6G Satellite Communications

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***Abstract*—As we move from 5G to 6G networks satellites will play an increasingly key part in providing coverage and resilience. Here we outline the timescales and some of the issues facing satellites in the 6G world.**

Keywords*—*satellite, NTN, 6G

I. Satellites Today

Today's satellite communication systems have mainly been based on large GEO satellites serving regions of the earth and providing services such as broadcast, broadband and backhaul to fixed, portable and mobile vehicle mounted terminals. Some spectrum in L/S (mobile), C/Ku/Ka (fixed) is available on an exclusive basis to satellite and has been the life blood of the business. Constellations of communication satellites emerged in the 1990's for narrow band global services via Iridium and Globalstar are now in their second generation. A MEO constellation (O3b/SES) for broadband was added in 2014 for equatorial region coverage and we are now right at the start of very large constellations of global coverage broadband satellites in LEO with two operational systems (StarLink, OneWeb). Satellite operators have remained separate from terrestrial telecom operators to date with the latter procuring capacity from the former as needed. There has been little attempt at integrating the systems up until 5G. 5G offered the opportunity for a satellite/terrestrial integration and to provide services across these domains. At present R&D studies and demonstrations have proved the concept but no real standards-compliant commercial offering is available.

The role of satellites has been to provide coverage into regions not economic for terrestrial infrastructure and to provide resilient backup to terrestrial services. We see these features remaining as key drivers in 6G. As terrestrial networks pursue lower latency service offerings satellite constellations at very low altitude (vLEO) with Inter Satellite Links (ISL's) offer comparable, and even lower latency for longer links. Thus these systems are of interest for inclusion in 5G and now 6G. Due to restricted spectrum and satellite power, capacities have in the past been limited and hence more expensive than terrestrial. However today, using frequency reuse, dynamic resource allocation and onboard processing both GEO and LEO satellites have increased to circa 1 Terabit/s and costs of the space system have drastically reduced.

II. The 6G Timetable

In order for satellites to play an integrated role in 5 and 6G, some commonality of standards is required. Until recently satellites remained outside mainstream standards bodies and had developed their own air interface standards — DVB-S originally based on video broadcast. More recently and seeing the advantages of integration, satellites have joined the 3GPP standards group responsible for 5G and now 6G standards. The 3GPP Rel. 16 (2017) on which the current rollout of 5G terrestrial networks is based does not include satellite. However, a Non Terrestrial Networks (NTN) group has now been established within 3GPP and is part of Rel. 17 (2022) and continues into Rel. 18 &19 towards the goal of integrated standards. There is thus a standards pathway from 5G integration to full 6G unification as shown in Figure 1 with the period to 2025 used to integrate satellites into 5G, and the period up until 2030 to establishing satellites (or NTN) as inclusive elements in unified 6G standards.

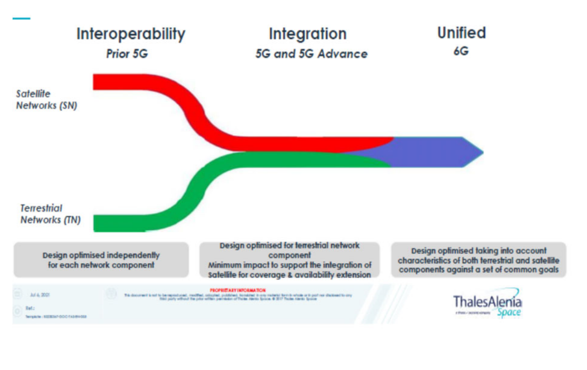

Fig. 1. Timescale for standards progression from 5 to 6G

III. The 6G Vision

There are many visions for 6G, and the ITU is currently in the process of defining 6G use cases. Our vision for 6GIC [1] is one which incorporates a range of human multi-sensory experiences enabled by digital solutions and hyper fine geolocation with context awareness provided by massive localized sensors. In addition to human and local information sensing, system level sensing will be essential for efficient and intelligent system operation. This implies fine time and frequency synchronization to microseconds and guaranteed ultra-low latency (ULL) not provided by 5G. This will enable the provision of a tranche of new services for verticals across telecom networks. The vision is of a hybrid network of networks from short range and ultra-high capacity to the widest coverage via space networks.

Extracting the key features from a number of 6G visions we arrive at the following common elements;

- New Human centric services—AR/VR/MR—Teleportation
- KPI's that exceed those possible in 5G in latency and reliability
- User sensing merged with communications
- AI based networks and massive virtualization.

- A 3D space network including UAV's-HAPS-Satellites (NTN)
- New Frequency bands
- Increased security across integrated networks
- Massive IoT
- Timing and positioning accuracy

Of particular note is the inclusion of the 3D space network (see Figure 2.) as a means of achieving the 6G coverage and providing resilience which have long been the features of satellites and NTN's. The vision remains one in which there is complementarity rather than competition between the terrestrial and space elements in the delivery of new services but the 3D structure offers opportunities for optimizing network function positioning and new service creation.

As shown in Figure 2 this leads to the concept of a multi-layer network which adds satellites in GEO, MEO and LEO to lower altitude HAPS and even lower aerial devices, UAV's, such as drones. The architecture connecting these components will be service dependent as some architectures will better suit the requirements of specific services. The network functions can also be distributed amongst the entities to optimise performance. The challenge here is not only to connect the layers, e.g inter-orbit LEO -GEO/MEO but also to connect UAV's to various satellites. The high mobility in the case of UAV's and LEO's will influence both the RAN as well as the network layers.

The 3GPP standards group, and NTN in particular, are continuing their work on 5G+ looking at applications into vehicle to everything (V2X) transport and 5G based IoT. Also considerations regarding energy and spectrum efficiency, location sensing, carrier aggregation and advanced antenna arrays are under way. In other areas advances in software defined radio (SDR) and digital processing will contribute to more flexibility in radio access and in core networks. Security across the whole system will be critical and will be embedded in the design. This will require the use of intelligent firewalls, context-aware domain level protection, and advanced cryptography supported by cloud quantum computing. These and other innovations will feed into the base definitions for 6G.

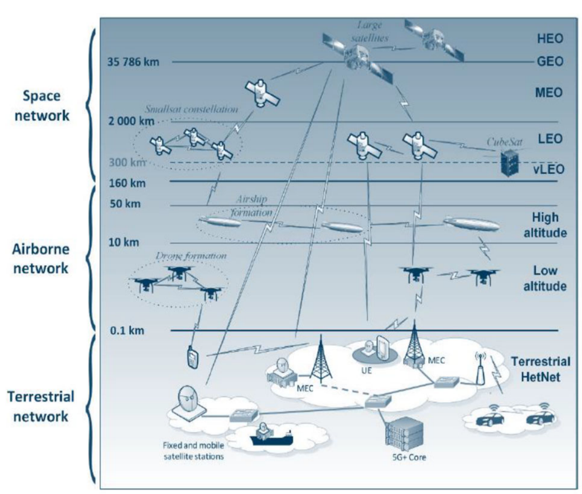

Fig. 2. 3D space network

IV. 6G Impacts for Satellites

For 6G we will need new and advance techniques that enable deeper integration between satellite and terrestrial networks which are seamless from a user perspective, moving from satellite to terrestrial coverage. With the introduction of large LEO satellite constellations with high mobility this introduces new challenges ranging from intelligent and dynamic spectrum sharing to seamless handover and maintenance of QoS.

Key areas and challenges for satellites in 6G include the following;

A. *Impact of new services on satellites:*

Next generation services will be much more human centric and incorporate massive local sensing and context awareness -AR/VR/MR, holographic, tactile/haptic, digital twin. These will require higher bandwidth and more spectrum pushing into higher millimeter frequency bands and optical. The synchronization of multiple flows to multiple devices requiring latency at the air interface <1mS and precision tracking of the order of 1cm in 3D space. This exceeds what is available in 5G and especially for the air interface design in constellations of satellites with high mobility. Timing and synchronization (PNT) will be key challenges in the search for an integrated air interface as well as in integrated management of 3D networks and earth sensing services.

B. *Satellites in a network of networks*

6G will bring together networks of varied scale (see Figure 2) and seamless integration and essential use of edge computing or service chaining. In 5G we have already seen virtualization of major network functions and some attempts at integration and network slicing, although E2E orchestration remains a target. In 6G networks, 6G edge nodes will have capabilities for AI resource runtime scheduling and orchestration. Neural center and global AI capabilities will provide services to users. This constitutes an overall native AI network with significant sensing and ML at the user terminals but with AI and ML permeating through the network. All this will be driven by massive improvements in efficiency and green energy.

Next generation AI will be a key technology, deployed across edge and core computing domains, supporting both integrated network control functions, such as network orchestration and QoS management, and intelligent user and machine level services. The layered 3D space structure can be considered as an E2E Software Defined Network with the network functions distributed across the layers to optimize service delivery and performance. Open networking will be a key element in 6G realization.

C. *Satellite spectrum sharing*

Satellite communication systems have until now had the luxury of exclusive spectrum bands in which to operate but even today we are seeing the need to operate outside these bands e.g. in Terabit/s vHTS satellites that require extra spectrum to satisfy the capacity demands, Also with non-GEO constellations having to overlap GEO bands for the same reason. As we move above Ka band there are no exclusive satellite bands and hence the need to share spectrum is key. The regulatory regime has dealt well with GEO satellites, but global coverage constellations have brought with them new challenges especially in sharing spectrum between constellations.

Satellites in 6G will need to have the capability to sense spectrum interference as they precess in orbit and use this to dynamically drive their resource allocation algorithms. AI and ML can be used here to manage this highly complex and dynamic process.

AI will build upon dynamic spectrum access introduced in the 5G era to deliver further improvement in spectrum efficiency both in space and between space and ground. by mapping spectrum resource to demand and Quality of Service requirements. This could make next generation spectrum auctions a thing of the past.

D. IP networking in constellations

We have seen that constellations of satellites are likely to form part of the 3D space network within 6G and today we are seeing the first generation of these LEO constellations (Starlink, OneWeb) start operation. Such systems have very large numbers of satellites and ground gateways but essentially are simple relay networks. Succeeding generations will reduce altitude (vLEO) and incorporate Inter Satellite Links (ISL) in order to optimize routing, reduce latency and cut the number of gateways. These satellites will have more complex on-board processing and include 6G functions on board. Thus, we will have an extremely complex and dynamic network with huge numbers of satellite and gateway handovers requiring high timing precision.

Current standards work in 3GPP NTN is mainly based on physical layer issues and does not consider lower layer protocol aspects and IP connectivity. The size and high dynamic connectivity in these networks pose problems for traditional routing and IP mobility which are not suited to such networks. Here we need to look for changes in some basic IP architectures.

E. Antennas and MIMO

Satellite antennas have graduated from shaped regional coverage to multi spot beam in order to employ frequency reuse and achieve capacity. Flexibility to meet dynamic changes in resources over specific areas requires dynamic beam shaping and techniques such as beam-hopping. Such techniques now need to be extended to satellite constellations in which there is constant change in requirements during a satellites orbit and much shorter time scales.

User terminals need to track multiple satellites and have fast tracking beams. Electronic beam tracking from flat plate antennas is in its infancy and the goal is to drive the cost down to that of a simple dish. In these constellations, gateway numbers can be in the thousands and are thus expensive. A move to optical will reduce numbers and thus optical feeders and smart gateway switching to redundant sites is a key challenge.

Frequency selective surfaces are becoming a feature of terrestrial 6G networks and we need to investigate whether they can play a part in future space networks.

Much of today's satellite networking is backhaul to larger terminals as distinct from direct to a handheld UT. At least two companies (AST Mobile and Lynk) are proposing to operate in the mobile band direct to a commercial smartphone. This requires very large antennas in space as well as regulatory issue on joint use of spectrum. However, it has been the holy grail in satellite communications for seamless handover, and is today still a research theme. The MIMO technique is in common use in 5G mobile networks and will continue to feature in 6G. So far it has not been pursued in satellite networks but given constellations where several satellites are in view of the user, it may be the answer to achieve power to the handheld.

The above are just some selected areas that will drive research towards satellites in 6G. As the process of standardization for 6G is due to start in 2025, R&D on some of these key technologies needs to be accelerated so that they can be considered as contenders in the uniform (terrestrial and space) 6G process. It will be important that the satellite community is in good shape to input the NTN case at the start of the standards process, lest it be forgotten.

Finally, we should mention sustainability of the environment as an overall key consideration for 6G. Regulation of the spectrum to include both terrestrial and space together and not separately will be needed for uniformity. Cognitive techniques to mitigate and avoid interference will be key. The space environment and in particular debris mitigation is of increasing importance with large numbers of satellite constellations and needs to be tackled Internationally.

REFERENCES

[1] https://www.surrey.ac.uk/sites/default/files/2020-11/6g-wireless-a-new-strategic-vision-paper.pd