On Architecting LEO Mega-Constellation Networks

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***Abstract*—Satellites offer advantage in their wide coverage and immunity from terrestrial disasters. Recently, the power of low earth orbit (LEO) satellites has been clearly demonstrated in many applications including communication and Earth observation. In addition, technical advancements are being made in both the space-grade hardware technologies and future network architecture. In this paper, an overview of network architecture and core technologies for LEO mega-constellation networks is presented, including onboard computing, optical inter-satellite link (ISL) communications, and network slicing. The state-of-the-art R&D efforts and future directions will be highlighted.**

I. INTRODUCTION

Low-Earth Orbit (LEO) mega-constellation networks will be a key differentiator of the sixth generation (6G) commercial networks by providing a seamless three-dimensional (3D) global coverage for broadband services [1]. The advent of the New Space Era with low-cost launching of recycled rockets makes it economically feasible to deploy mega-constellation space networks. It remains to be seen which satellite network will make commercial success for 6G, but it is obvious that the successful space network will take advantage of optical inter-satellite links (ISL) and onboard computing capability. In addition, the prevailing technologies of softwarization and virtualization should be adapted to the LEO satellites, so that they should be able to provision user-customized end-to-end slices over dynamically time-varying constellation topology.

Fig. 1 illustrates the evolution of the satellite communication network architecture. At birth, a communication satellite was usually located on the geostationary orbit (GEO) and the transparent satellite relayed signals from/to the ground by shifting frequencies and amplifying the signal power. Regenerative satellites were then introduced with the advancement of space devices for onboard processing (OBP) and free space communications for ISLs, reducing unnecessary hops and thus, improving the end-to-end latency. However, as the number of LEO satellites increases to form a mega constellation for global coverage, the application of software-defined networking (SDN) architecture is being actively investigated to support diverse quality of service (QoS) levels with the centralized SDN controller while cutting onboard router functions down. In the future, some satellites will be equipped with flying controllers onboard to overcome unreliable and long-delayed satellite-ground links, but full realization of "autonomous" and "intelligent" space networks will necessitate mass production of very reliable and low-cost space processors/devices first.

In this paper, an overview of core technologies for 6G satellite networks is presented, including onboard computing, free-space optical (FSO) ISL communications, and network slicing. Significance of each technology for 6G satellite networks will be emphasized, and then the current technical status and future direction will be discussed in brief.

II. ONBOARD COMPUTING

While OBP satellites can regenerate signals onboard in a similar manner with modems, onboard computing satellites are envisioned to process and store tasks in a similar manner with servers. The onboard computing capability will be a core technology to realize space edge computing, high-speed high-throughput inter-stellar networks, and distributed artificial intelligence (AI) in space. Software-defined satellites will be implemented with remotely reconfigurable and updatable payloads equipped with onboard computers.

Despite rapid advancement of semiconductor and device technologies and explosive market increase over decades, space semiconductors are still behind for their technical maturity and market volume compared to their terrestrial counterparts, mainly due to extremely tough technical and economical requirements for extreme space environments, including space radiation and a wide range of external temperature. Conventionally, high-price space-grade devices have been specifically manufactured to provide extra durability and reliability, by providing high redundancy in modules, extra protection/shielding of hardware, and periodical resetting/rebooting of embedded software [2]. Recently, a New Space Era philosophy preaches a use of commercial off-the-shelf (COTS) components mainly in a form of field-programmable gate arrays (FPGAs). Fabrication of the embedded FPGA (eFPGA) for space application is being attempted to integrate intellectual property (IP) core into system-on-chip (SoC). However, a real take-off of the space application-specific integrated circuit (ASIC) market has yet to come, and performances of space FPGA and eFPGA are still by a few decades behind compared to those of processors on the ground. Near-future deployment of mega-constellation LEO satellite networks and urban/advanced/regional air mobility (UAM/AAM/RAM) vehicles will be a catalysis to speed up technology innovation and to make mass production of space chips commercially viable.

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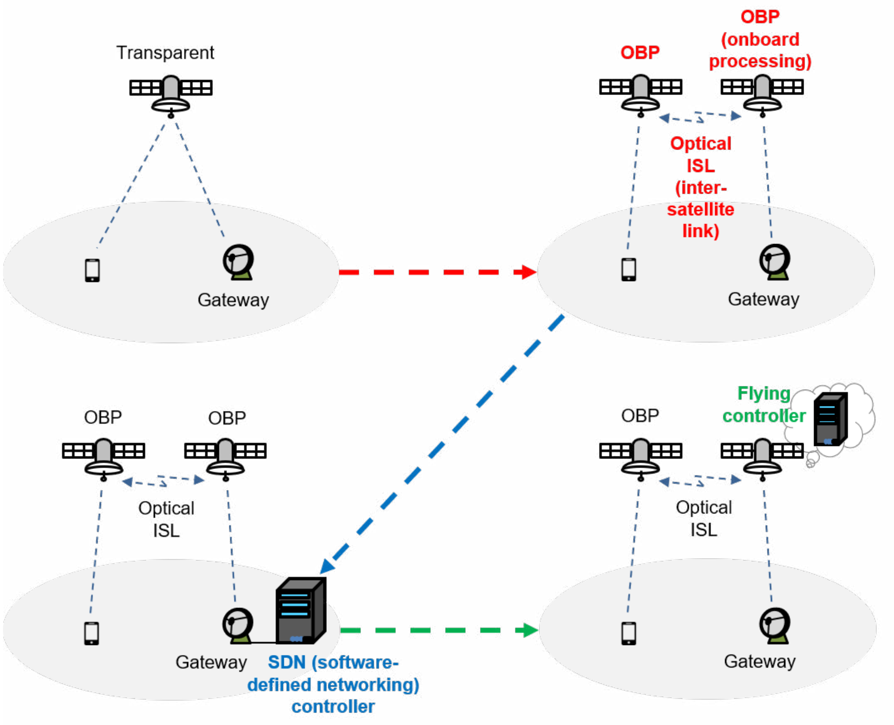

Fig. 1. Evolution of satellite communication network architecture.

III. OPTICAL INTER-SATELLITE LINKS

FSO communications can take advantage of broad spectrum, high field intensity with a large antenna gain, and system mass reduction. Since the challenge of atmospheric turbulence and attenuation is negligible, FSO can be made a good use of over ISLs of the LEO constellation. Currently, large efforts for technical R&D are devoted in pointing, acquisition, and tracking (PAT) systems of optical transceivers. A pointing process aligns transmission beams at the transmitter toward the receiver direction, and an acquisition process adjusts the receiver antenna and aligns the beams toward the direction of arrival. A tracking process maintains the link connection under continuous mobility and vibrations of satellites. Misalignment can occur very often due to narrow beam divergence with short wavelength of FSO signals, and a reliable design of the PAT control unit, both mechanical and electro-optical, is vital for successful ISL communications.

Widely used modulation schemes for FSO links are still on-off keying (OOK) and pulse-position modulation (PPM) with direct modulation. Coherent detection, required for high-order constellation schemes such as quadrature amplitude modulation (QAM), can provide an extra signal-to-noise ratio (SNR) gain, but needs high-cost hardware. In addition, optical power amplifiers have been in general restricted for low power applications, e.g., under 1 Watt output, yet. Thus, current FSO communications still have to employ simple modulation schemes with low signal power, but can overcome them with narrow optical beamwidth and broad spectral bandwidth for high data rate throughput. As of 2023, commercial LEO mega-constellations have yet to deploy full optical ISL communications. Full implementation of ISL capacity higher than 20 Gbits/s is expected for a timely delivery of 3D broadband services with low latency. In addition, a practical use of space optical terminals will make huge impacts to high layer protocol/algorithm optimization, such as routing and switching [3].

IV. NETWORK SLICING

With new emerging network technologies represented by virtualization and programmability such as virtual networks, edge computing, and SDN, satellites can provide various types of differentiated services in an efficient manner by utilizing onboard processing, computing, and caching capabilities.

In particular, network slicing, one of the key techniques in 5G networks, can provide each network customer with a dedicated service by virtually creating an independent virtual network, called a network slice, from a physically shared common network infrastructure. Challenges in realizing network slicing in satellite networks are unique because the network is constructed over long wireless links, and each satellite node moves at very high speeds, as illustrated in Fig. 2. For the given locations of ground network slice requests, access satellites should perform frequent handovers to serve the slice during the required service time. In addition, the ISL connectivity and link distances may vary over time.

Satellite network slicing requires an optimized design of the satellite edge computing architecture and scheduling policy of network traffic [4]. The results indicate that task offloading to satellite servers is more efficient for higher-altitude

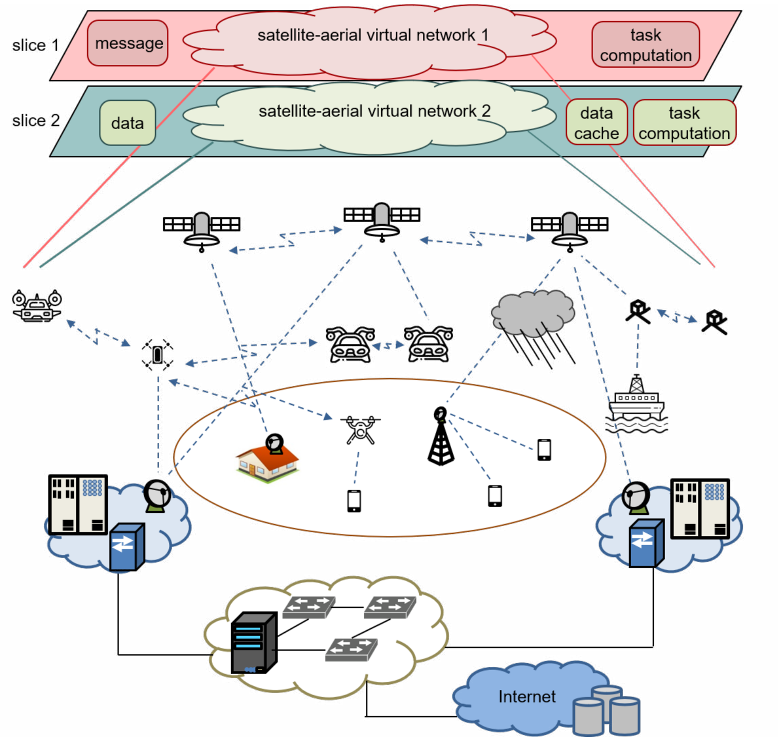

Fig. 2. Illustration of satellite network slicing.

satellites with respect to onboard transmission/computation power consumption, but lower-altitude satellites are more advantageous in terms of latency. An appropriate altitude of the satellite network should be decided with the target latency level of applications and the cost of satellite edge servers into consideration. Otherwise, the satellite edge servers may turn out to be less efficient as the number of satellite edge servers increases at low altitudes.

Slice planning in a satellite network embeds the virtual network requests (VNRs) and manages the embedded virtual networks during the required service time with handovers, if necessary, to handle the mobility of satellites. Handovers occur when the embedded satellite nodes are no longer available. Sizable ISL capacities are necessary to increase the overall network throughput because the system bottleneck is on the ISL, while sufficient access satellite capacities are useful for the system efficiency, represented by the throughput and cost ratio of the network. The end-to-end ISL routing path is jointly updated with access satellite handover, and then the end-to-end slice is also handed over by re-embedding the expired slice. Potential satellite network slice scheduling and planning strategies should be designed with handover and ISL routing management in joint accounts, and they will guide further research and hardware development with a proliferation of newly-emerging future satellite applications [5] .

V. CONCLUSION

LEO satellites are envisioned to be one of the main blocks for 6G networks along with AI and sub-terahertz spectrum. To achieve a full gain of the globally seamless 3D service, shortcomings of the satellites should be overcome, such as long propagation delay, time-varying network topology, and high costs of operational maintenance, with deployment of onboard computing, optical ISL communications, and network slicing. Significance of cross-layer optimization and inter-disciplinary design could not be emphasized more, and invaluable lessons could be learned from history of innovations in wireless and semiconductor technologies and endless efforts in the space exploration and launch industry.

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