtain the situational space awareness and can currently track objects down to 10 cm (Leosat 2019). Space sustainability rating system is also being developed (SpaceNews 2019i). In addition to space debris, space weather can possess unexpected threats like solar superstorms which may destroy satellites (Scientific 2019).

Priority and quality management is an important capability in a modern wireless network that is designed to support a multitude of services with different QoS requirements (Jarwan 2019). Obviously, the need is emphasised for joint use of commercial noncritical services and MCS. The priority control should be dynamic and quickly adapt to different emergency cases where the priority coordination of different users may also be location dependent. The QoS can be controlled via different allocated quality classes, as discussed in Section II. 3GPP uses the standardized quality of service class identifier (QCI) to address different requirements for different type of payloads (TS 23.203). Additionally, 3GPP defines additional set of requirements for 5G networks and call it 5G quality of service indicator (5QI), see more from (TS 23.501). The quality class tells the network controllers how to treat packets that has certain priority, packet loss rate, and allowed packet delay. Quality control in integrated networks is overviewed by (Niephaus 2016). To guarantee sufficient service quality, the most important challenges are found to be traffic requirement identification, link characteristics identification, and path selection over heterogeneous subnetworks.

The typical priority management approaches include access priority, resource allocation, and pre-emption capability of other noncritical users. The 3GPP priority management principles for MCS are described in (TS 23.280). In 5G, priority management can be done via software defined networking and slicing approaches discussed above. For instance, network slicing can be used to ensure enough radio resources for suddenly emerged ambulance communications even in congested networks (Höyhtyä 2018, Zhang 2019b). Priority-based slicing can be done at different networking levels and resources. Regarding the security issue, network slicing introduce several new security risks, as typically the network slices are deployed on cloud servers and some control plane functions are common to multiple slices of different users. In essence, the new softwarization-induced ecosystem with many types of network operators and service providers creates new challenges to manage the end-to-end trust chain.

4.2.4 IoT sensoring and machine-type communications

In the past, 2G-4G cellular technologies have been a significant IoT application enabler via machine-type communications (MTC) ranging from simple thermometer sensoring to more complicated remote control applications. Recently, narrowband IoT (NB-IoT) technology has received lot of attention in 4G systems (Feltrin 2019). In addition, several other terrestrial proprietary low-power wide area networks have emerged such as LoRa and SigFox. The interest in the development lies in the strong increase of IoT connections, expecting 4 billion IoT connections by 2024 (Ericsson 2019). There are currently 121 commercial cellular IoT networks launched worldwide (GSMA 2019).

Since a lot of attention was already given in 4G for cellular IoT solutions, a natural question is how 5G will still address the solution landscape. The basic requirements for massive machine type communications include supporting million devices per km^2 that has 10-15 years battery lifetime. NB-IoT technology has been adopted to 5G framework and therefore it coexists with other 5G technologies (GSMA 2018). The aim is to further improve the power efficiency, reduce latency, decrease complexity via lightweight protocols, improve security, and improve network interoperability with other 5G components (Lu 2019).

The inherent characteristic of IoT environment is that it is heterogeneous in many ways regarding applications, access technologies, and sensing devices (Qiu 2018). A typical heterogeneous IoT environment may be composed of high data rate multimedia sensoring and infrequent transmission of small packet transmissions for monitoring applications. As a result, connectivity between different kind of IoT devices is one key challenge. Although the vision of all-unified IoT network may be too demanding, sufficient interoperability between different devices should be enabled. As typical IoT devices transmit data infrequently, the minimal control overhead is of paramount interest.

The satellite IoT concept has been also recently put forward by several parties using terms *Internet of remote things* and *Internet of space things* (Cioni 2018, Bacco 2019, Sanctis 2016, Akyildiz 2019, Qu 2017, Sweeting 2018, Guidotti 2019). Satellite IoT can help to provide aforementioned interoperability and support for group communications by delivering remote IoT sensor data efficiently to a number of users by broadcasting, multicasting, or geocasting approaches. Even the relatively low bandwidth satellite systems can be beneficial in typical IoT scenarios. Similarly to other satellite applications, also IoT terminals could connect either directly or indirectly to satellites in hard-to-reach locations. While the direct mode allows fast connection to satellites, the cost of terminals is obviously higher than with that of indirect mode terminals. While many satellite IoT solutions are GEO IoT systems, LEO IoT systems can reduce the delay and lower the power consumption of direct-mode IoT devices. At the same time, many protocols relay on time-synchronous procedures which is more difficult to achieve compared to Earth static GEO IoT systems. Moreover, the routing strategies should encounter which LEO satellites are visible to particular IoT devices or gateways. Optimal routing in a highly dynamic environment indicates that each signalling may use different route. Other distinctiveness include high Doppler spread and wake-up periods, which can affect the efficiency of narrowband IoT transmission unless properly compensated.

4.3 3GPP nonterrestrial standardization status

The 3GPP standardization roadmap for 5G is shown in Figure 11 emphasising NTN activities. The standardization of 5G NTN systems was started already in Release 14 with some scenario development studies. In Release 15 and 16, the focus was on feasibility studies. The content of upcoming Release 17 will be decided in 12/2019 but it seems likely that NTN communications will be part of the framework. The focus may be then more on developing actual protocols and architectures. The recent announcement on 5G timeline is given in (3GPP 2019b). More information of standardization processes can be found from (Anttonen 2019).

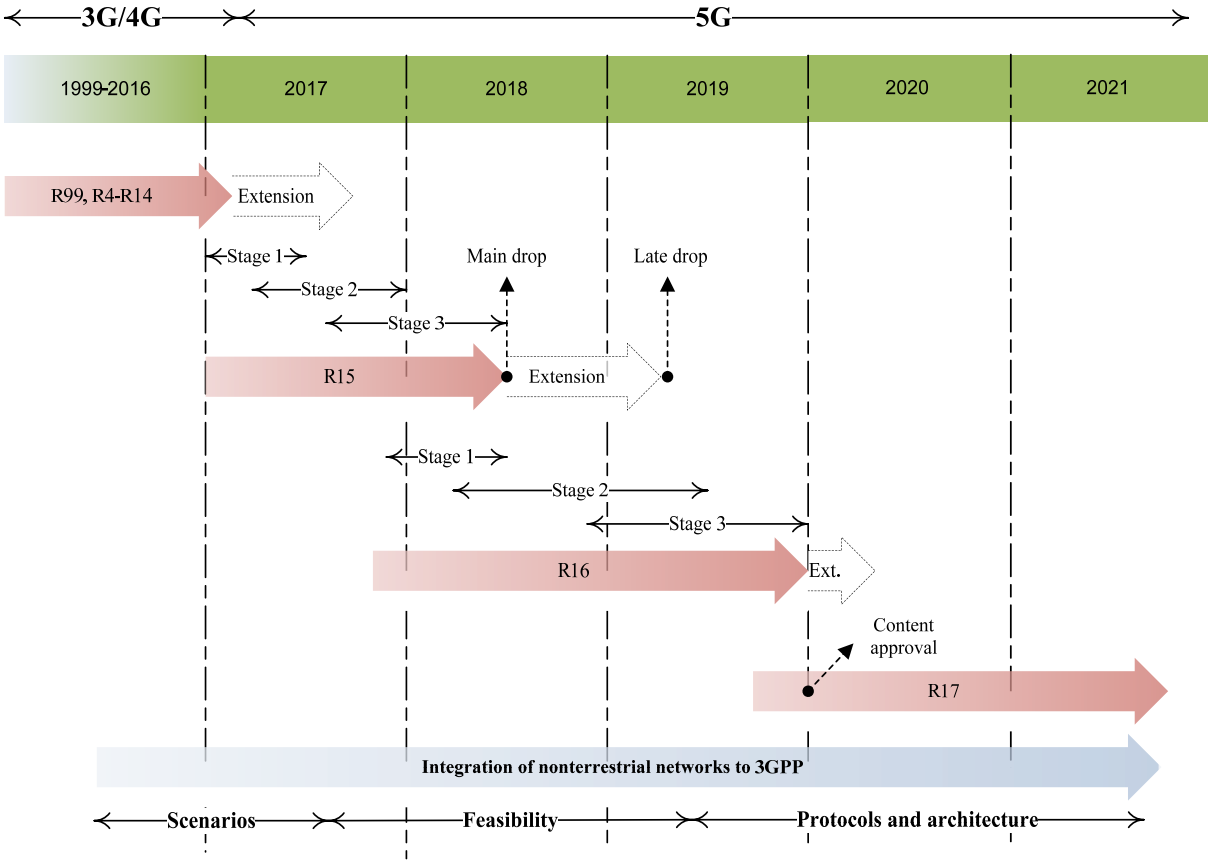

Figure 11. 5G standardization roadmap emphasising nonterrestrial activities.

The most relevant 3GPP specifications and technical reports can be found from Table 6 and the actual reports are available in (3GPP 2019) using the mentioned ID.

Table 6. Most relevant existing 3GPP documents for nonterrestrial activities.

ID	Main contributions	WG	Status
TS 22.261	Adapts most important 5G satcom requirements as part of overall 5G system requirements	SA1	UCC*
TR 23.737	Considers the system architecture challenges and potential solutions e.g. for mobility management, multiconnectivity, QoS control etc.	SA2	Draft
TR 38.811	Provides the first comprehensive technical study on feasibility of 5G NR for 3GPP NTN networks.	RAN1	UCC
TR 22.822	Proposes several use cases and requirements for nonterrestrial systems.	SA1	UCC
TR 38.821	More detailed performance assessment of nonterrestrial systems.	RAN3	Draft
TR 22.829	Proposes new use cases and requirements for aerial vehicles.	SA1	UCC
TR 22.819	Proposes use case on satellite access to support maritime communication services over 5G system.	SA1	UCC
TR 28.808	Softwarization and slicing concepts in integrated network	SA5	Draft

*UCC = under change control

There are currently six basic 3GPP architectural variants that dominate in the preliminary evaluations of satcom and primarily defined by:

- Ø satellite altitude,
- Ø payload type, and
- Ø beam steering policy.

These architectures and their main characteristics are outlined in Table 7 from (TR 38.821)

Table 7. Selected 3GPP satcom reference scenarios for more detailed investigation.

Scenario ID	1	2	3	4	5	6
Orbit	GEO	GEO	LEO	LEO	LEO	LEO
Payload*	Transparent	Regenerative	Transparent	Transparent	Regenerative	Regenerative
Beam form	Nonsteerable		Steerable	Nonsteerable	Steerable	Nonsteerable
Altitude	35786 km		600 and 1200 km			
Spectrum	2, 20, 30 GHz (also other carrier frequencies possible)					
Bandwidth	30 MHz (< 6 GHz carrier), 1 GHz (> 6 GHz carrier)					
Intersatellite	No				Optional	
Max footprint	3500 km		1000 km			
Min elevation	10°					
Max distance	40581 km		1932 km (600 km altitude), 3131 km (1200 km altitude)			
Max delay**	541.46 ms		25.77 ms (600 km altitude), 41.77 ms (1200 km altitude)			
UE power	200 mW (UE power class 3) - 20 W (satellite dish)					

* In this context, payload defines role of satellite, i.e. transparent payload is a simple repeater with amplification frequency modifications whereas regenerative payload includes part or all of gNB functions.
** Propagation delay including service (UE-satellite) and feeder (satellite-gateway) links

Regarding frequency regulations for satcom, the next ITU meeting WRC-19 will be organized in 10/2019, and the agenda can be found from (WRC 2019). Some new regulations might be expected especially for the higher bands, induced from the discussion between terrestrial and satellites communities (SpaceNews 2019b). Moreover, spectrum demands of emerging mega-constellations and satellites with short lifetimes, which orbit less than three years, are to be discussed (SpaceNews 2019c, SpaceNews 2019d). The current unclear situation on regulations is expected to put some pressure for the satellite community.

4.4 Early proof of concepts and plans

At the time of writing this report, there are only quite few proof of concepts available for early testbeds that demonstrate the performance of integrated 5G networks. For instance, many attempts are still largely based on 4G systems, or follow a simplified emulation approach. Nevertheless, several works contain important information on interesting applications and provides a first-hand impression of what can be expected in the future. The collected information is briefly outlined in Table 8. Perhaps the closest available over-the-air 5G satellite testbed activity for MCS is the one from (Politis 2019) which is part of the 5G-VINNI and Satis5, partially funded by EU and ESA, respectively. This work is currently in progress.

Table 8. Summary of recent over-the-air testbed activities for integrated networks.

Objective	Main conclusion	Source
4G backhaul over GEO	Obtained interference how the resource management should be done in integrated networks	(Zeydan 2019)
4G/5G backhaul over GEO	Measured average round-trip delay was 584 ms	(Völk 2019)
5G backhaul over LEO	Measured round-trip delay was 18-40 ms	(Telesat 2019a)
8K video signal over DVB	Showcase of real 8K video streaming to 82” TV with built-in satellite model	(SES 2019)
Direct UE access to satellite base stations	Initial tests performed successfully; use of standard cellular signals to enable direct access from a space base station to regular existing cellular phones	(Lynk 2019, Lockheed 2019)
IoT sensor data over satellites and 4G/5G networks	First tests performed successfully	(Satis5 2019)
LoRa over satellite	First tests performed successfully with off-the-self devices	(Zeppenfeldt 2018)
SDN-enabling satellite platform	Work in progress	(5genesis 2019)
Edge computing and caching in a 5G satellite system	Highlights capabilities of edge computing	(Sat5g 2019)

4K video streaming over 5G and satellite backhaul	Reduced initial video start-up delays down to 2-3 sec via edge computing	(Ge 2019)
Rapid response vehicle for MCS via 4G/5G and GEO/MEO	Work in progress; One of the rare 5G satellite testbeds for MCS	(Politis 2019)

There are currently only few companies that have announced more detailed plans to launch satellite services via LEO mega-constellations. There is no consensus for the exact definition of a mega-constellation but it typically implies hundreds to thousands of satellites in several orbital planes (Pultarova 2018). The concept has some similarities to recent ultra-dense network (UDN) concept in terrestrial cellular systems (Kamel 2016). The main differences to earlier satellite systems, such as Iridium and Globalstar, are to provide significantly better performance in terms of delay, reliability, and bit rate via low-altitude and high-density constellation structure and more advanced signal processing methods (Portillo 2019). Some parameters of different planned constellations are shown in Table 9. Note that the figures in the table indicate the plans at the time of accessing the sources and are subject to changes. Moreover, a number of other large enterprises, such as Samsung and Amazon, have announced plans towards mega-constellations. Many potential end users, such as US Army, are currently carefully monitoring the progress of the field (Spacenews 2019n).

Table 9. Plans to launch LEO mega-constellations for next-generation satellite-aided Internet.

Company	**Current size**	**Planned size (max)**	**Altitude/inclination**	**Expected performance***	**Schedule****	**Source**
SpaceX	60	12000	550-1125 km/42-81°	23.7 Tbps	2020	(T&T 2019b, Phys 2019)
OneWeb	6	648	1200 km/87°	1.56 Tbps	2020	(Oneweb 2019)
Telesat	1	300	1200km/ 37-99°	2.66 Tbps	2023	(Telesat 2019, Spacenews 2019e)
LeoSat	N/A	108	1400 km/N/A	N/A	2022	(LeoSat 2019)

* Expected performance is total system throughput which is analysed in (Portillo 2019) with selected assumptions that obviously affect the comparison results. No comparison to existing systems was provided but typically, a modern high throughput system (e.g. ViaSat-2) has few hundreds of Gbit/s maximum total capacity. **Estimated time for initial commercial services, subject to change.

5. Business prospects arising from nonterrestrial communications

5.1 Potential ecosystems

Having now discussed mission-critical applications, technologies and architectural choices, it is good to take a look at the business prospects, including key roles in the ecosystem in general as well as specifically looking at the status in Finland. As it is stated in (SpaceNews 2019j), the biggest challenge is not necessarily the technology but understanding the market behaviour and user needs.

The space business differentiates from many other industries in several ways. Seven distinctive features emphasised in (Gurtuna 2013) that have defined the traditional space business are: cyclical nature with boom and bust periods, strong linkage to defence, government as the main customer, lack of destination service, limited competition, long investment horizon, and curse of the single unit production. As indicated in (Gurtuna 2013), these distinctions are currently somewhat being changed with the concept of New Space Economy (NSE).

5.1.1 Key roles in the nonterrestrial ecosystem

Ground segment provides means and resources to manage a spacecraft, and enables reception, processing, and distribution of payload data and telemetry data among interested parties on the ground. The main components of the segment include operations centre (or mission control centre) enabling the control of the spacecraft, ground stations providing the actual radio interface to the satellite (or a HAP/UAV), and interfaces/gateway connecting the ground stations to a larger terrestrial network.

The *ground segment manufacturers* define the network management system (NMS) for bent pipe satellite communications. Ground segment has a key role in the satellite-terrestrial integration. Companies in this segment include iDirect, Newtec, and Viasat. Some newcomers to ground station services include Amazon and Lockheed Martin (SpaceNews 2018).

Space segment includes the actual satellite or satellite constellation and the uplink and downlink communication links. *Airborne segment* includes low altitude and high altitude platforms and their formations as shown in Figure 5. A communications satellite is composed of a communications payload (bent-pipe repeater/regenerative payload and antenna) and is typically capable of relaying multiple signals simultaneously. The supporting spacecraft bus provides energy sources for communication and enables signal transmission to the right direction (solar arrays and batteries, attitude and orbit control systems, structure and thermal control system).

Largest satellite manufacturers include Airbus Defence and Space (annual revenue of 10.8 billion €), Thales Alenia Space (2.5 billion €), SSL, and Boeing. Airbus and Thales provide also HAP platforms and so does e.g. Google. Notable nanosatellite manufacturers include Gomspace (12 million € annual revenue) and Pumpkin Space Systems that has been working on nanosatellites since 2003. Lockheed Martin is also putting efforts to space segment (Lockheed 2019).

Satellite operators provide broadband, broadcast and M2M communication services to the users and operate the satellites in the orbit. A successful satellite operator needs the right orbital slot(s) or constellation, and satellites that provide coverage and capacity to desirable regions and markets. Satellite operators such as SES, Eutelsat, and Intelsat operate large satellites and have annual revenue of over €1 billion.

Service provider companies provide services with the operational networks and are often linked with the satellite operators. For example, SES government solutions (owned by SES) provide secure, reliable and customised satellite communications solutions to the US Government all around the world (SES 2019b). Another significant provider is Inmarsat Government, providing satellite solutions to FirstNet.

Launch services providers carry the communication satellites to the space with their launch vehicles. There are different sizes of launchers capable of carrying payloads from couple of tens of kilograms up to thousands of kilograms to the space, see e.g (Isro 2019). Example service providers include ISRO in India, Soyuz launchers from the Plesetsk Cosmodrome in Russia, and SpaceX launchers from space center in Florida. There has been emergence of new launch services but it is challenging both from the product development and business viewpoints (Verge 2019, Ars 2019). Rocket Lab is one important launch service provider (RocketLab 2019). Launch services from airplanes is also one option (Virgin 2019)

Regulators need to be contacted always prior to satellite operations to obtain permissions for certain orbital slots and use of frequencies. Even though the effect is global the national contact points and regulatory authorities are the main places to start discussions to obtain the operational licenses. Traficom is the contact point in Finland and they can help also in international processes. Information about European processes and regulations including Earth stations on vessels, aircrafts, and other mobile platforms a can be found e.g. from (Cept 2019).

In addition, every satellite launch must include a plan how to cope with space debris. For example, nanosatellites are directed to the atmosphere to burn in the end of their mission to avoid creating additional space debris. In Finland, one needs to receive permission also from the ministry of economic affairs and employment to operate satellites.

Business modelling aspects are further outlined for MCS domain, satellite domain, and slicing based 5G network domain in (TS 23.280, Ferrus 2016, Berioli 2011, Afolabi 2018). In order to come up with effective business models for MCS in integrated networks, we need to understand specific characteristics in these different domains. In general, both cellular and satellite domains are undergoing significant changes in business modelling, largely due to emerging softwarization and backhaul functions and NSE developments. Our objective is not to propose new business models in this report but merely shortly outline different involved aspects. Mapping between these different sides must consider many things, including population density, potential ownership distribution consequences as well as various risk models (e.g. launch schedule) and cost models (e.g. cost per kg or cost per MHz). For instance, an optimal threshold for population density for LTE based public safety network is analysed in (Peltola 2015) whereas (Ferrus 2014) analyses potential ownership distribution consequences for LTE based public safety network. The role of newly introduced service broker between satellite and terrestrial operators is expected to stand out and analysed in (Watts 2018). 5G business models for network sharing and multi-tenancy using a service broker are described in (Samdanis 2016). Billing relationships, which are typical for satellite communications, are outlined in (TR 101 984 2007). A business model, called as condo constellation, may be interesting for those actors who want to task their own payloads but don't want to have own satellites (SpaceNews 2019m).

Using the available information from aforementioned references, we summarize some essential but not comprehensive information in Figure 12. In the upper-left corner, selected important business cases are listed, as suggested in (Berioli 2011). The typical service agreement model for MCS is presented in the lower-left corner from (TS 23.280).

In the upper-right corner, satellite community has specific business roles (Ferrus 2016, TR 101 984 2007), namely satellite operator (launching and operating satellites), network operator (ground segment, control), access provider (resource mapping between operator and service provider), service provider (sells the service to customers). These roles can be mapped to

several different kind of business models, including integrated model (a single company plays all the roles), managed model (a single company plays the all the roles except it outsources the service provider role), and virtual model (a single company plays only the satellite operator role and outsources other roles to virtual network operators).

Finally, in the lower-left corner the business roles that rises from 5G network softwarization and slicing concepts (Afolabi 2018) are infra providers (physical network structure), cloud providers (computation and storage resources), virtual operators (leasing resources from infra provider), service broker (interacts with physical network and virtual resources), application providers (end user services, e.g. Netflix), and vertical players (nontelecom industrial players).

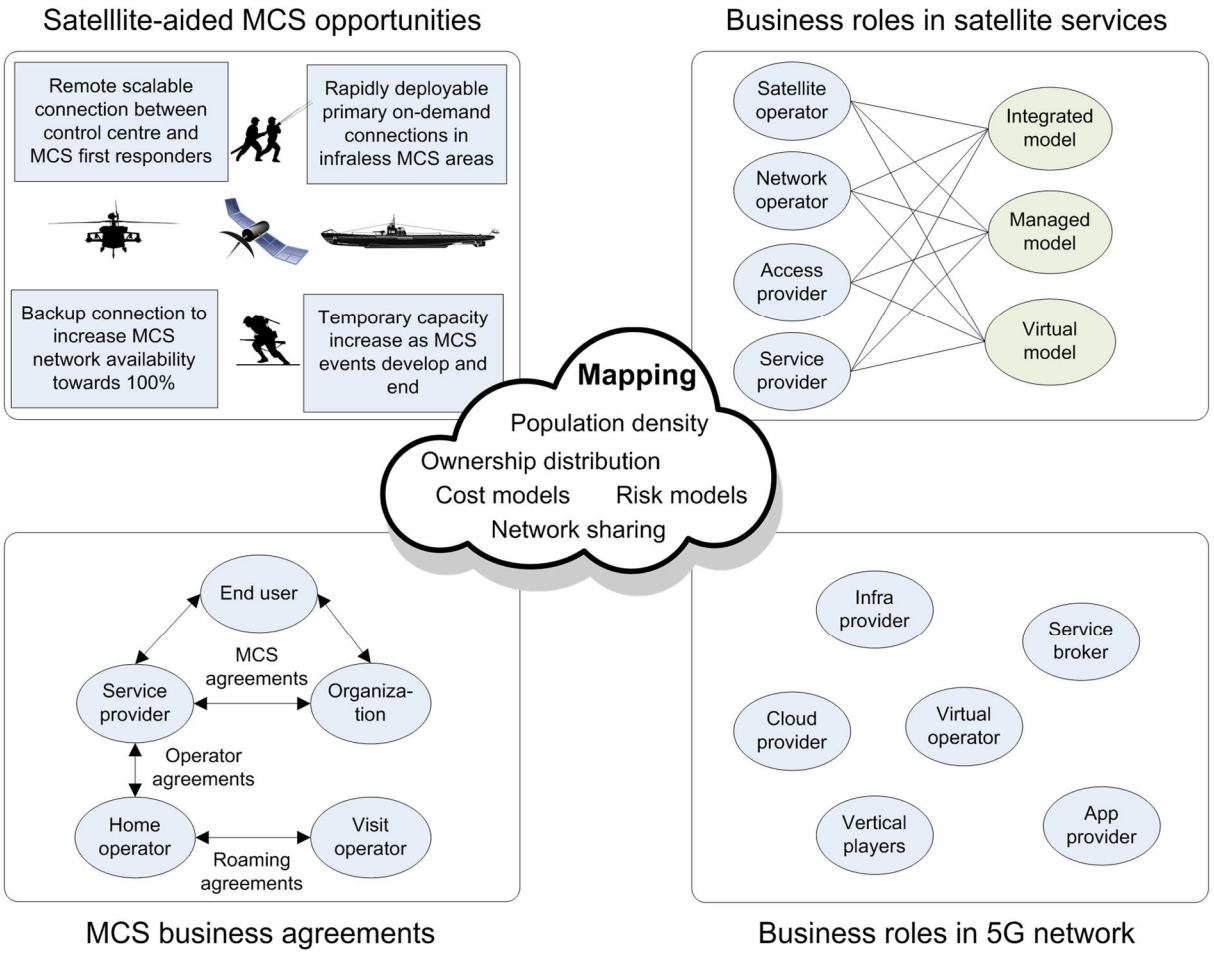

Figure 12. Illustration of different factors affecting the business modelling for MCS in satellite-aided 5G network.

5.1.2 NSE ecosystem in Finland

NSE and companies in Finland form a national ecosystem having already established international connections especially in Europe. According to (TEM 2019), the four central space areas in Finland are: Earth observation, satellite-based positioning, space industry, and scientific space research. Finland has also quite extensive satellite communication expertise. Space activities require prior authorisation by the Ministry of Economic Affairs and Employment. The national strategy for Finnish space activities can be found from (TEM 2013) and an update from (TEM 2018) e.g. to develop Finnish space administration. Business Finland has its own funding program for NSE (BF 2019). There are couple of tens of companies working in the space business in Finland and some of the national players were already

mentioned in Section 3.4. The most interesting ones from this study point of view include the following actors.

Space Systems Finland (SSF) is developing safety critical software and data analytics and has been the largest player in Finland with 7 M€ annual revenue, approximately half of the revenue coming from space projects. SSF was integrated lately to RD welho and continues SW development for many satellite missions. SSF has developed flight and ground software for the European MetOp weather satellites and develops also navigation and positioning technology e.g. to Galileo satellites.

Bittium has been working a long time with public safety and military communications, specializing in reliable, secure connectivity. Tactical communications networks work includes both terrestrial and satellite connectivity. Bittium has been working on integrated satellite-terrestrial systems since 3G (Terrestrar Genus phone) and is currently developing mobile phones for Mexican government program Mexsat. The satellite-terrestrial phones can be operated in both the satellite network and the terrestrial network.

Reaktor Space Lab (RSL) is a Finnish nanosatellite manufacturer. Together with VTT, that is participating in providing the payloads (hyperspectral cameras, radios, and antennas), RSL has built and also launched operational nanosatellite Hello World that has been already one year in the orbit and built a W-cube communication channel characterization satellite, ready to be launched soon. The W-cube satellite is the first Finnish satellite ordered by the European Space Agency. RSL has also developed their own S-band satellite radio, capable of transmitting up to couple of hundreds of kilobits per second between the satellite and the earth station.

Iceye builds and operates synthetic aperture radar (SAR) satellites with the size of around 100 kg to be used e.g. to track vessels and to analyse ice coverage in Arctic areas. It employs more than 100 people and has already launched three satellites in the orbit. The target is to create worlds' largest SAR satellite constellation (up to 50 satellites) to provide close to real-time information globally. The X band radios of Iceye satellites have maximum download speeds of over 100 Mbit/s to transfer SAR images to the ground stations. Some satellite providers (e.g. Inmarsat) are planning mobile broadband payload dedicated to the Arctic region (Inmarsat 2019b). In addition, Nokia has started nonterrestrial 5G studies (T&T 2019).

Finally, there are researchers working in universities and research institutes to develop connectivity solutions from physical layer up to services related to satellite-terrestrial integration. For example, University of Oulu is part of European Sat5G project and VTT has started 3-year strategic collaboration with European Space Agency in 5G satellite-terrestrial integration topics, supporting many national companies directly and e.g. in the joint ESA projects. More information on VTT's satellite-related contributions can be found from Appendix 0.

5.2 Market status, prices, and predictions

The commercial space market size globally has been recently estimated to be USD 350 billion (Morgan 2019) and it is growing rapidly. The global market is projected to grow to USD 1.1 trillion by 2040 (Morgan 2019, Nato 2019). A large part of the business is related to well-established markets (e.g. positioning services and related consumer equipment around USD 100 billion and satellites for the television industry — a business valued at USD 95 billion). A very good up-to-date review of the current market status is provided in (Nato 2019). As is explained in the report, space enables a large variety of economic activities and satellite systems are also displacing traditional systems. "In the Flanders region of Belgium, for example, geo-fencing and satellite communication have replaced underground sensors in the tram network. In the commune of Alban (Tarn, France), a satellite communication system is

used to manage the city's drinking water and to provide real-time management and security of those supplies. (Nato 2019)"

A good analysis focusing on small satellites (i.e. <500kg) is made by (Frost 2019) with the following key findings: about 12 000 launches will be conducted during 2018-2030 with total revenue of USD 69 billion. Regarding the mega-constellations, an inflection point for business development is foreseen by Northern Sky Research to come within next 12 months where we probably see which companies really have resistant business models to continue the operation (SpaceNews 2019l).

The deployment cost of LEO satellite launch is typically rated USD 10 000 - 20 000 per kg and in the future the price is expected to reduce down to USD 1 000 per kg (Eib 2019). For a tailored two-way unicast connection, which uses VSAT equipment and GEO satellite links, the operational costs per subscriber connection can easily be more than USD 20 000 per month for the high throughput service. For low rate phone connections as well as high rate broadcast services, the costs per subscriber per month are naturally much lower down to the level of few tens or hundreds of euros. Prices are coming down due to many competing constellations and their connectivity services but currently the prices are significantly higher than in the terrestrial networks. It is important to note that the launch costs do not reduce linearly with weight (Sweeting 2018). A nice roadmap for the launch cost development is given in (Future 2019).

The estimated speed of market growth is visualized in (Morgan 2019) where exact numbers for each segment can be also found. As an example, a clear growth is expected to happen in consumer broadband services. *This is actually the most significant short- and medium-term opportunity: Satellite broadband Internet access.* The revenue in 2018 is around USD 2 billions, in 2024 the market is above USD 20 billions, and in 2040 it will be close to USD 100 billions. Many segments remain roughly at the current size and another large growth may happen in the future in the category "Second order impacts". It is visioned in (Morgan 2019) that "Packages today delivered by airplane or truck could be delivered more quickly by rocket. Perhaps private space travel could become commercially available. Mining equipment could be sent to asteroids to extract minerals—all possible, theoretically, with the recent breakthroughs in rocketry."

In the current NSE, one of the trends is that there is an increasing amount of small players working actively e.g on remote sensing and connectivity services. This is also a major effect in the market growth. From 2012 to 2017 the number of satellites has increased from 994 to 1457. Due to new players and small satellite systems, including many mega-constellation initiatives (Ars 2019) the number of satellites has been estimated to increase to 7000 in coming years. Naturally the revenue is expected to increase significantly. As is stated in (SpaceNews 2019f) bandwidth prices are coming down so fast that some fairly low-mileage satellites are struggling to keep up; capacity prices dropped between 35 and 60 percent over the last two years and will continue to decline into next year.

Due to declined prices the traditional GEO operators are not so willing to invest hundreds of millions of Euros to develop satellites that are planned to be in the orbit for 15 years (a single satellite can cost e.g. 200 M€). In addition, it takes several years to build and launch such a system and there is a risk that in the coming years such a satellite could be falling behind the emerging fast-moving small satellite industry. Many new initiatives consider using serial production to push prices down and enable fast building and launch of satellites. In addition, satellite operators aim to reduce costs of future satellite connectivity by using software-defined satellites (e.g. Telesat) that enable radio updates with the latest standard features, such as on-the-fly control and management based on extensions of software defined networks concepts that are already used for the terrestrial components (Xu 2018, Höyhtyä 2019). 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.

Coming mega-constellations (fleets of hundreds or even thousands of relatively small satellites orbiting the planet in LEO and MEO orbits) are depicted in Figure 13. These systems will challenge traditional GEO systems by providing faster connections with lower latency. As can be seen in the figure, initiatives such as Telesat and Starlink already have prototype satellites launched, and OneWeb has also launched first satellites in 2019 and will start providing broadband services in the Arctic in 2020 (Oneweb 2019). The total capacity of satellite service is estimated to be 375 Gbps, which is then divided to the end users.

According to (NSR 2019) the small satellite market will be USD 37 billion by 2027 and constellations will be the dominating factor of this growth, making up over 70% of the total market. While growth is anticipated across all applications, communications will drive the largest share of revenues.

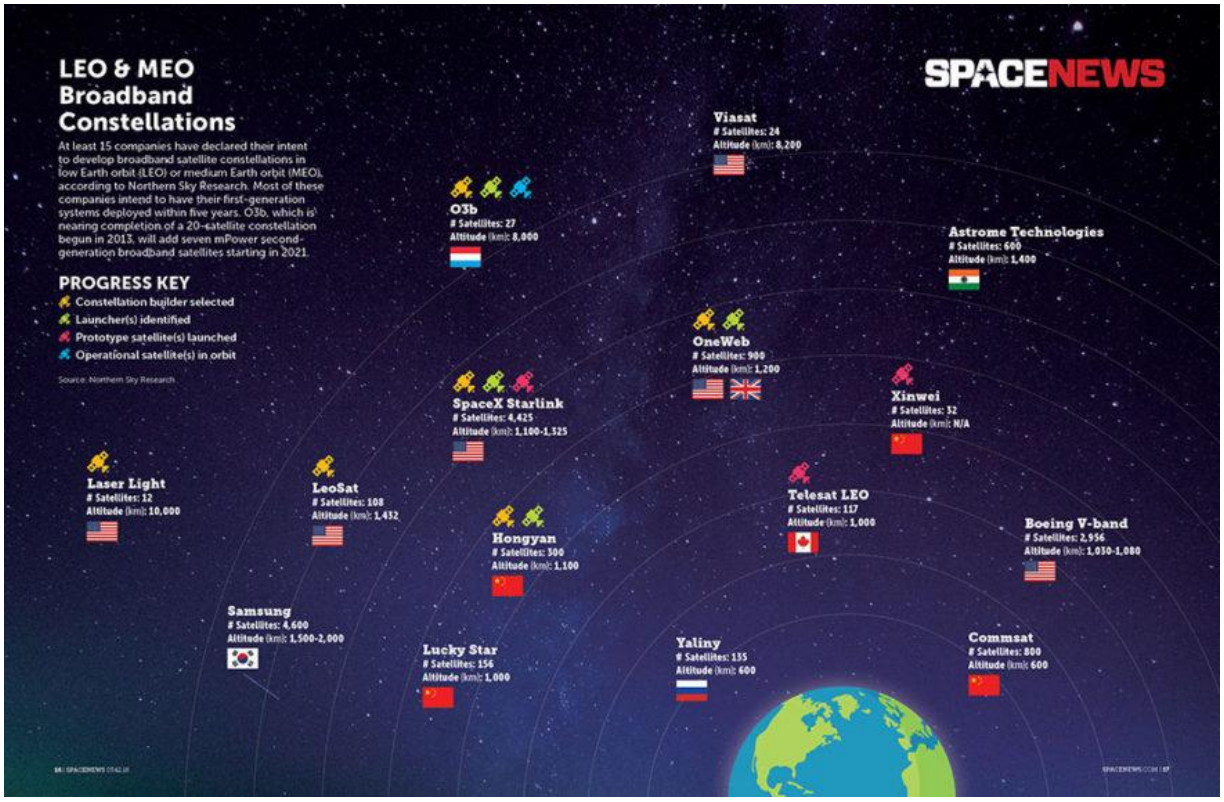

Figure 13. Emerging LEO and MEO mega-constellations to provide broadband services (Henry 2019). Used with permission.

Finally, an analysis of financing challenges, market maturity and sector risks, and role of public sector can be found in (Eib 2019). The report also provides finance related recommendations. For example, it is found in the analysis that most space entrepreneurs are looking for private capital outside of the EU, especially from USA. It is also found that European public innovation instruments play an important role in unlocking private capital for the space sector. “40 % of the companies seek public funding as it is a precondition for private investment. Public funding serves as a seal of approval in the market.”

Hybrid communications networks that will serve both critical and commercial users is going to be important part of authoritative communications in near future. During the discussions with public safety organizations it has become clear that they aim to use more and more civilian network and COTS devices in their use operations while it is important to ensure that cybersecurity stays at the high level. This is of course dependent on the required security levels

and in the most critical communications there is a need to have only military-grade devices in use. The advantages of COTS devices include easy use, availability, and low costs.

Most probably Finnish authoritative users do not want to launch and operate their own satellites in the near future but rather rely on available commercial satellites. However, other NTN systems such as drones and HAPs are very promising parts of the systems providing services only to critical users.

Critical users may lease part of the commercial (satellite) network capacity for their use in a way that a secure virtual network is created within the same infrastructure that is mainly serving commercial and civilian users. At the same time they are sharing the costs. It could be e.g. that 10 % of the commercial satellite capacity is dedicated to serve critical users and thus, 90 % of operational costs are covered by civilian users.

Emerging 5G systems enable world-wide standard based networking which will in the long term lower costs and especially improve interoperability of the devices. When critical communication users can use the same devices to access both critical services (with a dedicated critical network slice) and civilian services it will reduce costs and enable vast array of services. This is especially true if 5G connection can be used to access both terrestrial and NTN components of the network.

6. Discussion

6.1 Proposed overall assessment

6.1.1 Synopsis

The emerging ***mega-constellation-enabling LEO communication systems*** are expected to appear during the next 10 years in the spirit of NSE concept. There are many well-grounded companies as well as start-ups (e.g. LeoSat, OneWeb, SpaceX, and Telesat) announcing ambitious plans varying from hundreds to thousands small satellites per constellation. These plans are in an early phase with no or only a small portion of the constellations currently orbiting. Perhaps the most mature technology is from OneWeb and SpaceX aiming to start commercial operation already 2020. While LEO constellations are now in the top of hype cycles, a turning point is foreseen to come within next 12 months where the community will see which expectations will more probably realize and which companies have to exit. The mainstream applications, but certainly not limited to, are often seen to be a more advanced satellite-aided broadband Internet and pervasive ***Internet of space things*** for unserved/underserved users and devices which can leverage many application fields, including critical communications.

LEO constellations with a large number of small satellites will not replace either the existing terrestrial systems or large GEO satellites but rather complement them in terms of i) coverage/scalability improvement for terrestrial systems and ii) delay/cost reduction for GEO systems. The swarms of small form factor satellites indicate the need for high network efficiency and new distributed operational skills. To ensure such high efficiency, ***deeper integration*** (i.e. in comparison to earlier GMR standard) to terrestrial and airborne communications systems is expected via ongoing ***3GPP 5G specification*** activity where more concrete specifications can be expected from Release 17 by 2021. The 5G ecosystem enables a divergent position to renew the past integration efforts by reconsidering holistically relevant subnetworks jointly and from the beginning. In the meanwhile, some vendor-specific 4G/5G-ready NTN proof-of-concepts have already been provided in addition to those currently under work, as summarized in Section 4.4. Since the deployment time of user terminals for new technologies is typically quite long, an interesting possibility is that some solutions may be able to provide ***a satellite base station connection to a regular cellular phone*** without any modifications needed to the phone itself. The operational skills of future satellites can be improved via more sophisticated ***cooperation and softwarization*** of networking functions.

Regarding the ***MCS framework*** in Finland and Arctic areas, the emerging satellite technology development can be seen as a potential successor of upcoming VIRVE 2.0 after we have learned how VIRVE 2.0 will perform in actual use. A clear amendment to existing legacy communications systems can be expected to be vital especially in hard-to-reach locations. It is important that there will be constellations with sufficient density that are inclined so that they are visible to Arctic areas, i.e. having latitudes higher than 60 degrees. Moreover, the operation of an ***MCS is often phased*** where different phases possess different requirements for the communication system depending on the conducted emergency management approach. A winning accomplishment is to contribute, in part, for achieving the ***ultimate 100 % MCS availability,*** fulfilling the security and service quality requirements, at all times and locations by ensuring that the necessary communication resources are available to MCS users when and where needed. Local and remote access should be provided simultaneously. The satcom is largely seen as a supporting technology for MCS to enable better service availability. This development is already seen e.g. with the FirstNet system using several legacy satellite technologies. In comparison to *no-service* situation, *degraded-service* situation is still better, indicating that a satellite component could be inferior to primary terrestrial communication systems in some quality parameters.

Simply put, an MCS user wants to focus on conducting the critical mission at hand. This requires a user experience of using ***a single network that works*** so that the possible integration aspects are invisible to the user. Such operation is enabled via smart integrated network that should be autonomous, well integrated to daily used mobile terminals, and extremely reactive to unexpected events such as sudden power outages, environmental changes, or disasters. Raw data or high-resolution video does not yet help much in providing understandable situational awareness for the first responders, but the ***data should be properly processed to mine the essential information.*** We are not there yet and emerging large-scale LEO satellite communications, when available, likely provide only a partial solution to above challenges.

6.1.2 Qualitative feasibility

Our qualitative feasibility analysis is provided via Figure 14 and Table 10. A number of major feasibility attributes are first selected and divided into opportunities and risks in Figure 14. More justifications for the division are then given in Table 10, including a rough guestimate on the foreseen impact of a given attribute. That is, positive angles are described with **orange font** and negative aspects with **green font**. The impact is then evaluated using a four-step scale defined at the bottom of Table 10. We emphasise that the *division and impact assessment is by far not definitive or exhaustive* and there are many ways to do the division and foresee the impact, depending on the selected perspective and baseline (e.g. terrestrial or GEO system) on which the comparative assessment is made. Moreover, the given justifications are not time-independent and may change as the technology barriers are overcome. Nevertheless, by the time, we believe that the proposed assessment is a good objective starting point for further discussion of merits and demerits of the emerging technologies at hand. Table 10 provides also a section number of this report to find more information on the particular attribute.

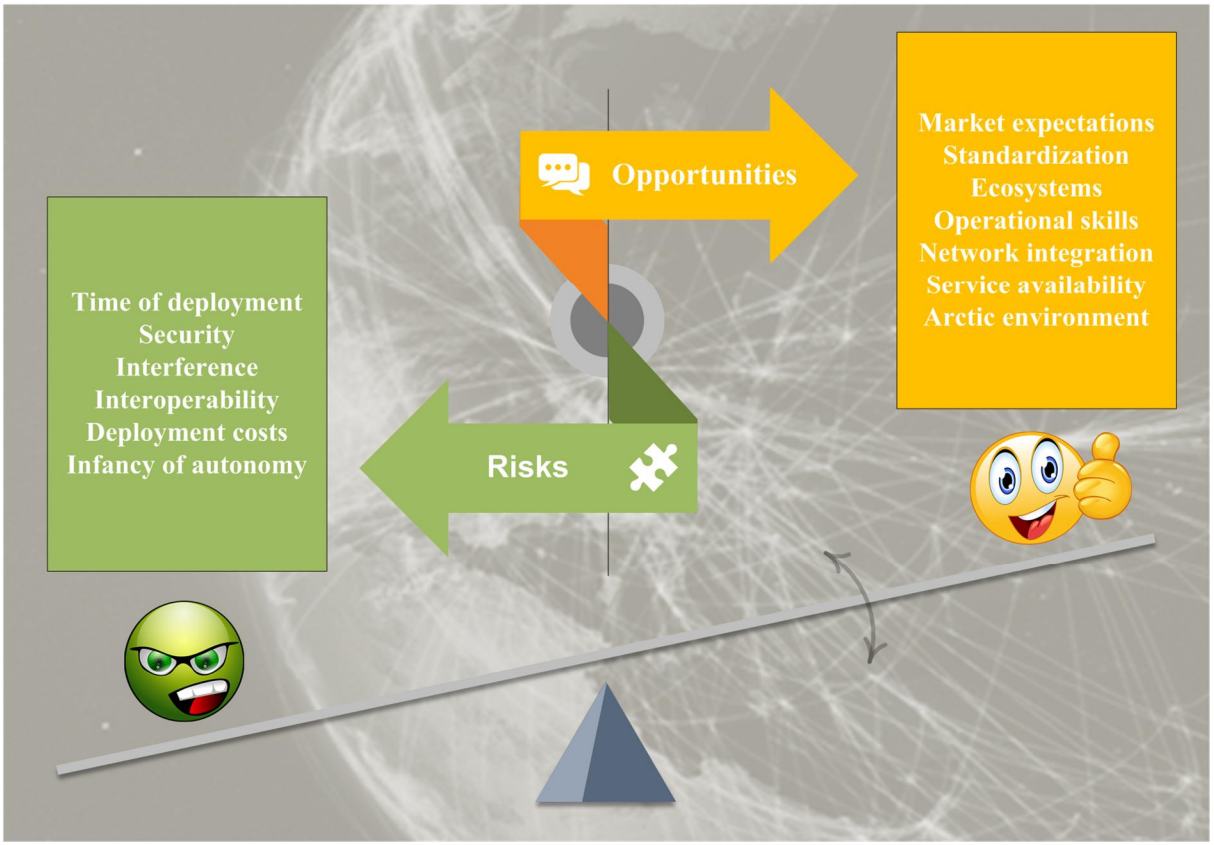

Figure 14. Feasibility illustration of emerging satellite-aided networks.

Table 10. A qualitative feasibility evaluation of emerging satellite-aided networks.

Attribute	Observations	Impact*	Section
Market expectations	Small LEO satellites use is one of the top items in the innovation trigger in many alliances. The total revenue with about 12 000 smallsats is expected to be about USD 70 billion during 2018-2030 while the whole space market approaches about USD 1 trillion by 2040. Internet of space things is commonly used as one key application.	+	5.2
	Underneath of the hype, many stakeholders still remind of past mistakes done with commercial satcom systems and associated unrealistic expectations. The high expectations and plans on NSE have not realized yet.	-	
Timeline of deployment	Several companies have already started to launch capable small LEO satellites with ambitious plans for expanding towards larger mega-constellations with up to thousands of satellites per constellation within next 10 years. E.g. OneWeb and SpaceX aim to start commercial operations already in 2020.	+	4.4
	Expected full-scale deployment of LEO mega-constellations in 10 years might be too long to boost current commercial use case development. It is unclear if very large constellations are practical from regulation point of view. Satellite launches may cause additional deployment delays. Small form factors and batteries further challenge the payload capability.	--	
Standardization and regulations	3GPP standardization will potentially enable very effective deep integration of satcom to cellular networks. 3GPP R17 is expected to be ready by 2021 and first 5G NTN technologies will be available with some delay after that, say few years, but it is difficult to predict accurately at this point. Frequency regulations of emerging LEO mega-constellations are currently being put forward by ITU. Non-3GPP satellite standards, such as DVB, will continue their development and can also be integrated via inter-working functions.	++	4.3
	Many satcom integration standardization attempts have been already made in the past. 3GPP R16 is in finalizing phase where satcom was still only preliminary studied although the work was already started in R14. The spectrum regulation race between terrestrial and satellite seems not vanishing. Different regional frequency regulations complicate interference management.	--	
Ecosystems	Emerging NSE concept with many promising new start-up companies complements traditional big companies and governmental actors. Possibility to invent new agile business models in cooperation with major players. Old space economy will not disappear and remains in parallel to NSE.	++	5.1
	While the turnover of start-up companies is typically high, the business profit might be low, challenging the operation. The situation can be expected to improve with time but the time is critical especially for new start-ups. It is important to recognise which companies are truly focused on space technologies to properly allocate the available funding.	-	
Security	In upcoming 5G systems, the cybersecurity aspects have improved considering also security of non-3GPP systems. There are still open potentials such as physical layer security and blockchain approaches to improve cybersecurity. Emerging rules for space sustainability, rapid de-orbiting, and new tracking tools help to mitigate space debris.	+	4.2.3
	The new threats arising from emerging quantum computing and artificial intelligence affect especially the cyber security of complicated integrated networks. Very long keys consume limited bandwidth and are difficult to share reliably. Aggressively increasing amount of small satellites affects significantly the physical security of satellite communications.	--	
Operation lifetime	The operation lifetime of typical commercial LEO satellites is from few years to 15 years which is sufficient for many purposes.	++	3.3
	Mega-constellations are expected to be partly in very low orbits approaching 100 km. In these conditions, atmospheric drag, energy limitations, station keeping, frequent handovers, and propulsion technologies are difficult to address.	-	

Deployment costs	The trend of launch cost per satellite is decreasing especially when using rideshare approaches with multiple small satellites. It is already possible to launch over hundred satellites with a single launch.	++	5.2
	Although the trend of launch costs per satellite is decreasing, the launch costs of large satellite constellations still remain relatively high compared to terrestrial systems with possibility of unsuccessful launches incorporating multiple satellites. Moreover, launch costs in €/kg in general do not decrease linearly with size.	--	
Operational skills	Key emerging techniques for satcom are softwarization, slicing, edge computing, advanced antenna arrays, and inter-satellite swarming or formation flying for IoT. Cooperation with different satellite layers and terrestrial stations help to mitigate the size limitation of smallsats. In addition to typical performance and user interface issues, autonomic operation is one of the most important user attributes. That is, the communication technology should be transparent and not burden the MCS user in any way. Emerging deep learning and swarm intelligence approaches with large constellations can be expected to be useful in the future in that matter.	+	4.2
	There are currently some obstacles to fully deploy these techs already in terrestrial systems, which indicates challenges also in NTN domain. Moreover, the size of small satellites limits the available energy and skill level of the payload. Given the fact that autonomic features of current networks is still in its infancy, complicated integrated network with small form factor LEO satellites, at least in the early phase, may pose some risks on the high usability expectations of MCS users regarding autonomic operations.	-	
Network integration	Efforts are now aggressively tuned towards a high integration degree of satellite, drone, and terrestrial systems. Different stakeholders are now working more tightly together. Previous integration attempts, such as GMR, can be used as a baseline to find improvements and avoid mistakes. Some efforts aim at satellite base stations, which would require no modification to existing terrestrial phones.	++	4.1
	A key challenge is to find feasible and generalized subnetwork-agnostic and -dependent protocol splits at different layers that overcome the interoperability problems inherent to heterogeneous integrated system characteristics. It is essential to support the end-to-end IP network architecture that might be challenging in an integrated architecture.	--	
Performance	Current early proof of concepts for integrated 5G networks show promising results to improve the delay performance of traditional GEO satellite systems. Currently, delay (typically 20-80 ms) using one satellite relay seems not to be a significant bottleneck with LEO satellites with respect to typical MCS delay requirements in a basic single relay scenario. Many MCS scenarios would apply satcom as a supporting system for which delay performance requirements can be relaxed. Although, the coverage of cellular systems is rather good in Finland, there are still relatively large areas, both land and sea, that lack of cellular coverage which provides good opportunity for satcom to assist in achieving close to 100% availability required for future MCS services.	+	3.3/4.4
	Future MCS delay requirements may become more demanding via added haptic or augmented reality information. Moreover, very low altitude satellites may require multihop inter-satellite links, which obviously increases end-to-end delay. Large mega-constellations possess similar challenges as ultra-dense cellular networks, i.e. they increase the traffic load, the risk of interference, handover frequency, and retransmissions, which affect the overall reliability and end-to-end delay jitter and is already quite high in many cases.	-	
Arctic environment	Flexible small LEO satellite mega-constellations have good position to support Arctic MCS communications with polar orbits. The number of international programs and interest on Arctic environment is increasing, new Finnish companies emerging, NSE funding programs from Business Finland. Some satellite providers (e.g. Inmarsat, OneWeb) are planning mobile broadband payload	++	3.4/5.1

	dedicated to the Arctic region. Artic possesses a clearer need and motivation for coverage improvements via satcom compared to many other environments.		
	Arctic environment has limited access to satellites unless specific conditions, such as constellation's inclination, are valid. Focusing on optimizing services just for sparsely populated areas might be challenging from business point of view.	--	

* Impact is a vague guestimate of the authors on the relative effect on overall feasibility of different satellite-dependent attributes based on currently available status information in the open literature at the time of writing the report (Q3/2019). The assessment is further dependent on the selected viewpoint from the given attribute and is therefore inherently ambiguous but provides a baseline for further discussion.
Symbol interpretation: '++' = impact is seen positive and positive realization is plausible; '+' = impact is seen positive but positive realization is dubious; '-' = impact is seen negative but negative realization is dubious; '--' = impact is seen negative and negative realization is plausible;

6.2 A roadmap and potential study cases

Given the emphasis of this report, we further overview the development paths for terrestrial MCS networks and satellite networks in Figure 15.

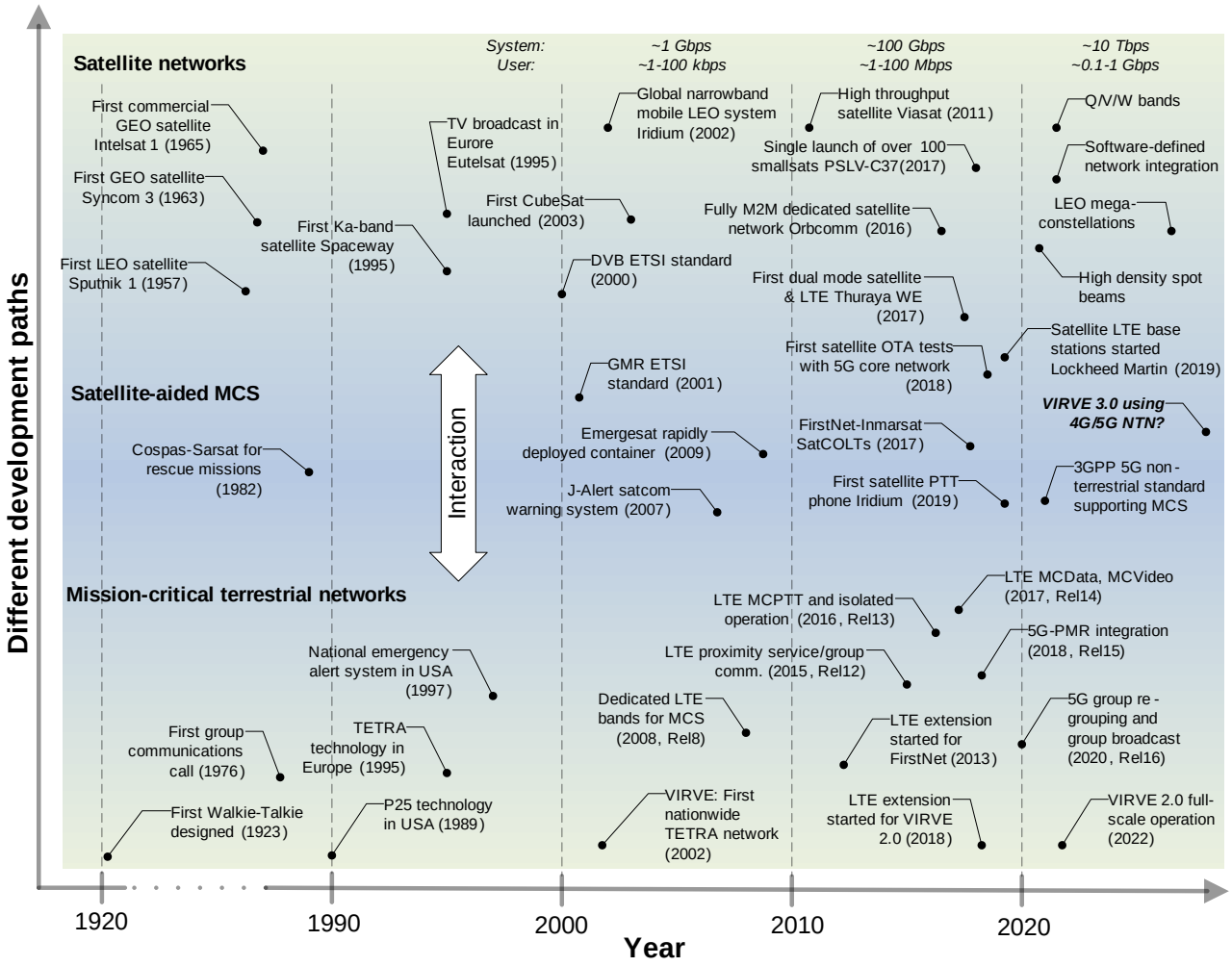

Figure 15. A roadmap with selected milestones for satellite networks (top, green area), terrestrial MCS networks (bottom, green area), and overlapping satellite-aided MCS networks (middle, blue area). Satellite networks and mission-critical networks have their own development paths but they do interact and slowly converge towards each other.

The information is selectively gathered in part from (Sweeting 2018, Evans 2015, Guttman 2018, Guttman 2019, Onireti 2018, Raza 2019). See also more related discussions from

Sections 3-4 and references therein. It is seen that satellite networks and mission-critical networks have their own development paths but they slowly converge towards each other. This observation can be used to address potential roadmap e.g. towards *VIRVE 3.0*. Furthermore, the role of Krivat service platform should be included in future studies (ERVE 2019f).

Based on discussions in the previous subsection, it is clear that the NTN communications as well as MCS are in strong turbulence phase. As a result, there are a number of possible development topics in the future. We only briefly present them in Table 11 in arbitrary order and we recommend sources for further information on different topics. While some of the topics are more far-reaching, some other topics could realize in short-term.

Table 11. Summary of important topics that needs further attention with excellent surveys to find further information.

Topics for further investigations	**Source**
Orbital data for existing and emerging operational satellites	UCS 2019
Software-defined networking for NTN communications	Shi 2019
Network slicing for MCS	Höyhtyä 2018
Security issues of NTN communications	Jiang 2017
Integration of terrestrial and NTN	Cao 2018,Liu 2018
Integration of Earth observation and communication network service	Theia 2019
Business models for NTN	Eib 2019
Space situational awareness for debris mitigation	Torky 2019
Small satellite formation and fractionated spacecraft concept	Radhakhrisnan 2016, Sweeting 2018
Performance of LEO mega-constellations	Pultarova 2018, Portillo 2019
Edge computing with satellites	Zhang 2019a
Phase-oriented NTN communication platform for MCS	Berioli 2011, Erdelj 2017
Big data analytics and machine learning for MCS	Wang 2016, SpaceNews 2019k
Small GEO satellites	SpaceNews 2019g
Haptic information for MCS	Simsek 2016
Digital humanitarians to assist MCS responders	Pervez 2018
Advanced battle management systems	SpaceNews 2019h
Seeing with radio	Adib 2019
Gadget-free communications	Ijaz 2018
Augmented reality for MCS	Verizon 2019
Autonomous MCS	Sole 2018
Quantum-based secure satellite communications	Hosseinidehaj 2019
Space sustainability rating system	SpaceNews 2019i
AI-driven security threats for MCS	Yuan 2019
Very low Earth orbits	Dakka 2018
Millimetre waves for satellites and MCS	Sacchi 2019, Mezzavilla 2017
Full-body teleoperation	Ramos 2019
Multisensory human bond communications	Iftikhar 2019
Emerging 6G paradigms	Yang 2019, Zong 2019

7. Conclusions

The main objective of this report is to provide a survey and feasibility study on emerging satellite-aided networks with respect to target MCS. The performed analysis is mainly qualitative and based on nonpublic interviews and publicly available state-of-the-art literature.

Following the introduction section, we first provide essential information on target MCS and their main requirements in Section 2. More specific information from the field is obtained via selected interviews (presented in confidential appendices) including applications from military, border control, and rescue services. A summary of existing technologies is then provided in Section 3. In Section 4, we discuss the on-going 5G integrated network process, including integration, some important 5G architectural functions that affect MCS, the standardization status, and some early proof-of-concepts. Finally, in Section 6, we present our overall assessment, a roadmap, and potential topics for future work.

While terrestrial VIRVE 2.0 is now being deployed, there is a movement towards satellite-aided terrestrial network to support future versions of VIRVE. There are already many satellite technologies available that can support MCS e.g. in hard-to-reach locations but the eternal question in any technology development is: *can we do things better from (MCS) user perspective?* A significant boost is expected from recent 3GPP/5G NTN specification activities, which are still in early stage as Release 17 efforts are just starting, to clue the terrestrial and NTN communities together more efficiently. Another boost is coming from *NSE* and low orbit *mega-constellation* frameworks. Both of these are expected to realize during the next decade solving the previous problems of low profitability of satcom business and high delays from large high orbit constellations. Nevertheless, small LEO satellites will not replace large satellites but complement them while not being fundamentally different. Underneath the hyped up expectations, there are number of challenges as summarized in Section 6.

In short, the main takeaways of the report are the following:

- Ø The report is rather comprehensive with connections to user scenarios, requirements, existing and emerging technologies for terrestrial, airborne, and space, business perspectives, standardization, international and Finnish aspects, etc.
- Ø The report provides up-to-date information on current proof-of-concepts for 5G integrated networks (Section 4.4) and a roadmap for terrestrial and satellite MCS networks (Section 6.2). Satellite networks and mission-critical networks have their own development paths. However, we can see that they are slowly converging towards each other.
- Ø The report includes more static information on fundamentals found in the scientific literature as well as more recent developments gathered from news and interviews.
- Ø The report, with a concise assessment summary (Section 6.1), is expected to be useful in supporting decision-making processes related to deploying satellite-aided networks for MCS.

Considering the future work, the current limitations of the report are the following:

- Ø Since the scope of the report was (purposely) very wide, we were able to only touch some important issues and had to leave out some interesting topics that serve to be treated more carefully in the future.
- Ø Some important stakeholders (e.g. network and satellite operators) and potential end users (e.g. police) were not yet involved in the interview survey.
- Ø The focus was on qualitative aspects and more quantitative approach is needed in the next steps to evaluate the performance in more detail.
- Ø The satellite technology is at a turning point in which significant and rapid changes are inherent. Therefore, some items discussed in the report may become quickly outdated, calling for a constant monitoring of the progress of the field.

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Appendix 0: VTT's key research topics on satellite technologies

VTT's competence areas are illustrated in Figure 16, including i) satellite applications, ii) satellite communication technologies, and iii) satellite payload component development.

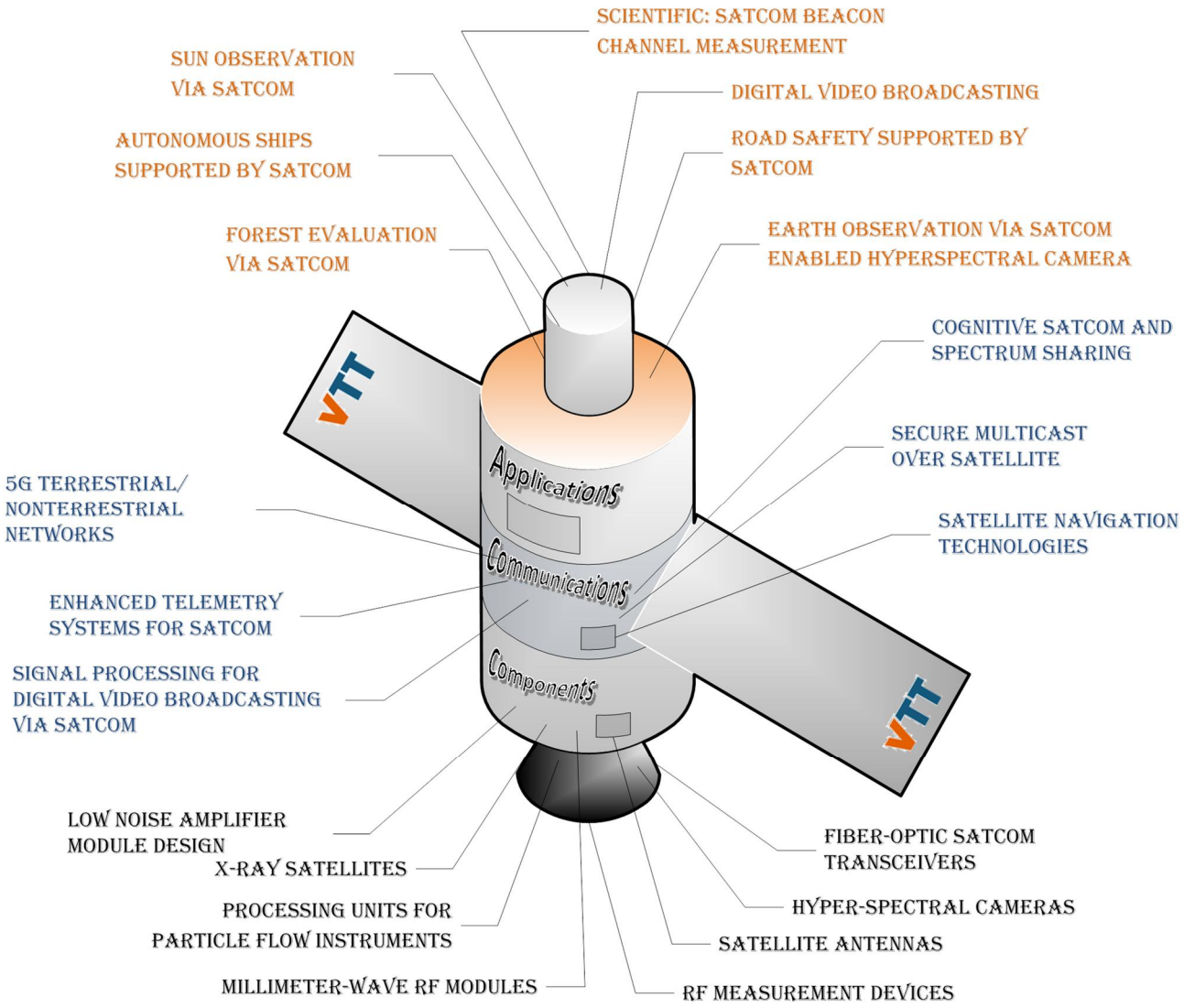

Figure 16. Snapshot of VTT's previous focus areas on satellite technologies.

A snapshot of VTT's contributions to find more information:

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Appendix 1 (confidential): Enquiry for Finnish Defence Forces (FDF)

This material is provided only in the confidential version of this research report.

Appendix 2 (confidential): Enquiry for Finnish Border Guard (FBG)

This material is provided only in the confidential version of this research report.

Appendix 3 (confidential): Enquiry for Department of Rescue Services (DRS) and Emergency Services Academy Finland (ESAF)

This material is provided only in the confidential version of this research report.

Appendix 4 (confidential): Summaries of enquiry responses

This material is provided only in the confidential version of this research report.