Satellite and Terrestrial Network Convergence on the Way toward 6G

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Compared with traditional satellite communication systems, the recent advancement by 5G non-terrestrial network (NTN) technology offers a disruptive solution by enhancing mobile cellular technology to support satellite communications. It allows satellite operators to leverage the mobile cellular ecosystem and its economies of scale to penetrate satellite communications from a niche market to mainstream consumer market. On the other hand, it also facilitates the integration between the networks operated by terrestrial and satellite operators via the common radio/core network technology and architecture. With the key enabler by multi-mode devices, which could flexibly switch between terrestrial and satellite networks, NTN technology can turn terrestrial and satellite operators from competitors toward partners (e.g., complement service coverage, traffic roaming, and service platform). It is generally believed that satellite and terrestrial network convergence will be a mega trend from 5G toward 6G. The following sections will further investigate the potential use cases and advantages.

Fixed Broadband Wireless Access via Satellite

Satellite communication is one of the most fast-paced technology fields, thanks to the recent advancements by SpaceX reusable rocket technology to significantly reduce satellite deployment cost and its Starlink Low Earth Orbit (LEO)'s satellite technology [1]. As part of the Federal Communications Commission (FCC)'s drive to close the digital divide, its Rural Digital Opportunity Fund (RDOF) Phase 1 Auction resulted in an allocation of $9.2 Billion in 2020, with the goal to expand broadband to over 10 million rural Americans over the next decade. SpaceX won $885.5 million, as one of the largest shares among the 180 winning bidders. Starlink has committed to provide high-speed Internet service to nearly 643,000 homes and businesses in 35 states. Moreover, FCC expects that 99.7% of the locations covered under RDOF Phase 1 awards will receive broadband service with speeds of at least 100 Mb/s downstream and 20 Mb/s upstream. In this context, Starlink's early subscribers can expect download speeds in the order of 50 – 100 Mb/s [2].

One should note that these advancements require a Customer Premise Equipment (CPE) with antenna array to be installed in homes and businesses, enabling fixed broadband wireless access via satellite communications.

Smart Phone Access to Satellite

Compared to a traditional satellite phone with bulky antennas, both satellite operators and consumers are eager to see how satellite communication could be enabled on smart phones. Since 2022, the development progress of such products has been stimulated as referenced by a series of announcements. The solutions behind the announcements could be classified into four technical options, as represented in Fig. 1:

Option one consists in integrating the legacy satellite communication solutions into new 5G smart phones. Because the legacy LEO satellites have limited capability (e.g., equivalent isotropic radiated power (EIRP), antenna gain-to-noise-temperature (G/T)), and are unable to make up for the link budget loss caused by replacing bulky antennas with regular smart phone antennas, the achievable data rates will be generally low and only suitable for messaging services (e.g., emergency use).

Option two relies on proprietary satellite onboarded Long Term Evolution (LTE) base station, i.e., eNB technology implementation to compensate for the latency, Doppler, and link budget limitations. Due to various LTE user equipment (UE) capability restrictions (e.g., 10 ms scheduling delay tolerance and maximum Doppler tolerance in high speed train scenarios), the interoperability testing (IOT) could be quite challenging in the field because legacy LTE UE implementation did not assume the eNB signal may come from LEO satellites instead of terrestrial base stations.

Option three makes use of the Third Generation Partnership Project Internet of Things NTN (3GPP IoT NTN) technology implementation on smart phones for satellite services (e.g., messaging, small data). According to previous field experiments [3], new 5G satellite Narrow-Band Internet of Things (NB-IoT) technology establishing a bi-directional link with several kbps from MediaTek's satellite-enabled standard NB-IoT devices to a commercial Geosynchronous Equatorial Orbit (GEO) satellite would be feasible, thanks to sophisticated radio technologies designed for cellular IoT. By leveraging the global coverage strength of the GEO satellite technology, the vision of "always-connected" smart phones was recently realized for satellite messaging systems with Bullitt Satellite Connect service [4, 5].

Option four makes use of the 3GPP New Radio (NR) NTN technology on smart phone for wideband satellite services (e.g., voice call, satellite data services). Although NR NTN can support wider signal bandwidth compared to NB-IoT NTN, the experiment observes that more advanced LEO satellite capabilities (e.g., EIRP, G/T) are essential to close the link budget gap and offer Mb/s level data rate. This option promises to be the long-term trend, enabling future 5G smart phones to directly connect with LEO satellites [6].

3GPP NTN Standard Solution Concepts

This section gives an outline of 3GPP specified solutions common to NB-IoT NTN and NR NTN. Three types of satellite service links are supported in 3GPP standards, as illustrated in Fig. 2:

Earth-fixed: provisioned by beam(s) continuously covering the same geographical areas all the time.

Quasi-Earth-fixed: provisioned by beam(s) covering one geographic area for a limited period and a different geographic area during another period.

Earth-moving: provisioned by beam(s) whose coverage area slides over the Earth surface.

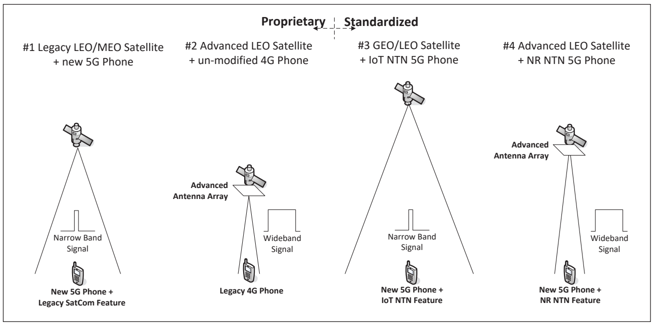

FIGURE 1. Technology options for smart phone direct access to satellite.

The network type (i.e., cellular network or NTN) should be known to UEs from System Information Broadcast (SIB) by the network. Based on configuration, a NTN UE can prioritize Terrestrial Network ((TN), i.e., cellular network) over NTN. Idle mode and connected mode measurements are used for cell selection and hand over, respectively. As an option, UE location and a reference point in the beam footprint broadcast on SIB can be used to trigger UE measurements closer to the beam boundary based on a configured threshold. Time assisted cell reselection can be used for quasi earth-fixed cell to indicate the time when a cell stops covering the current area. In NTN, more than one Tracking Area Codes (TAC) fixed to geographical locations on earth per Public Land Mobile Network (PLMN) may be broadcast in a cell for paging procedure.

In a TN, the maximum two-way transmission delay between UE and eNB/gNB is in the order of 666 μs for a maximum cell radius of 100 km. In a NTN, the two-way UE-satellite delay can be in the order of several ms to 100 ms, depending on the satellite constellation. This results in the downlink (DL) timing at the UE and the uplink (UL) subframe timing at the eNB/gNB being not aligned for scheduling of signaling and data. Figure 3 illustrates the Service link Round Trip Time (RTT), Feeder link RTT, and Reference Point (RP) for DL-UL timing alignment. To solve ambiguity of misaligned timing at the UE and the eNB/gNB, the DL timing and UL timing are frame aligned at the UL time synchronization RP. The RP is configurable, i.e., it can be on the satellite, at eNB/gNB, or a certain point in the feeder link. The start Random Access Response Window and Contention Resolution timer is offset by the UE-gNB RTT during initial access. The timing relationships for scheduling of UL physical channels are enhanced by higher-layer parameters configured by the network in connected mode.

A key challenge in NTN was to specify a solution that allows a device to synchronize in time and frequency when transmitting to a satellite, where very large satellite delay and Doppler shift can be experienced. For example, in LEO at 600 km orbit with a carrier frequency of 2 GHz on the satellite service link, the Doppler shift can be up to +/-48 kHz, while the maximum service and feeder link RTT can be 25 ms. For GEO, the maximum service and feeder link RTT can be 541.46 ms. Figure 4 illustrates a transparent mode satellite system architecture. The satellite delivers GNSS measurements to the ground, typically via dedicated telemetry channels between the satellite and the NTN GateWay (GW), which are collected in the NTN Control Center (NCC) for satellite orbit determination. The satellite ephemeris may also be performed in the NCC, making use of the satellite's position and velocity.

The UE calculates and pre-compensates the satellite long propagation delays and large Doppler shift in NTN, using its UE GNSS location and satellite ephemeris broadcast on SIB before transmitting on the uplink. The satellite ephemeris is valid at a reference time for UL synchronization denoted by the Epoch time. The accuracy of the UE pre-compensation of delay and Doppler over service link is sufficient for UL synchronization (e.g., with one sample or 32.5 ns and a few Hz accuracy with 30 s prediction ahead for LEO at 600 km orbit).

3GPP NR and IoT NTN features were standardized in Release 17. However, the baseline NR and NB-IoT waveforms and protocols were defined in Release 15 and Release 13/14, respectively. Hence 5G NTN is an add-on solution which leverages all the legacy NR and NB-IoT R&D effort for economics of scale advantage. It also means there is still room for enhancement if NTN requirements are considered from Day 1 when redesigning the radio interface for 6G. The following sections will introduce potential areas of enhancement with a NTN native design of the future 6G radio interface.

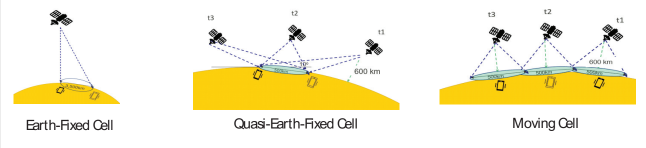

FIGURE 2. Satellite service link types.

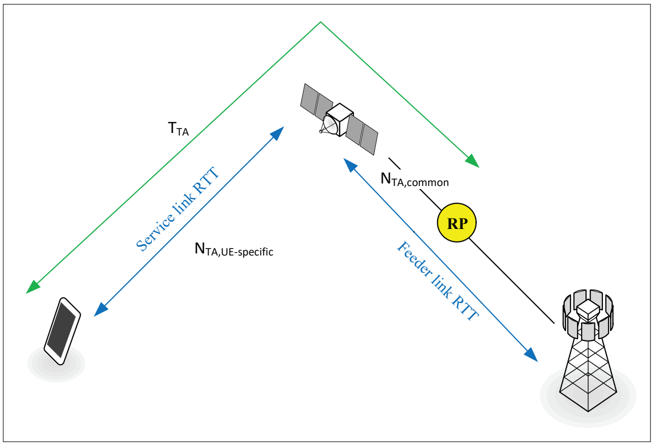

FIGURE 3. Service link RTT, Feeder link RTT, and RP for DL-UL timing alignment.

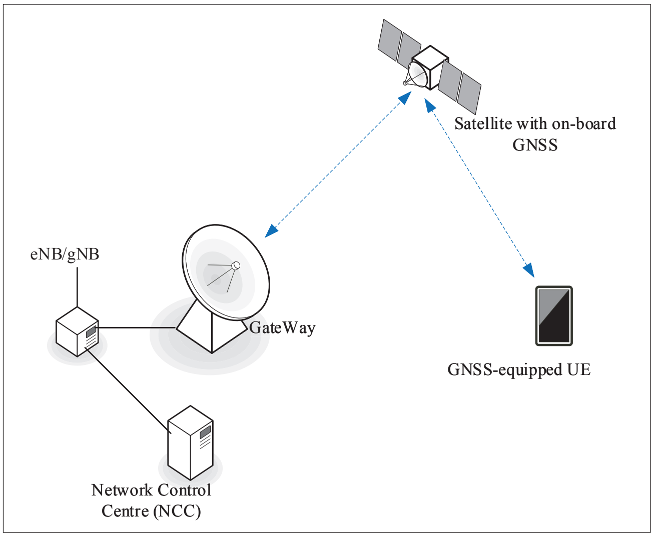

FIGURE 4. Illustration of a satellite system.

EFFICIENT WAVEFORM AND TRANSMISSION TECHNIQUES FOR COVERAGE ENHANCEMENTS

Coverage enhancements to support NTN LEO scenarios in smart phones are currently within the scope of 3GPP Release 18. The combination of path loss due to the long propagation distance and antenna loss in the device results in low Signal to Noise Ratio (SNR) on both DL and UL directions. One solution is to increase the transmission power either in the device or in the satellite. Using legacy waveform design in 3GPP NTN, peak-to-average power ratio (PAPR), and out-of-band (OOB) power leakage make this solution inefficient and with increased complexity.

To avoid inter symbol interference (ISI), a rectangular pulse shape is adopted in 5G NR. The corresponding signal in the frequency domain is a Sinc function, whose sidelobe drops slowly and causes OOB power leakage. OOB power leakage can

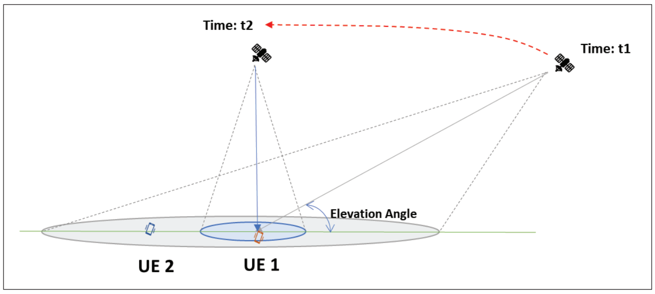

FIGURE 5. Beam footprint when the satellite is at different elevation angles.

be mitigated for terminal devices in the same 5G NR system synchronized using reference signal. However, synchronization between devices operating in different systems may not be feasible. Spectrum sharing across multiple systems that are not synchronized would result in high level of interference from OOB power leakage of the rectangular pulse and lower spectrum efficiency. Further, the maximum transmission power would need to be reduced to prevent unacceptable leakage interference to the nearby band, which is detrimental to enhancing the coverage area in a LEO satellite scenario.

The PAPR of cyclic prefix orthogonal division multiplexing (CP-OFDM) modulation significantly reduces a power amplifier's efficiency. This is a known drawback of CP-OFDM. To reduce PAPR on the UL, DFT-s-OFDM has been widely adopted in 4G and 5G systems. In the LEO UL channel, where the UE must concentrate its transmission power on a small number of resource blocks (RBs) to compensate for large propagation loss, mitigating PAPR would allow UE to transmit with a higher number of RBs. Therefore, one area of future research should explore modulation coding.

Satellite Beam Footprint Adaptation for Coverage Reliability

A key technology to achieve high data rates in 6G NTN is to utilize phased array beamforming. By adjusting the phase of each antenna element, the satellite can steer the beam to illuminate a particular area on the earth surface for a limited period and concentrate the power to this area. It can further provide more service time without handover interruption comparing with using a non-steerable beam.

Although a phased array beamformer can bring benefits in terms of higher data rate and more service time, its beam footprint on the ground is not fixed at different elevation angles, as shown in Fig. 5. When the satellite is flying from time t1 to t2, the beam footprint size is shrinking.

To provide more reliable beam coverage, maintaining the beam footprint size is a critical issue. A phased array beamformer with control of the number of active antenna elements can adjust the beam footprint size (i.e., reduce the elongated beam footprint size).

Spectrum Sharing Across Satellite and Terrestrial Networks

Terrestrial and satellite operators have been competing for spectrum resources for a long time. In International Telecommunication Union – Radiocommunication (ITU-R) sector spectrum allocation, the International Mobile Telecommunications (IMT) spectrum (for cellular/terrestrial) and satellite spectrum is allocated in exclusive manner. One of the difficulties arises because most of satellite networks use proprietary technologies, which are difficult to coordinate with terrestrial networks, or even other satellite networks. However, the situation starts changing because the open standard satellite communication system based on 5G technology, i.e., 5G NTN, is now deployed. The 5G NTN satellite network largely shares the same PHY/protocol/network architecture with cellular 5G networks. It makes the coordination across satellite and terrestrial networks become easier, e.g., better mobility handling, improved coexistence interference coordination, and eventually makes the sharing of the same spectrum resource across terrestrial and satellite operators become much more feasible. Although this may be a sensitive topic from a business perspective, it is critical for academia to explore the feasibility boundary and quantify the benefits for regulatory reference. This may be the ultimate approach to resolve the spectrum scarcity problem encountered by satellite and terrestrial industries today.

Conclusion

We anticipate that the satellite and terrestrial network convergence will be a mega trend as the world migrates from 5G into the 6G communication era. In this column we have described a set of scenarios aiming at enabling satellite communications on smart phones and elaborated several challenges that are being addressed by the technical community.

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