Onireti, O. and Imran, M. A. (2018) Role of satellite communications in 5G ecosystem: perspectives and challenges. In: Sharma, S. K., Chatzinotas, S. and Arapoglou, P.-D. (eds.) *Satellite Communications in the 5G Era.* The Institution of Engineering and Technology, pp. 1-24. ISBN 9781785614279 (doi:10.1049/PBTE079E)

Chapter 1

Role of Satellite Communications in 5G Ecosystem: Perspectives and Challenges

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The next generation of mobile radio communication systems—so-called 5G—will provide some major changes to those generations to date. The ability to cope with huge increases in data traffic at reduced latencies and improved quality of user experience together with a major reduction in energy usage are big challenges. In addition, future systems will need to embody connections to billions of objects—the so-called Internet of Things (IoT) which raise new challenges. Visions of 5G are now available from regions across the world and research is ongoing towards new standards. The consensus is a flatter architecture that adds a dense network of small cells operating in the millimetre wave bands and which are adaptable and software controlled. But what is the place for satellites in such a vision? The chapter examines several potential roles for satellites in 5G including coverage extension, IoT, providing resilience, content caching and multicast, and the integrated architecture. Furthermore, the recent advances in satellite communications together with the challenges associated with the use of satellite in the integrated satellite-terrestrial architecture are also discussed.

1.1 Introduction

Mobile cellular communication systems have evolved through a series of standards known as Generations from Analogue (1G) through GSM (2G) via IMT 2000 (3G) to today's LTE (4G) systems. Satellite mobile systems have developed independently of the terrestrial systems and have largely been proprietary e.g. the Inmarsat system. There has been a loose connection in that the latter have generally used the GSM network model and more recently there have been versions of GSM/GPRS and 3G adapted for satellites e.g. the ETSI GMR series of standards. The result of this separation between the communities is that it is very difficult to integrate the two networks and thus join them so as to provide seamless services over both. Recently we are waking up to this problem and work is on-going to enable some integration of 4G between satellite and mobile. The next generation of cellular networks, i.e., 5G, is likely to come into operation around 2020. It is seen that satellites will integrate with other networks rather than be a stand-alone network to provide 5G services. Satellite systems are fundamental components to deliver reliably 5G services in all regions of the world, all the time and at an affordable cost. Thanks to their inherent characteristics, the satellite component will contribute to augment the 5G service capability and address some of the major challenges in relation to the support of multimedia traffic growth, ubiquitous coverage, machine to machine (M2M) communications and critical telecommunication missions whilst optimising the value for money to the end users.

In this chapter, we set out to discuss the 5G vision. Then, the historical review of the mobile satellite systems (MSSs) is presented stating the key ideas behind each generation and the main operational/proposed satellite systems. Next, the key areas where satellites can play a part in 5G are defined while also illustrating how satellite services can contribute to the 5G key performance indicators (KPIs). In particular, the key areas discussed include coverage, massive machine type communications, resilience provisioning, content caching and multicast, satellite-terrestrial integrated network (trunking and head-end feed, backhauling and communication on the move), and ultra reliable communications. The recent advances in 5G satellite communications are also highlighted and discussed. The discussed topics include the terrestrial and satellite spectrum in 5G, mega-low earth orbit (LEO) constellation, on-board processing technology, Gallium Nitride (GaN) technology, software-defined networking (SDN) and the integrated signalling. Finally, the concluding remarks are drawn.

1.2 The 5G Vision

The global consensus developing is that 5G will be the integration of a number of use cases, techniques, and use environment rather than the development and deployment of a new radio access technology (RAT). 5G aim to provide ubiquitous access to high data services, applications from any device, anywhere and anytime. 5G is expected to be based on customer experience and quality of service (QoS) with the aim of giving the customer the impression of an infinite capacity experience. In order to create such environment, there is the need to integrate various service applications, emerging from various services and access via a mix of access to different wireless and fixed networks. The vision of 5G mobile [1, 2, 3] is driven by the predictions of up to 1000 times data requirement by 2020 and the fact that the traffic could be 2/3rds video embedded. Another key driver for 5G is the emergence of Internet of Things (IoT) and the vision of Billions of objects being connected to the internet. This is the enabler to 'smart cities' and other such 'smart' environments and the emergence of what is called 'Big Data' applications where massive amounts of data can be processed to feed a plethora of new applications. For 5G this implies being able to handle large quantities of low data communications efficiently covering widespread sensor networks and M2M communications. There are two remaining pillars of the 5G vision. The first is ensuring availability, reliability, and robustness. The second and increasingly important issue is that of reducing energy. The target is a reduction by 90% of today's total energy by 2020 at no reduction in performance or increase in cost. Thus 5G network design becomes a complex task involving link

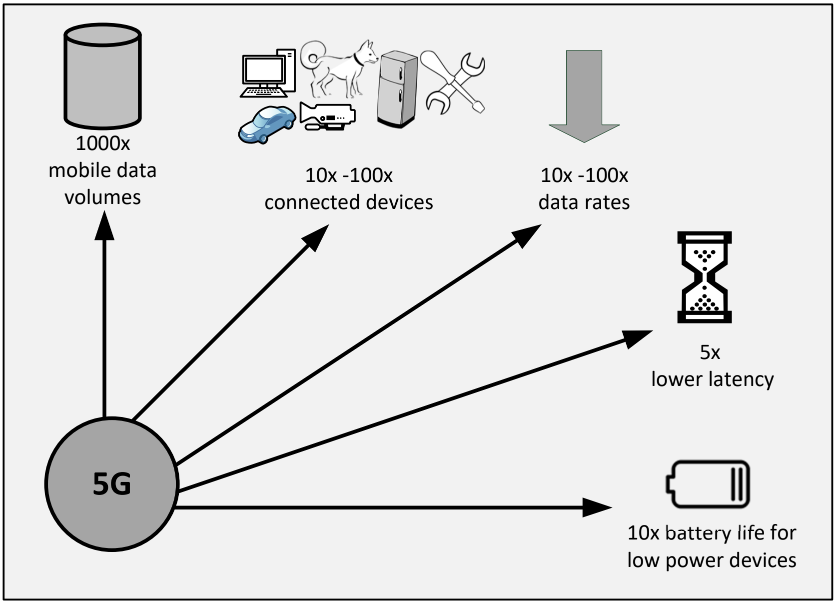

Figure 1.1 5G Requirements

and area spectral efficiency together with energy efficiency [4]. The overall technical requirements for a 5G network as highlighted by the 5G Infrastructure Public Private Partnership (5G PPP) can be summarised as follows [5, 6]:

- 1000 times higher mobile data volume per area,
- 10-100 times higher number of connected devices,
- 10-100 times higher typical user data rate,
- 5 time reduced end-to-end latency,
- 10 times longer battery life for low power devices, and
- Ubiquitous 5G access including in low-density areas.

Figure 1.1 shows the estimated requirement in 5G as compared with the 4G system. Of all the technical goals for 5G, the higher data rate requirement is the one that gets the most attention across the board and this will be achieved in terrestrial systems through the combined gain from three key technologies namely [7]:

- Increase spectral efficiency, through advance multiple-input multiple-output (MIMO) technology, to support more bits/s/Hz per node.
- Extreme densification and offloading to improve the area spectral efficiency, i.e., more active nodes per unit area and bandwidth.

- Increase bandwidth, by moving to the millimetre wave (mmWave) spectrum and by making better use of the unlicensed spectrum in the 5-GHz band.

The combination of more Hz (bandwidth), more nodes per unit area and Hz, and more bits/s/Hz will lead to many more bits/s per unit area. In general, 5G research activities are in an effort to deliver the technology that meets the ambitious KPIs of the 5G vision highlighted in the 5G-PPP. Meanwhile, the 5G research activities are mainly driven by the terrestrial operators, and hence, they do not adequately consider and evaluate the requirements from use cases which are specific to the satellite operators.

1.3 Satellites and Previous Cellular Generations

Table 1.1 shows the evolution of the MSS and the key ideas behind them. The first major satellite operator, Inmarsat, came into existence at around the same time as the first cellular operators providing 1G analogue services. Over this period, using the L band and global beam coverage satellite, Inmarsat provided low data rate services and speech services to the maritime market of ships. In the early 90's, Inmarsat was able to add aeronautical services to passenger aircraft with its advancement into spot beam higher power satellites. Later in 1997/78, worldwide spot beam operation, paging, navigation and higher rate digital to desktop terminals were introduced in the MSS. In the mid 90's, several regional geostationary earth orbit (GEO) satellite systems such as OPTUS, AMSC, EUTELTRACS, and OMNITRACS emerged focusing on land vehicles while using both the Ku and L bands. Research activities in the late 80's and early 90's focused on non-GEO constellations and resulted in the proposal of medium earth orbit (MEO) and LEO satellite system. Typical examples such as Globalstar and Iridium MSS came into service but were too late to compete with the spread of terrestrial GSM. A major issue with both companies was the business case as the cost of constellations were too expensive leading to their bankruptcy. Other companies such as ICO and Orbcomm have also suffered a similar fate.

In the mid 90's, super GEO satellites were proposed with around 100-200 spots rather than the earlier generation GEOs' with 5-10 spots. Of the proposed systems, Thuraya [8] was the one that reached the market in the early 2000's, offering GPRS and GSM like services to Asia and much of Europe. Super GEO found a niche with travellers, trucks and in areas where terrestrial mobile was too expensive to deploy. Inmarsat IV a super GEO took the digital service rate from 64 kb/s to 432 kb/s—from the global area network (GAN) to the broadband GAN (BGAN) [9]. Despite the move of terrestrial operators to code division multiple access (CDMA) in 2004-2005, Inmarsat developed its proprietary time division multiple access (TDMA) system to deliver 3G equivalent packet services. High data rate (HDR) BGAN, which exceeds symmetric 700 kb/s, became available since 2013. HDR also supports bonding for a total bandwidth exceeding 1 mb/s. Regarding M2M communications, Orbcomm offers data-only M2M services with a constellation of LEO in the VHF band, and in partnership with Inmarsat, they offer M2M

Table 1.1 Mobile Satellite Developments

Cellular		Research Ideas	Operational/Proposed Systems
1G	70's	Mobile satellite expts ATS-6	Inmarsat formed
	80's	Non-GEO mobile cellular architecture proposed	Inmarsat operates - maritime
2G GSM	1990's	Motorola announce Iridium system LEO Orcom system proposed Teledesic announce non-GEO fixed systems Globalstar/ICO proposed Super GEO's announced Agrani/Apmt/Aces/Thuraya	Inmarsat operates - land/aero Regionals: Omnitracs, Euteltracs, Amsc, Optus Inmarsat Sats-spots Iridium operational Orbcom operational Globalstar operational World space radio
3G IMT-2000	2000's	Integrates S/T/UMTS for content proposed Satin EU project DVB-S2 standard	Iridium/Globstar/Orbcoms Thuraya operational Inmarsat IV's -100's spots and DSP processor Xm, SIRIUS, DARS MBSAT
4G	2010's	High throughput satellite	Inmarsat Global express constellation -100's fixed spots and additional steerable spot beams Iridium-NEXT operational-features data transmission O3b satellite constellation
5G	2020's	High throughput satellite Several hundreds spot beams Higher frequency bands – Q/V/W Optical for gateway connections Up to 30 m deployable antennas at L/S bands Adaptive beam hopping and forming Mobility management integration Progressive pitch technology	OneWeb satellite constellation SpaceX satellite constellation Samsung satellite constellation LeoSat Constellation

services in the L band. Inmarsat also offers the M2M version of BGAN called BGAN M2M while Iridium's low bandwidth modes are also often used for M2M.

For the period 2020/5, a trend to larger and more powerful GEO satellites that will take capacities from 100's Gbps to over a Terabit/s is expected. The capacity increase will be achieved via several hundreds of spot beams and higher order frequency reuse despite the limitation in the spectrum. Furthermore, higher frequency bands such as the Q, V, and W bands will be used together with optical technology for the gateway connections. Also, advances in satellite payload technology through optimised designs and new materials will enable an increase in the payload power from 20 to 30 kW and the use of up to 30 m deployable antenna. Techniques such as adaptive beam hopping and forming, and interference management will be utilised to improve connectivity and flexibility to fluctuating traffic demands and patterns. In addition, following the innovations of using different orbits by O3b, new non-GEO systems that utilises all-optical technology, i.e., between satellites and from satellite to ground, are likely to appear.

1.4 Areas Where Satellite Can Play A Part In 5G

Satellite communication is becoming an important element in the 5G ecosystem, complementing wireless and fixed terrestrial communications. In the light of this, the third generation partnership project (3GPP) has identified 5G use cases wherein non-terrestrial network components and in particular, satellites have a role. The three main roles identified by 3GPP for satellites in 5G are [10, 11, 12]:

- Fostering the roll-out of 5G service in un-served areas that cannot be covered by the terrestrial 5G network (e.g. isolated/remote areas, onboard aircrafts or vessels) and under-served areas (e.g. sub-urban/rural areas). Furthermore, to upgrade the performance of limited terrestrial networks in a cost-effective manner.
- Reinforcing the 5G service reliability by providing service continuity for M2M/ IoT devices or for passengers on board moving platforms. Also, to ensure service availability anywhere especially for critical communications.
- Enabling 5G network scalability by providing efficient multicast/broadcast resource for data delivery toward the network edged.

In this section, we expatiate further on the key areas where satellites can play a part in the 5G ecosystem. The areas discussed include coverage, massive machine type communication, resilience provisioning, content caching and multicast, satellite-terrestrial integration (trunking and head-end feed, backhauling and tower feed, and communication on the move), and ultra-reliable communications.

1.4.1 Coverage

The overall aim of 5G is to provide ubiquitous connectivity for any kind of device and any kind of application. This can only be realized by the integration of satellites with the 5G network. Compared to the terrestrial cellular operators, satellite communications operators can provide a single global network and reduced operational and business support cost. This makes cost-effective global service and data delivery only possible via satellite technology. Hence, data and service delivery to remote locations, passengers in aircrafts, trains, and vessels, difficult to reach areas (emergency and critical scenarios) as well as beyond country boarders are the leading market opportunity for the satellite network operators. Moreover, the advantage of satellites regarding coverage are expected to further increase in the light of the following

- A mega constellation of LEO satellites that can offer services such as effective global transit and fine-grained geo-location ubiquitous access.
- Future deployment of cloud computing resources in space.
- Capacity increase due to new concepts such as spatial reuse of frequencies and spectral efficiency gain via new modulation codes.
- Advancement in technologies that exploit the predictive position of satellites and the geo-location of ground equipment leading to devising adaptive and more efficient schemes.

1.4.2 Massive Machine-type Communications

Massive machine-type communications entail the ability to support a massive number of low-cost IoT devices (connections) with very long battery life and wide coverage including the indoor environment. The exponential increase in the number of connected devices requires that new technologies towards massive data aggregation and data broadcasting which are beyond terrestrial radio must be considered. The intrinsic broadcasting capabilities of satellites which enable them to reach a very high number of devices while consuming only a limited number of resources makes them highly suitable for dispersed M2M networks. Satellite networks offer the means for massive data aggregation through the geo-observation environment as well as a means to share uplink connectivity in a very efficient manner from a very large number of connected network area. In addition, satellites already support asset tracking applications which can be scaled to support future M2M/IoT communications.

On another note, the deployment of a large number devices poses a clear operational challenge, as the devices have to be maintained (security patches, etc.), configured and upgraded from time to time. Satellites can support/overcome the operational challenges associated with the massive deployment through the following

- Efficient distribution of data on a massive scale and with global reach, complementing terrestrial deployments.
- Offering an on-demand backhaul capacity without the need for deploying additional terrestrial infrastructures. The on-demand nature is due to the fact that majority of the M2M services require intermittent backhaul.
- Providing a very efficient connectivity alternative for M2M communication. Satellites can also provide an alternative for remote and isolated areas as well as in dense inter-domain networks where data packets have to be passed through multiple autonomous systems to reach their destination. This represents the current market of the satellite network, where M2M is now becoming one of the important connectivity services.
- Roaming using a single satellite operator. Satellite networks can reach a wide area, crossing any type of boarders and through this ensuring the availability of connectivity through a single provider.
- Device activation and configuration via satellite for using local network infrastructure.
- Backup for continuous connectivity availability of the communication when no terrestrial network is available.

1.4.3 Resilience Provisioning

Global coverage and dependability are and remains the pivotal added value of the satellite (space) related communication services while using the minimum amount of infrastructures on the ground. Due to this unique characteristics, satellite networks are currently used for highly reliable communications and for safety and security critical systems such as navigation information in the maritime domain. Satellites have an important potential role to play in supporting the overall resilience by complementing other communications infrastructures. Satellites can support a resilient 5G network to mitigate the problems of overload/congestion to meet the 5G KPI "ensure for everyone and everywhere access to a wider portfolio of services and applications at lower cost". In order to achieve this, intelligent decisions can be made about traffic routing by placing an intelligent router functionality (IRF) at the radio access network (RAN). The IRF specifically make decisions concerning traffic routing over heterogeneous links taking into account the requirements of the applications. For example, in times of congestion on the normal terrestrial links, the IRF ensures that traffic flows over the satellite link in a seamless manner until the terrestrial links are restored. Hence, the satellite can be used to sustain ultra-high availability from the end-user perspective. Moreover, the cost can be scaled by sharing the satellite capacity over a large number of sites.

1.4.4 Content Caching and Multicast

Caching in terrestrial networks has been proven as an effective approach for improving the network performance in terms of delay and throughput. The limitation in the terrestrial storage capacity and the tendency for it not to be available in network scenarios such as for sailors on board of a ship makes the satellite option very important. Also, the larger storage capacity and the introduction of more advanced on-board processing have made satellites to become more powerful [13]. Satellites have a major role to play in content caching near the edge, i.e. bringing the content closer to the user in order to achieve the 5G KPI of zero perceived delay and 1000 times higher wireless capacity. The benefits of using satellite for providing content multicast and caching include

- It offers a wide coverage with low number of intermediary autonomous systems;
- It offers ultra-low content access latency;
- Offloading the cache content population from terrestrial networks.

Caching content close to the edge using efficient multicast delivery will improve the end user quality of experience (QoE) and reduce backhaul traffic load. This form of content delivery can be managed using information centric network (ICN) systems or other variations incorporating SDN/network functions virtualisation (NFV) with a centralised controller function that optimises delivery using satellite links when appropriate to provide immediate and on-demand content access.

1.4.5 Satellite-Terrestrial Integration in 5G

The integration of satellite communications with the terrestrial mobile communication systems has always been difficult due to the stove pipe approach of each sector [4]. Hence, massive re-engineering and cost are usually associated with such integration. For instance, the current satellite networks mainly support 2G network backhaul for fixed sites with limited connectivity and emergency scenarios while 3G and LTE networks are now following an extensive engineering effort for standards adaptation towards the specific satellite characteristics. Meanwhile, the convergence requirement of the new 5G ecosystem offers a rare opportunity of overcoming some of the barriers associated with integration in the previous generations of terrestrial

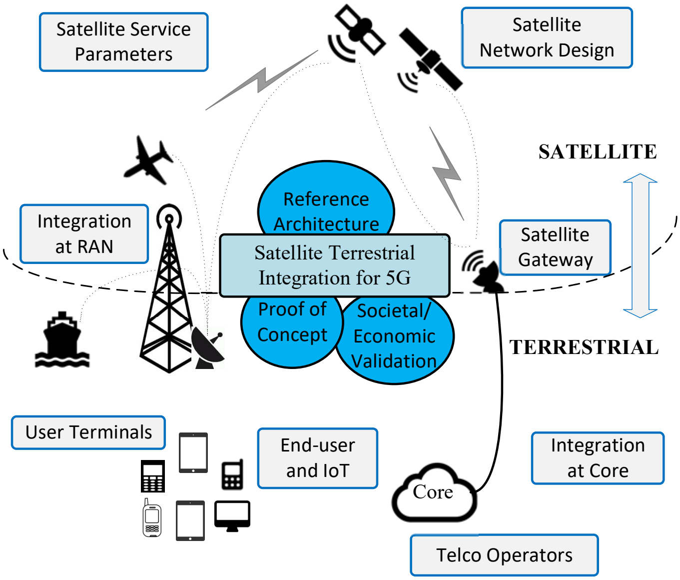

Figure 1.2   Integrated Satellite-Terrestrial Architecture

network deployments through the development of a single environment from the initial stages of development. In addition, it also enables the satellite and mobile communication industries to work together on defining and specifying a holistic 5G system. Such holistic approach will ensure that satellite communication can address some of the challenges associated with supporting the requirements envisaged for 5G networks.

An integrated satellite-terrestrial network ecosystem is shown in Fig. 1.2 with integration at the RAN as well as the core network. The network model assumes the satellite network architecture consisting of satellites which connect to the satellite gateway and the satellite terminals via asymmetric links. The terrestrial RAT could include the new 5G radio, WiFi, and the LTE, as well as radio technologies developed for ship-to-ship and device-to-device communications. The integrated satellite-terrestrial architecture requires a holistic evaluation in terms of proof of concept for various scenarios. Key components of such evaluation include adding the satellite parameters to the 5G requirements, new satellite-based service and the end user which consist of a multi-radio terminal. The societal, economical and business validation of the integrated architecture is also very important.

Integrating satellites with the terrestrial system is perhaps the key area that enables many advantages. One of such is improving the user's QoE by intelligently routing traffic between the delivery systems and caching high capacity video for onward transmission terrestrially. This can be empowered by the inherent multicast/broadcast capabilities of satellite systems, while propagation latency is no longer an issue thanks to intelligent caching. Offloading traffic from the terrestrial system to save on valuable terrestrial spectrum opens up the possibility of improving resilience and security using the two networks. Three main uses cases can be identified for the integration of satellite-based solution in 5G namely, trunking and head-end feed, backhauling and tower feed, and communication on the move.

1.4.5.1 Trunking and Head-end Feed

Satellites can provide a very high-speed direct connectivity option to remote/hard to reach locations. A very high-speed satellite link, which can be up to 1 Gbps or more, from GEO and or non-geostationary satellite will complement the existing terrestrial connectivity to enable:

- High-speed trunking of video, IoT and other data to a central site, with further terrestrial distribution to local cell sites (3G/4G/5G cellular), for instance neighbouring villages.
- Inter-cluster satellite link for remote clustering.
- Inter-cluster satellite link for edge communities.
- Inter-cluster satellite link for overflow communities.
- Remote IoT system with satellite integration.
- LEO satellite providing low latency control plane offloading.

1.4.5.2 Backhauling and Tower Feed

One of the major issues in 5G is seen to be the increased demands on the backhaul with very large numbers of small cells. Hence, an obvious application of satellite communication in a 5G delivery architecture is in the backhaul segment of the network. High throughput satellites (HTS) can be used here to complement terrestrial provision and provide backhaul in areas where it is difficult to do so terrestrially. HTS can provide a high-speed connectivity complement (include multicast content) to wireless towers, access points, and the cloud, as illustrated in Fig. 1.3. In general, a very high-speed satellite link (up to 1 Gbps or more) direct to base stations, from GEO and or non-geostationary satellite will complement the existing terrestrial connectivity to enable:

- Backhaul connectivity to individual cells with the ability to multicast the same content (e.g video, HD/UHD TV, as well as non-video data) across a large coverage area and
- Efficient backhauling of aggregated IoT traffic to multiple sites.

In a virtualised and SDN, it might also be possible to include some of the network node functions on board the satellite and thus save on physical sites on the ground. Moreover, satellite in the backhaul can assist with populating content caches close to the edge, deliver over-the-air configuration updates and software patched for M2M solutions and support the instantiation of network functions at the edge in mobile edge computing solutions through replication of virtual machines via broadcast.

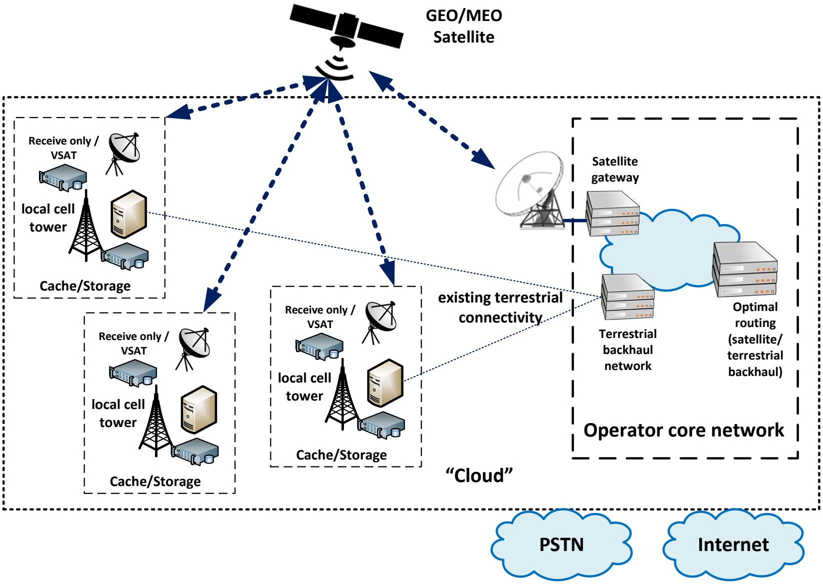

Figure 1.3 Satellite for Backhauling and Tower Feed

1.4.5.3 Communication on the move

One of the 5G aims is to cover mobility use cases that are beyond the reach of the current technology. This entails providing support via a global network that spans across different countries and to high-speed platforms such as airplanes, train and automotive. In such use cases, satellite networks have already proven themselves to be a viable alternative. The integrated satellite and terrestrial solution offer an efficient solution for both the relatively low-speed mobility use case via terrestrial means and through satellite communication for the high-speed mobile device while offering a smooth handover and seamless user experience [14]. Satellites provide a direct and/or complementary connection to users on the move (e.g. on airplanes, trains, automobiles, and ships), as illustrated in Fig. 1.4. Very high speed, multi-cast enabled satellite link (up to 1 Gbps or more) direct to plane, train, car or vessel, from GEO and or non-geostationary satellite will enable:

- Backhaul connectivity and multicasting of (e.g video, HD/UHD TV and non-video data) where it may not be otherwise possible.
- Direct connectivity and/or efficient backhauling of aggregated IoT traffic.
- Entertainment update with satellite integration for air (connected aircraft) and sea (connected ships).
- Freight and logistics.
- Lorry monitoring and communications in a dual mode terrestrial and satellite solution.

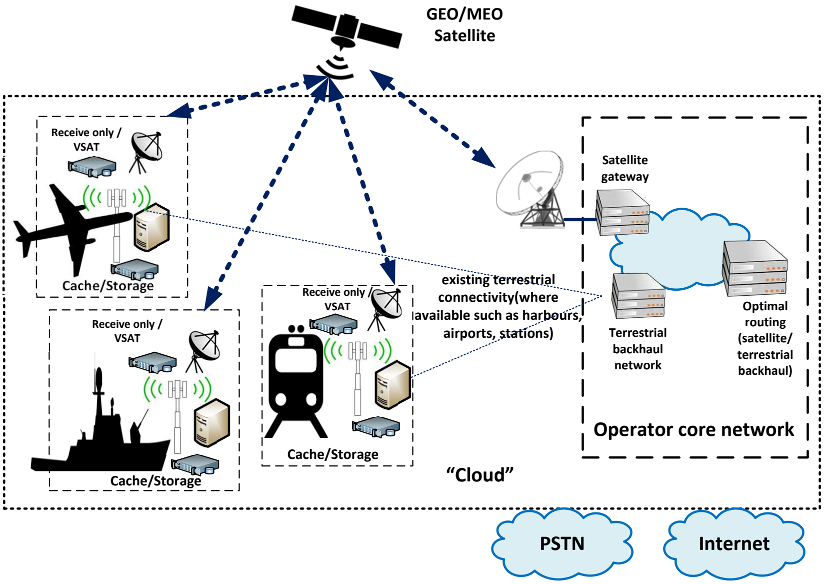

Figure 1.4 Satellite for Communications on the Move

1.4.6 Ultra-reliable Communications

New applications and use cases in 5G, such as mobile healthcare and autonomous vehicles, require the support of a very low latency typically sub 1ms, and very high availability, security and reliability. Hence, a very low latency over the radio network is one of the aims of 5G. Achieving a low latency over the end-to-end service level communication is restricted by the physical limitations and is impossible without moving the functionality to the edge of the network, at a location close to the termination of the very low delay 5G radio network. Consequently, in order to meet the delay requirements the only economical alternative is to make available compute capacity at the edge of the network and short-circuit the end-to-end network for the stringent latency services [14]. Services requiring a delay time less than 1 ms must have all their content served from a physical location very close to the user device. Possibly at the base of every cell, including the many small cells that are predicted to be fundamental to meeting the densification requirements [15]. In order to achieve the short service path, all the obligatory functionalities for the service delivery should be made available at the edge, thus making the backhaul capacity and delay characteristics beyond the edge node irrelevant to the actual service delivery delay.

The propagation latency of GEO satellite, which is about 270ms (540ms round trip), is acceptable in some 5G use cases. The MEO and LEO satellite network will be able to support more latency sensitive applications. The propagation latency of the connectivity service will also be managed by an adequate size and topology of the constellations, the dynamic configuration of client beams as well as delay-tolerant networking (DTN). Meanwhile, the processing latency can be managed by an adequate distribution of the execution of the virtual functions across space-and ground based data centres.

1.5 Recent Advances in 5G Satellite Communications

In this section, we present the recent advances in 5G satellite communication. The recent advances covered include on-going project on satellite-terrestrial integration, terrestrial and satellite spectrum, mega-LEO constellation, on-board processing, GaN technology, SDN, multi-casting, and integrated signalling.

1.5.1 On going Project Works on Satellite-Terrestrial Integration

European Commission-funded projects on the satellite-terrestrial integration under the horizon 2020 (H2020) framework include

1.5.1.1 Satellite and terrestrial networks for 5G (SAT5G)

SAT5G will bring satellite communication into 5G by defining optimal satellite-based backhaul and traffic offloading solutions. It will research, develop and validate key 5G technologies in order to take the best value of satellite communication capabilities and mitigate its inherent constraints such as latency. SAT5G will identify novel business models and economically viable operational collaborations that integrate the satellite and terrestrial stakeholders in a win-win situation [16].

1.5.1.2 Shared Access Terrestrial-Satellite Backhaul Network enabled by Smart Antennas (SANSA)

The aim of SANSA project is to boost the performance of mobile wireless backhaul networks in terms of capacity and resilience while assuring an efficient use of the spectrum. SANSA project proposes a spectrum efficient self-organising hybrid terrestrial-satellite backhaul network based on three key principles:

- a seamless integration of the satellite segment into terrestrial backhaul networks;
- a terrestrial wireless network capable of reconfiguring its topology according to traffic demands;
- a shared spectrum between satellite and terrestrial segments.

It is expected that a combination of the principles will result in a flexible solution that can efficiently route the mobile traffic in terms of capacity and energy efficiency while providing resilience against link failures or congestion and easy deployment in rural areas [17].

1.5.1.3 VIrtualised hybrid satellite-TerrestriAl systems for resilient and fLexible future networks (VITAL)

The VITAL project addresses the combination of terrestrial and satellite networks by pursuing two key innovation areas, by bringing NFV into the satellite domain and by enabling SDN-based, federated resources management in hybrid satellite communication-terrestrial networks. Enabling SDN- based, federated resource management paves way for a unified control plane that would allow operators to efficiently manage and optimise the operation of hybrid satellite communication-terrestrial networks [18].

1.5.2 Terrestrial and Satellite Spectrum in 5G

The use of the larger bandwidth in the mmWave band is fundamental to meeting the 5G terrestrial networks requirement. With part of the mmWave band currently allocated on a co-primary basis to a number of other applications such as the fixed satellite services (FSSs), the Federal Communications Commission (FCC) wants a more flexible framework for the use of the electromagnetic spectrum above 24 GHz. Recently field test data were used to assess the potential interference between terrestrial mobile broadband (5G) and FSS systems sharing the 28 GHz band [19]. The aim of the work in [19] was to create service rules for the use of four spectrum bands to be shared by terrestrial and satellite systems. The bands are namely, 28 GHz (27.5-28.35 GHz), 37 GHz (37-38.6 GHz), and 39 GHz (38.6-40 GHz) bands, and an unlincensed band at 64-71 GHz. These high frequencies were traditionally for satellite or fixed microwave. The field test measurement showed that the interference from existing transmit FSS earth station into 5G networks can be controlled by limiting the power flux density (PFD) at 10 m above the ground level to $-77.6\ \mathrm{dBm/m^2/MHz}$

The feasibility of the coexistence between FSSs and mmWave terrestrial network was also investigated in [20] by evaluating the interference to noise level at the FSS and different terrestrial base station deployment and configurations. The configurations considered include multi-tier distribution of base stations and having RF beamforming at the transmitters. It was shown that by exploiting the characteristics of the mmWave scenario such as large antenna array and high pathloss, the coexistence of the mmWave terrestrial base station and FSS in the same area can be made possible. Furthermore, it was established that parameters such as the FSS elevation angle, the base station density, and the protection distance are vital in the network deployment in order to guarantee the FSS functionalities.

1.5.3 Mega-LEO Constellation

HTSs provide large capacity connectivity via multi-spot beam technology and frequency reuse at a reduced cost. The integration of GEO HTS with the terrestrial systems will provide a global large-capacity coverage.However, this comes with the challenge of a large propagation delay. Mega-LEO constellations, which are LEO systems of hundreds of satellites, can circumvent this issue and it has recently received significant attention. Mega-LEO constellation can be used to provide LTE broadband services to areas that are not connected to a terrestrial infrastructure as

Table 1.2 Planned LEO-HTS Mega Constellations

Constellation	LeoSat	SpaceX	OneWeb
No. of Satellites	78-108	4000	640+
Altitude	1400 km	1100 km	1200 km
Latency	50 ms	20-30 ms	20-30 ms
User Speed	1.6 Gbps	1 Gbps	50 Mbps
Cost	\$3.5B	\$10B	\$2.3B
Announced market	Enterprise, Mobility, Backhaul	Broadband, Backhaul	Broadband, Mobility

demonstrated in [21, 22]. In [21], the authors analysed the impact of propagation delay and Doppler shift in LEO systems on the LTE PHY and MAC layer procedures. An extension of the analysis with a focus on the waveform design, random access and hybrid automatic repeat request procedure is presented in [23]. The effect of the Doppler shift in LEO systems on the waveform can be compensated by accurate location estimation. Furthermore, the impact of the propagation delay on the random access procedure can be limited by increasing the random access response timer Table 1.2 shows some planned Mega-LEO constellation and their specifications.

1.5.4 On-board Processing

In on-board digital processed systems, the received waveforms are demodulated and decoded to the digital packet or bit level. This leads to increased system flexibility in terms of signal and information routing, mesh connectivity and resource management. Other gains include higher user and system throughput and higher link efficiency, which are gained from predistortion and interference mitigation, use of newer waveform and full duplexing. On-board digital processed systems are thus the future for satellite communications and this is stimulated by the following

- an increase in the operational lifespan of the satellite. Over this period new access characteristics may be required or the need to support a new service/user connectivity topology may arise.
- an increase in the flexibility of the payload in terms of bandwidth and agility in frequency configuration at the payload level.
- increased configurability and reconfigurability of the payload to support cross-band inter-transponders and/or inter-beam configuration in a high spot beam coverage.

Even though many applications only need the conventional bent-pipe delivery of bandwidth, as it remains the most efficient way of supporting services such as broadcast television. The evolution in technology and trend in service providers means an increase in the contents that are being personalised and delivered in unicast or multicast rather than the traditional broadcast. Hence, on-board processing will play a prominent role in the future as more and more services and content are delivered by Internet protocol (IP) connection. Meanwhile, a hybrid payload where the bent-pipe and on-board processing technologies co-exist such as the Intelsat 14 payload, reflects how the near future satellite could look like. Such hybrid deployment is expected for many years until the volume of space routers go up and the technology cost goes down. The new potential solutions for the next generation on-board processing systems must consider the following:

- reduction in the size, weight, and power (SW&P) consumption at the payload level;
- reduction in the component integration scale;
- improvement in the payload reconfigurability and flexibility;
- improvement in the uplink and downlink performances.

1.5.5 GaN Technology

Gallium nitride (GaN) technology is a promising candidate for the next generation satellite communication subsystems [24]. Satellites in existence rely on the proven Gallium Arsenide (GaAs) and Travelling Wave Tubes (TWT) technologies for most of its radio frequency (RF) front-end hardware. Moreover, the maturation of GaN technology and its commercial adoption gives way to striking advancement in the space industry. The advantages which make GaN the main candidate for space include reliability, radiation hardness and high-temperature operation, in addition to the generic advantages of high added efficiency, high power density and high operational frequency [25, 26]. The latter three, which also improves the overall efficiency in the RF chain makes GaN technology very suitable for the 5G base station design where MIMO and mmWave technologies will be operational.

The cost advantage of GaN over TWT amplifiers (TWTAs) and GaAs solid-state power amplifiers (SSPAs) is realised by eliminating kW power supplies for TWTAs and cooling hardware for GaAs SSPAs. This leads to a reduction in size and weight which saves fuel and area on the payload. GaN technology's offer of a lightweight compact form factor is undeniable and also offers the possibility for achieving small form-factor nano and micro-satellites where the physical size, mass, power consumption and cost pose serious restrictions. It is expected that the development of the GaN technology will continue to be by the high power RF properties [26]. The potential to achieve the whole receive front-end of the satellite with GaN technology will further create the advantage of a lower cost and improved integration [24]. To this end, several projects have been initiated to perform intensive test and analysis on GaN technology in order to exploit its potential. Such project include GaN powered Ka-band high-efficiency multi-beam transceivers for SATellites (GANSAT), GaN Reliability Enhancement and Technology Transfer Initiative (GREAT), AlGaN and InAlN based microwave components (AL-IN-WON).

1.5.6 Software Defined Networking

SDN and NFV technologies are key enablers of a more flexible and improved integration of the terrestrial and satellite segments. SDN involves decoupling the control and user planes of the network equipment and logical centralisation of the network intelligence, i.e, the control plane [27, 28, 29]. The user plane i.e., the underlying network infrastructure, is abstracted for external applications requesting services through the control plane. On the other hand, NFV involves decoupling the network functions from the proprietary hardware, thus making it possible to run such functions in general purpose commodity servers, switches, and storage units, which can be deployed in a network's data centre. Network virtualisation enables the creation and coexistence of multiple isolated and independent virtual networks over a shared network infrastructure [30, 27]. NFV provides improvement in the use of the physical resources by allowing multiple instances of the same or different virtual network functions (VNF) to coexist over a common pool of compute, network and storage resource. Hence, these technologies provide the satellite network with further innovation in service and business agility via cutting-edge network resource management tools. Unlike SDN, NFV does not necessarily introduce any architectural change in the network functions. The introduction of SDN/NFV within the satellite network will contribute toward the following objectives among others [29]

- Automated customized on-demand networking with efficient and optimal sharing of the satellite network resources and infrastructure.
- Improved profit on resource and customer satisfaction via the availability of wide range of services such as on-demand QoS and on-demand bandwidth.
- Support satellite as a multi-service network with each service requiring a specific performance guarantee.
- Efficient and dynamic sharing of the satellite core network infrastructure by many satellite network operators (SNOs) and other players such as satellite virtual network operators (SVNO)and service providers.
- Simplification of the management of network services and integration via the provisioning interface for resource provisioning and invocation.
- Determining the functionalities that can run in a cloud-based environment, the right functional split between the virtualised and the non-virtualised part of the satellite.

Some of the use cases of SDN/NFV in satellite communications include 1) On-demand satellite bandwidth via SDN, 2) Satellite virtual network operators (SVNO) 3) Satellite network as a service (SatNaas) where the satellite hub functional entities are implemented as software workloads instantiated on a cloud infrastructure using the Infrastructure-as-a-Service and Platform-as-a-Service (IaaS/PaaS) paradigms.

The key challenges to this objectives include

- Support of SDN and NVF techniques by remote terminal and satellite gateways for different use cases.
- Support for dynamic network configuration for on-demand purpose and making the satellite network resources available when prompted.
- Using SDN/NVF techniques to enhance multi-tenancy of the satellite hub components among multiple SVNOs. This entails enabling each SVNO to have advanced control via more programmability and flexibility of the resources allocated to it by the satellite hub.

1.5.7 Multi-casting

Radio resource management (RRM) techniques for offering multimedia content in LTE-satellite networks was presented in [31]. The RRM is performed on a per-group basis, since a group of users is served by the satellite in one radio transmission. Consequently, the selection of the modulation and coding scheme must take the channel qualities of all multicast members into consideration. The conventional approaches such as opportunistic and conservative multicasting scheme suffer [32] from inefficiencies relating to inadequate short-term fairness and poor spectral efficiency, respectively. A promising RRM approach in 5G satellite multicasting environment is subgrouping. All multicast terminals are served in every time slot by splitting the group into different subgroups based on the experience channel qualities. It has been shown in [31] that multicast subgrouping overcomes the weakness of the conventional techniques and allows for the efficient delivery of multimedia content over the emerging satellite systems.

1.5.8 Integrated Signalling

The 5G environment is driven by a very dense deployment of small cells delivering high data rate communication services to the user equipment. A key challenge with such architecture is the limited available capacity for user data due to the increased signalling capacity. Furthermore, the base station's signalling cost contributes to the total system energy consumption, and thus, hampers energy reduction. Decoupling the control (C) plane and data (U) plane together with SDN has recently been identified as one of the promising techniques towards meeting the 5G KPI target for energy reduction. The techniques also provide an improvement in the manageability and adaptability of the 5G networks. In the split C&U plane architecture the base stations deliver data on the U plane using terrestrial link when present and route the C plane via an overlay macrocell backhauled over a satellite link [33]. Consequently, this gives the network operator more flexibility, since the small/data cells can be activated on demand to deliver user-specific data only when and where needed. Thus, the energy consumption is improved, since the split architecture also leads to longer data cell sleep periods, due to their on-demand activation [34, 35, 36]. In the rural context, the focus is to identify C plane traffic that can be managed locally and only utilise the satellite link when required. The hybrid system with split C&U planes can achieve approximately 40% and 80% energy efficiency improvement in sparse and ultra-dense networks, respectively, as compared with the conventional LTE networks [37].

1.6 Challenges and Future Research Recommendations

In this section, we discuss the challenges associated with the some of the recent advances in satellite communications. Furthermore, some future recommendations are also presented alongside.

1.6.1 Integrated Satellite-Terrestrial Architecture

Focusing on multimedia distribution, significant research and development effort on the integrated architecture is required in order to satisfy the challenging requirements of future users in terms of cost, performance, QoE, and QoS. Such challenges include parallel and transparent access of the user to both the broadband and broadcast networks, smart management of both the broadband and broadcast resources, and managing the user content. Also, service continuity is an essential feature of the integrated satellite-terrestrial architecture as it aims to provide seamless service delivery to 5G end-users while roaming between the terrestrial and the satellite backhauled cells. The key challenges associated with this include i) seamless mobility support in terms of vertical handovers, ii) design of networking protocols which can cope with the different latencies iii) design of cost-effective 5G devices which supports the satellite-terrestrial dual mode operation iv) designing the business model for access points and addressing the service level agreement issue that could arise between the satellite and terrestrial service providers.

For the M2M application of the integrated satellite-terrestrial architecture, the key research challenges relate to designing protocols that are appropriate for the satellite M2M. Noting that significant research effort has been put into the terrestrial IoT design in terms of battery powered M2M systems, security and integrity, energy efficient waveforms and hardware design, a similar effort is also required toward the satellite IoT design. Furthermore, routing protocol redesign is also required for IoT scenarios that involve the satellite since delay becomes more crucial in such deployment. Also, with the planned utilisation of the frequencies above 10GHz for terrestrial deployment in 5G, there is the need to investigate various scenarios of the integrated satellite-terrestrial architecture in terms of the resource allocation (specifically, carrier, bandwidth, and power) between the satellite and the terrestrial systems. The multiple antenna satellite system brings significant gain in terms of coverage an capacity. Hence, investigating its performance within terrestrial and satellite networks requires attention in a future study.

1.6.2 Integrated Signalling in Satellite Communications

Similar to the terrestrial C/U plane split architecture, the satellite integrated split architecture must also meet the 5G engineering requirements. In addition to this, the requirements for managing ultra-dense cells must also be met in such integrated architecture. These requirements include handover and mobility management, backhauling management and data cell discovery. User association with the data cells in the conventional split architecture are managed by the macro cells which provide control plane functionalities, whereas, in the integrated architecture, satellites will handle control signalling and, hence, user-data cell association. One of the propositions in the conventional split architecture is for the macro/control cells to handle data transmission for high mobility and low rate users in order to reduce handover failures; the feasibility of satellites serving high mobility and low data rate has to be investigated.

Specifying the functionality of each plane and dimensioning their physical layer frames is a challenge in both the conventional and the integrated split architecture. This challenge arises from the fact that certain user activity such as handover requires several functionalities such as broadcast and synchronisation functionalities, while the frame control signal is required for more than one network functionality [34, 36, 35]. Hence, the signalling and functionalities associated with each plane must be correctly allocated. Moreover, the ability of satellites to cache certain user information and its associated latency and channel condition issues further add to the challenge experienced with the conventional split architecture.

1.6.3 On-board processing

On-board processing functionality in satellites implies having additional hardware which could lead to an increase in transponder mass and power consumption. In the light of this, the additional heat generated by the processor must be properly managed. Reliability is another key challenge with on-board processing. The backup digital signal processing (DSP) which is required in case of component failure can scale-up the cost significantly. Other challenges associated with on-board processing include the limitation to the reconfigurability of the hardware chains and the sampling capability. Low cost and reliable processing techniques are key to on-board processing in satellites.

1.7 Conclusion

This chapter has presented the key areas in which satellite can play a part in the 5G network. The examined potential areas include coverage, massive machine type communications, resilience and overspill, content multicast and caching, integrated network, ultra reliable communications, and spectrum utilisation. We have also highlighted the recent advances and a number of research challenges associated with the satellite-terrestrial integrated architecture. It has been emphasized that to achieve and exploit the potential of satellites in 5G and stimulate investments, the satellite community must work in close collaboration with terrestrial players in the 5G activities on areas including technology standardisation, demonstration and regulatory issues.

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