Service Management & Orchestration of 5G and 6G Non-Terrestrial Networks

Brian Barritt
Meta Connectivity
1 Hacker Way
Menlo Park, CA 94025
barritt@fb.com

Wes Eddy
MTI Systems, Inc.
Avon, OH 44011
wes@mti-systems.com
(on contract to Meta Connectivity)

Abstract—**The Third Generation Partnership Project (3GPP) has been adding support for Non-Terrestrial Networks (NTN) into the 5G standards, with increasing NTN features included between Release 17 and 18 of the 3GPP's 5G standards. To enable NTN services to users, the 5G Service Management & Orchestration (SMO) functions will need support for directing the physical link topology, routing, and radio resource management of satellite and airborne nodes in the radio access network. These networks may include mobile Integrated Access & Backhaul (IAB) nodes and mechanically steered, highly-directional beams. These new requirements motivate the development of non-real-time and near-real-time Radio Intelligence Controller (RIC) implementations that leverage a relatively new paradigm called Temporospatial Software-Defined Networking (TS-SDN). The 5G Core Network will also need to support internetworking with untrusted, non-3GPP access networks that use contemporary protocols, like DVB and Link 16. This paper provides an overview of these new requirements and motivates the necessary changes to the 3GPP backend software architecture and interfaces.**

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1. INTRODUCTION

Many modern commercial satellite communications systems are operating based on the Digital Video Broadcasting (DVB) family of protocols, which have evolved from broadcast media use cases in order to now support bidirectional wideband communications in the DVB-S2X and DVB-RCS2 standards. Due to costs, latencies, and other factors, satellite services do not usually compete with terrestrial-based mobile cellular access where it is available. Nonetheless, there is generally no seamless roaming of devices between cellular and satellite-based access, and there are challenges with vendor and satellite provider interoperability due to proprietary tailoring or other differences between provider systems.

Meanwhile, the 3GPP cellular standards have evolved from earlier generations, which were exclusively focused on mobile telephony, to now support broadband and many other use cases envisioned for 5G, 6G, and beyond. The user experience of roaming between cellular providers, device portability between providers, and interoperability in general is much different than with DVB. The volume of devices and associated hardware is vastly larger as well, and the economies of scale enable lower-cost user equipment, provider equipment, and a richer software ecosystem for managing and controlling cellular networks. At the same time, the 5G standards have also been growing to now include support for Non-Terrestrial Networks (NTN) with access provided via satellite and/or aerial vehicles such as High Altitude Platform Stations (HAPS) [1].

Other survey papers on NTN are useful references [1] [2] for greater depth in 5G NTN architecture, however, Table 1 in this paper provides a mapping between related terminology between traditional commercial satellite communications (satcom) such as DVB-based networks (e.g. using DVB-S/S2/S2X and/or DVB-RCS/RCS2) and corresponding terms used in 5G architecture and 5G NTN.

Figure 1 illustrates the basic components of 5G network architecture in a terrestrial setting in Figure 1a, contrasted to different example NTN implementation options that operators might pursue in different cases through. The 5G User Equipment (UE) connect using the New Radio (NR) air interface to the 5G base station, called a gNodeB, within the Radio Access Network (RAN). The RAN is managed by Service Management and Orchestration (SMO) functions, and provides connectivity via the 5G Core network, to other networks (symbolized by the cloud icon). 5G NTN uses cases include, for instance, traditional bent-pipe GEO relays in Figure 1b, regenerative payloads in GEO, MEO, or LEO in Figure 1c, or using multihop intersatellite link networks in a LEO constellation in Figure 1d. The 3GPP acronyms in Figure 1 are explained in Table 1. These are just examples, and other implementation approaches are possible. The scope of the Radio Access Network (RAN) components and aspects that need to be understood and handled by the Service Management and Orchestration (SMO) are expanded significantly between basic 5G and more complex NTN scenarios.

Basic features required to support NTN have been included in the 3GPP's Release 17 specifications[2]. Enhanced functionality for NTN with much greater capabilities are being discussed for inclusion in Release 18 [2]. Beyond 5G, many organizations are releasing their visions for 6G, and these have tended to include satellite and aerial Radio Access Network (RAN) components to provide the needed global coverage. This goes well beyond well-known use cases of rural/remote connectivity, emergency or disaster response, and other scenarios involving airplane or maritime access. Recent work conducted in both industry and academia has explored a number of more advanced use cases leveraging

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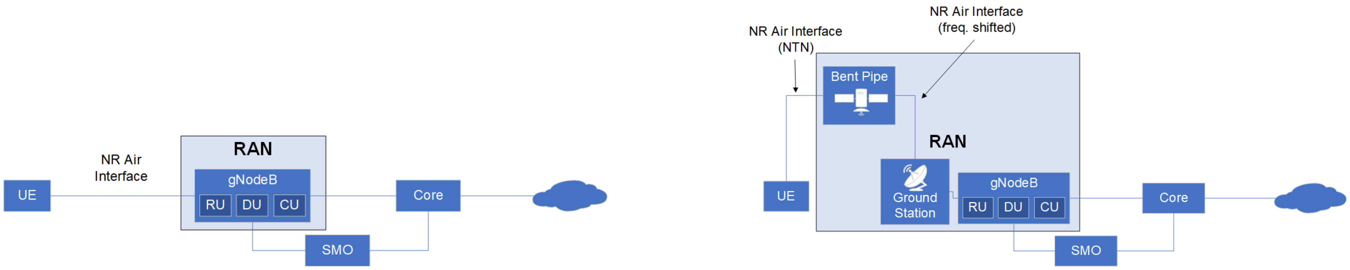
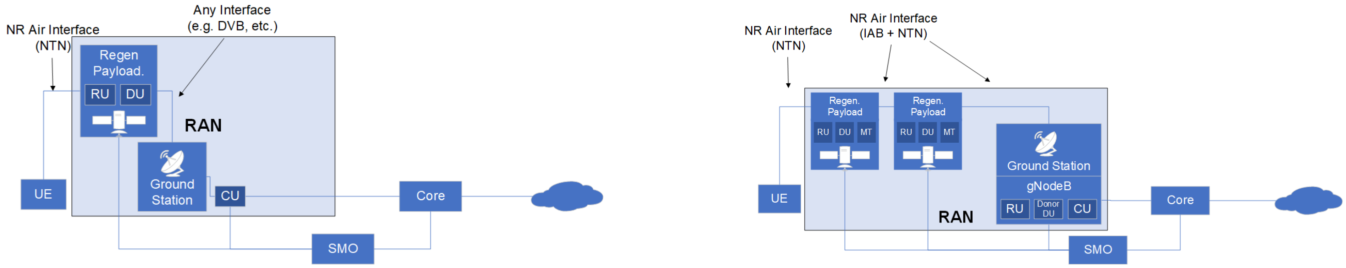
[2] https://www.3gpp.org/specifications/releases



(a) **Basic 5G architecture.** (b) **Basic NTN bent-pipe architecture.**



(c) **Basic NTN regenerative architecture.** (d) **NTN regenerative relay architecture.**

Figure 1: 5G and NTN Architecture Elements

NTN coverage [3], including use of 5G architecture features like dual connectivity (from multiple RAN components) and the integration of non-3GPP radio access technologies, which leads to the possibility to support seamless authentication and roaming for users between terrestrial cellular and access provided by other layers of connectivity – with no additional equipment.

However, most of the research, development, and standardization work to-date has been focused on the RAN and user plane capabilities and services. Much less attention has been paid to the network "backend" that operators will need in order to manage these services over the highly dynamic and wide-ranging types of networks with satellite and/or HAPS elements. In this paper, we describe our approach to unified service management and orchestration (SMO) for these types of non-terrestrial networks. We leverage contemporary developments that are occurring in the direction of "open RAN" technology as well as software-defined networking (SDN). This builds on our prior work on an implementation of Temporospatial SDN (TS-SDN) controller software at Google, X (the moonshot factory), and Loon – and enhances that general architecture to harmonize with O-RAN Alliance specifications and support 5G NTN, DVB, and other types of satellite networks.

Section 2 includes a detailed problem description based on the coming NTN features in 3GPP Release-17, Release-18, and visions for 6G, highlighting the missing SMO functionalities, and the possibility to unify SMO for NTN and terrestrial mesh networks. Section 3 explains how features and capabilities of the TS-SDN approach can be adapted to meet these unified SMO needs. Section 4 then details the unified SMO architecture, while Section 5 describes ongoing industry and standards activities we are participating in to progress these non-terrestrial connectivity solutions.

2. PROBLEM DESCRIPTION

Softwarization of network functionality has been a massive change in cellular networks, facilitated by Open RAN concepts, and is reflected in not only the 5G core architecture but also the O-RAN Alliance and TIP's OpenRAN, Open Core Network, and other specifications. This is bringing operators new flexibility and changing the way that services can be orchestrated and delivered in terrestrial telecom networks. In contrast, the satellite and HAPS industry has not developed any comparable interface compatibility or multiple vendor ecosystem for network backend products. Single-vendor solutions are still dominant.

Widespread industry adoption and commercial deployment of the NTN capabilities from the upcoming 3GPP releases will lead to several benefits for both terrestrial and satellite network users and providers. It will enable new types of service provider relationships – and amplify the ongoing adoption and use for satellite and HAPS-based services. The much higher user and device volumes, along with standardization, should lead to significantly reduced user equipment costs, network operator equipment costs, and network operational burdens. Additionally, this standardization and interoperability has the potential to provide end users with seamless authentication and roaming between terrestrial cellular, HAPS, and satellites – with common user equipment or customer premises equipment.

It could also massively reduce the barriers to entry for HAPS and satellite constellation systems by driving towards common platforms for service management and coherent orchestration of radio and optical resources, mobility, and forwarding path functions. However, the work towards these specific NTN orchestration capabilities has been investigated far less, to-date, and is the focus of this paper.

NTN Development in 3GPP

The 3GPP has recognized the need to mainstream the network equipment and control plane signaling required to support dynamic, directional, steerable-beam network equipment

Traditional SATCOM Term	5G NTN Term	Comparison / Contrast
User Terminal (UT)	User Equipment (UE)	Both traditional satcom or 5G NTN can serve fixed or mobile users, and may incorporate either a VSAT or direct-to-handset mode of operation. Due to the large number of terrestrial cellular users, there are larger economies of scale in the UE chipsets than for UT modems.
DVB Hub	gNodeB (or basestation)	The network operator equipment for DVB hubs are more tightly integrated, whereas 5G gNodeB implementations can be disagreggated and composed of pieces from multiple vendors. Sometimes DVB "access gateway" elements are discussed, comprised of physical and baseband gateway functions, but this is not defined in the standards, in contrast to the 5G decomposition of the gNodeB into Radio Unit (RU), Distributed Unit (DU), and Centralized Unit (CU).
C-band, S-band, etc. and Ka-band	FR1 and FR2	In 5G, FR1 corresponds to sub-6GHz frequencies, and FR2 to higher frequencies, new for cellular use.
Antenna Frontend (not a specific standards term) and Antenna Management Systems (AMS)	Radio Unit (RU)	Traditional satellite network ground terminals incorporate analog-to-digital conversion (and vice versa) and AMS systems built specifically for compatibility with the operator's satellites, feeder uplink/downlink spectrum, and system designs. The 5G RU functionality covers similar topics.
Hub Modem and Gateway	Distributed Unit (DU) and Centralized Unit (CU)	There are differences in functionality and factoring of the processing, but both families of specifications describe subsystems that include data link layer processing, modem and packet encapsulation functions.
UT Baseband	UE Chipset	DVB UT baseband hardware needs to be specifically matched for compatibility with the Hub vendor options and features implemented, whereas 5G UE chipsets and gNodeB implementations are largely independent.
Gateway and Satellite Network (no specific term)	Radio Access Network (RAN)	5G defines a specific system architecture with RAN and Core components, whereas DVB focuses more on the functionalities specific to hubs, satellites, etc. and doesn't have a specific inclusive term comparable to the RAN.
Digital IF	Fronthaul	Transport of digitized signals between antenna frontend and modem systems is common in both cases, however different encapsulation formats are commonly used used, such as VITA-49 in satcom compared to eCPRI in 5G.
Broadband Network Gateway (BNG)	Core Network	The 5G Core Network is well specified and covers functions and external network interfaces that are not explicitly part of the DVB specifications, but need to be part of operator solutions, partly met with BNG and other products.
Various Management Systems (no specific standard terms)	SD-RAN Radio Intelligence Controller (RIC), Service Management and Orchestration (SMO)	Radio resource management in DVB networks is coupled to features and interfaces of the hub and UT baseband implementations, whereas in 5G systems it is more independent and interoperable with defined interfaces and control parameters.

Table 1: Terminology Comparison

topologies. 5G Release 16 adds support for Integrated Access and Backhaul (IAB) topologies [4]. With IAB, the same protocol (e.g. 5G New Radio) can be used both to provide access services from base stations, and to provide the backhaul from base stations towards the network core. For NTN, this is particularly valuable because it enables more homogeneous and flexible mesh architectures; these architectures are important for maintaining a connected network topology.

Beyond this Release 16 basic IAB capability, 5G Release 17 builds additional support for mobile IAB nodes, 60GHz channels, and support for centralized orchestration of the physical link topology. While the specific logic and algorithms for orchestration are not standardized, the required interfaces and information models are. 5G Release 17 also adds support for the channels, waveforms, and propagation timing expected in HAPS, LEO, MEO, and GEO satellite constellations. It further adds support for informing user equipment (UEs) and gNodeBs (gNBs) of the coordinates or ephemeris data pertaining to the other endpoint of a link. This can be used in scheduling its handoff or enactment of routing between different bearers. Unlike in prior 3GPP generations, there is finally a critical mass of industry participation in 5G NTN. Broad alignment and coordination on the standards has been fostered by leaders such as the European Space Agency (ESA), via its portfolio of funding programs like ARTES, the Satellite Standardisation Interest Group (SSIG), and ESA's advocacy for space 5G convergence.

In contrast, while the DVB standards have also been maturing (e.g. support for beam hopping), the pace is less rapid, and the industry participation is more insular than that of 5G. Support for several aspects relative to operating NGSO constellations is lacking, and there are no concepts comparable to IAB. The DVB standards also lack support for signalling scheduled user handoff between satellite spot-beam sectors or for managing radio resources in the face of the continuous changes to spot-beam geometry created by the continuous changes in link direction vector and geometry as the satellites progress in their non-geostationary orbits.

As a result, the DVB hub vendors (or satellite manufacturers) may be left to implement their own proprietary adaptations or modifications to the standards. Even worse, they may implement their own proprietary technologies at the datalink, MAC, PHY and other layers, which further compounds the lack of inter-vendor and inter-provider interoperability. The end result is vendor and provider lock-in, relatively low volumes, and high prices for gateway hardware, communications payloads, and user terminals for satellite and HAPS systems. Additionally, this further complicates the ability to unify network service management and orchestration capabilities. As 5G NR radio access becomes better adapted for efficiency and operation over satellite channels, it could displace DVB as dominant for forward and return, feeder and access link usage.

Need for Unified SMO

Efforts to develop terrestrial, steerable beam mesh networks face similar, though slightly different challenges. Projects like Meta's Terragraph[3] have developed 60GHz connectivity solutions based on 802.11ay. This approach for RAN backhaul requires the deployment of specialized equipment, and there can be regulatory complications to operating these systems, even for network operators with licensed millimeter wave spectrum (like 5G FR2 bands). Operators of these systems also rely on bespoke network planning and operations tools, since traditional planning and OSS/BSS tools used for RANs typically does not provide visibility to this kind of mesh.

Via IAB, 5G NR may be able to provide unification of the RAN and backhaul mesh. In this case, the SMO capabilities for 5G NTN can be leveraged for control and management of both the RAN and backhaul mesh networks. This is a role that can be filled via the Non-Realtime (Non-RT) RAN Intelligent Controller (RIC) and SMO layer in the O-RAN Alliance architecture. The Non-RT RIC is the main component of the SMO, however, it really exists as a platform for execution of rApps that contain the real algorithms and intelligence for resource management and monitoring.

The rApps use the software interfaces of the Non-RT RIC to obtain information about the network elements and their parameters, as well as to affect control over them. The Non-RT RIC serves as a platform hosting the data, programming interfaces, and other aspects of mediating between rApps and the network infrastructure. The intended cases for rApps are management processes that do not require tight (¡100 msec) control loop latency. The delays for rApps through the Non-RT RIC (¡1 sec) are suitable to perform functions like interference management, radio resource management, and other network management applications.

Unified SMO for NTN and wireless mesh can build upon the concepts of Non-RT RIC and rApps to meet the new goals of NTN network operators.

- Unified SMO can support network planning tool interfaces for network operators to evaluate inclusion of both directional mesh and non-terrestrial networking elements in their capacity planning and coverage solutions.
- Unified SMO can allow terrestrial network operators to leverage their own terrestrial network backend systems and spectrum to make transient use of HAPS and/or satellites as part of their RAN. This alleviates the need for user and subscriber data to flow through a third-party core.
- Unified SMO can enable regulators and network operators to define more efficient RF spectrum sharing policies, thereby increasing the total number of directional mesh and non-terrestrial networks that can operate in each region.

3. TS-SDN APPROACH

In addition to basic 5G NTN RAN support, it will be important for RIC-hosted rApps to have abilities for directing the physical link topology, routing, and radio resource management of dynamic, directional steerable beam networks, as these will often be part of the access link setup as well as within the backhaul (or IAB) supporting access. Support for motion of platforms and beams, directionality of antenna beam patterns, millimeter wave, and optical wireless signal propagation requires us to extend the the information base of software defined networking systems. There have been small starts in this direction within some of the early open source RAN control software, like ONF's ONOS xRAN (also related to ONF's micro ONOS and SD-RAN projects), which adapts a typical SDN controller software package (µONOS), adding a Radio Network Information Base (R-NIB)[4], however this only scratched the surface by addressing the RAN topology, without going all the way into the set of parameters needed to model RF propagation rApps such as those performing RRM and other tasks.

Google and Loon made significantly more progress in this area with their development of a TS-SDN controller [5] [6] [7]. The TS-SDN controller, code named "Minkowksi"[5], was responsible for operating Loon's flying mesh network of stratospheric balloon HAPS communication payloads that were distributed in flights around the globe. The balloons formed a dynamic mesh network between one another and ground stations using highly directional links, while supplying LTE services through other antennas directly to users. The LTE traffic as well as in-band network control and management were routed through the mesh to a core network implemented in the cloud. Figure 3 shows a mesh of 33 balloons that formed a network spanning 3,500 kilometeres over Kenya and the Indian Ocean in October 2020[6]. This provides a good basis demonstrating use of the TS-SDN approach for operation of NTN service networks. Based

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[3] https://terragraph.com/

[4] https://wiki.onosproject.org/display/ONOS/xRAN+Controller+Integration

[5] After the mathematician who worked on relativity and the unification of space and time. "Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality." H. Minkowski

[6] This graphic is from the Loon Library https://x.company/projects/loon/the-loon-collection/.

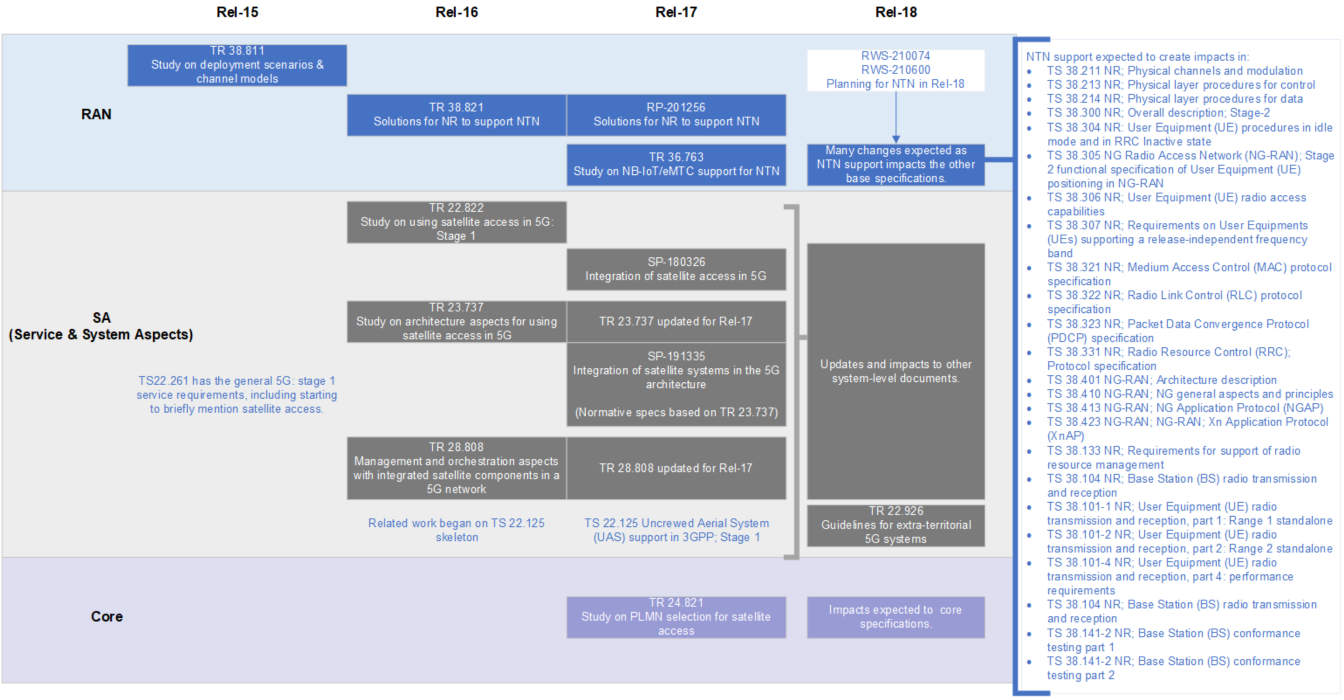

Figure 2: **Increasing support for NTN capabilities in the 3GPP standards.**

on this experience, we describe in the next section how for unified SMO, a non-RT RIC can leverage the TS-SDN design and interface adaptations.

SDN in general builds a holistic model of the network within the SDN controller layer and provides that view to the SDN applications (like rApps) via the northbound interfaces. A TS-SDN controller like Minkowski builds on this, providing more than just a logical graph of the wired connectivity in the network – it also understands the time-varying positions and orientations of platforms hosting network nodes. It treats the world they inhabit as a wireless signal propagation environment, including antenna gain patterns, optical photoreceptor properties, lists of allowed channels and bandwidth and power levels (e.g. based either on physical or regulatory limitations), and a forecast of the weather conditions, as well as other factors impacting communications. The ability to understand planned motion and compute corresponding changes in the wireless signal propagation environment allows the TS-SDN controller to provide northbound applications with the information necessary to pre-schedule the evolution of the physical wireless link topology. This planning can be done in advance, and can coordinate plans across the network elements ahead of time for predictable outages due to motion, weather, or changing business/mission requirements. This pre-scheduling is especially necessary in many NTN scenarios because of the slew time inherent in the mechanically-steered apertures that are commonly used for satellite and HAPS feeder links – and may also be used in access and/or mesh crosslinks.

The Minkowski TS-SDN implementation met the needs of the Loon network at the time. However, it predated the emergence of the 3GPP IAB and NTN feature sets in Releases 17, 18, and other future releases. It also predated the recent O-RAN work defining the non-RT RIC specifications and interfaces. In light of these developments, the TS-SDN controller concepts can be adapted for use in non-RT RIC software towards the unified SMO goals outlined earlier.

4. UNIFIED SMO FOR NTN

Figure 4 illustrates the concept of unified SMO supporting a mesh network based on the O-RAN architecture. The RAN nodes in this figure could be fixed antenna towers or NTN platforms without impact. In this concept, there is a global packet data network (illustrated with the cloud in the lower left), a 5G core network (illustrated by the Magma icon[7] and user plane access gateway), and a number of RAN components serving users, all overseen by the SMO (and near-RT RICs for appropriate functions).

The SMO contains capabilities for SDN-based control of networking functions (illustrated by P4 as an example interface), orchestration (illustrated using Magma orc8r as an example), FCAPS functionality (as would typically be provided by a provider's Network Management System), and finally a Non-RT RIC that facilitates specific RAN management, monitoring, and control functionalities through rApps.

Supporting IAB and NTN with a TS-SDN approach necessitates that rApps using the SMO layer of the network be able to reason about the following types of possibilities:

- **Reconfigurability** - A network resource (i.e., a millimeter wave beam) might be dynamically reconfigured to participate in a point-to-point backhaul link or to provide access layer coverage.
- **Propagation Analysis** - The Non-RT RIC will not be able to rely solely on empirical channel state information because it will not exist for hypothetical / candidate link direction vectors. The RIC must therefore be able to leverage a digital twin representation of the wireless signal propagation

[7] Magma is Meta's open source core network software.

Figure 3: Example Loon mesh network operating state.

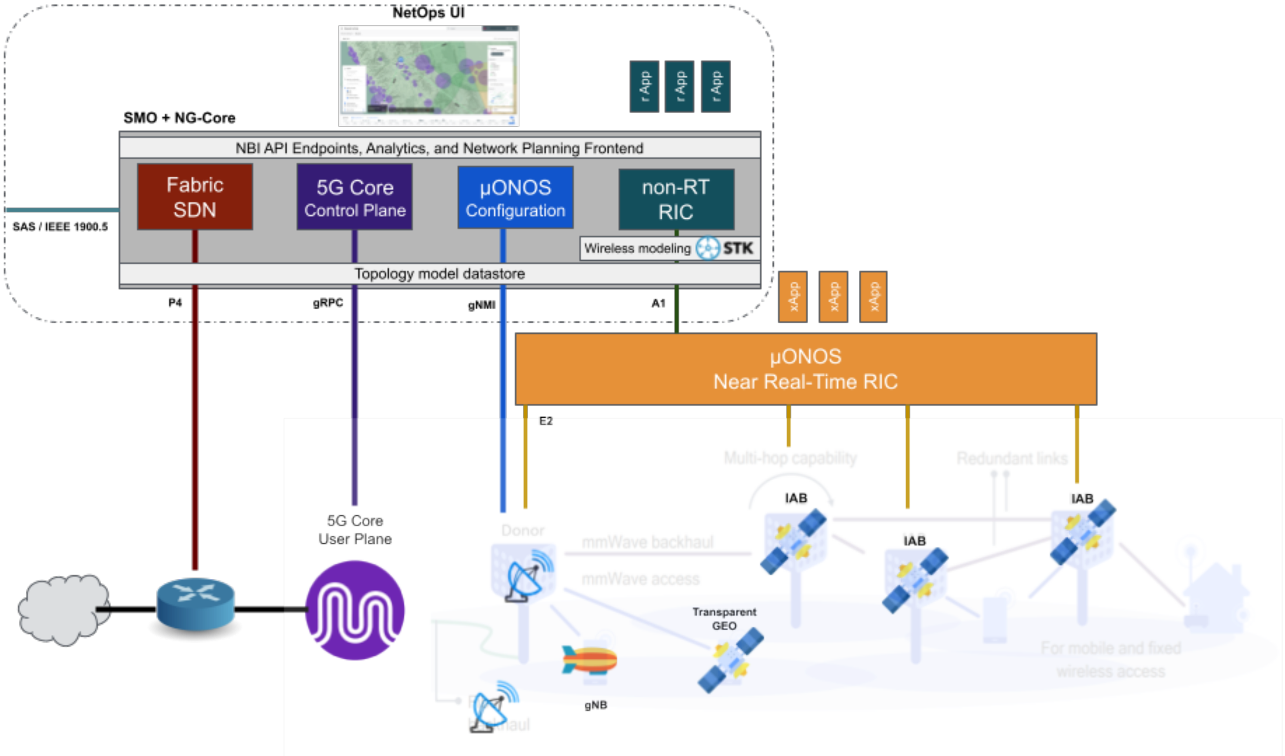

Figure 4: Unified SMO with O-RAN Architecture

environment in order to reason about hypothetical links.

- **Motion in space & time** - While terrestrial nodes and geostationary satellites are both fixed in Earth's reference frame, HAPS, LEO, and MEO satellites are all constantly in motion relative to the Earth's frame. The slew times of directional apertures may be non-trivial and necessitate that the RIC be able to utilize the digital twin to model and predict upcoming signal fades, geometric obstructions, or other constraints and reconfigure the access and backhaul networks to avoid user plane outages.

These capabilities need to be very flexible in order to work in the many different types of possible deployment scenarios for NTN solutions. Figure 5 illustrates a range of different possibilities for how functionality and equipment may be distributed within the network. Starting on the left, there are different types of equipment possible in the User domain. The User Equipment (UE) can take different forms, and might consist of either traditional Very Small Aperture Terminals (VSATs), or typical cellular phone handsets. VSAT approaches with larger apertures and more power can close satellite links with higher performance, but some operators are seriously pursuing Direct To Handset (DTH) offerings, and have conducted demonstrations of basic services.

Another distinction exists between the NTN Access Network and the User, which is whether the NTN Access Network is being used to support UEs directly, or (at the bottom of the diagram) it may be serving as backaul for a provider's remotely deployed gNodeB (gNB) units [8]. This case may be especially present early on, and while it seems simple, there are still open challenges. For instance, there is ongoing work to optimize use of satellite backhaul, by mapping 5G bearers to different channels of the backhaul. Unified SMO could help in this regard using its knowledge of the available carriers and their capabilities to create optimal mappings of the 5G QCIs and bearer flows.

Additionally, there are a number of different RAN implementations possible, closely related to different functional splits in the Open RAN sense. These are discussed starting from the bottom.

- For operators with transparent payloads in air or space, offering bent pipe services, traditional radio systems like DVB might still be used, but with an NTC Non-3GPP Interworking Function (N3IWF) introduced to support interconnection with 5G Core Network elements. This would, for instance, allow operators to support "dual mode" access between 5G NR where available on the ground, and traditional satcom access elsewhere.
- Another option is for the operator of transparent relay payloads to simply implement the 5G NR radio technology within its ground-based systems (e.g. at a gateway site, or through digitized signal processing in the cloud). This could be either through a traditional integrated gNB, or the individual functions factored out to RU, DU, and CU. We distinguish the NTN gNB and radio unit (RU), distributed unit (DU), and centralized unit (CU), because to support NTN there are initially (in Release 17) wider parameter ranges needing to be supported, and may be more features in Release 18 (e.g. an additional waveform option for improving the peak-to-average power ratio).
- NTC operators may start to support gNB implementations fully or partially within their flight segments. One possibility is for just the RU to be in flight, with the DU and CU on the ground, and some type of fronthaul protocol operating over the feeder links and any type of backhaul that might be present[8]. This may be a challenging case, due to timing and synchronization needs in the fronthaul network, and means to support these over the feeder links.
- Another functional split that is feasible is for the RU and DU to both be implemented onboard a flight payload. This would then use IAB or other backhaul to carry the "midhaul" between DU and CU, which should have lower bandwidth and time synchronization or latency constraints than fronthaul traffic would, if only the RU was onboard.
- Finally, it would be feasible for a fully integrated onboard gNB to be implemented, in which case all of the RU, DU, and CU capabilities would be hosted onboard a satellite or aircraft. In this case the IAB or other backhaul would carry backhaul traffic as intended, and the least latency and timing constraints are present. The tradeoff, of course, is that it requires the most functionality and processing capability onboard, compared to other functional splits, and thus is also more difficult to upgrade and maintain the software/firmware for in contrast to more ground-based implementations.

The O-RAN architecture splits network control capabilities between elements based on the responsiveness required. A DU itself handles responses needed in under 10 milliseconds that are considered to require "realtime" (RT) control, while a near-realtime RIC offloads control loops with looser needs to function only in a sub-second realm, and a non-realtime RIC is available for all slower control and management tasks where latencies over a second are tolerable.

The non-RT RIC is considered to be part of the SMO layer, and can be cloud-hosted terrestrially in typical data centers. The near-RT RIC, on the other hand, is often envisioned to be hosted via a mobile edge computing (MEC) infrastructure, physically closer to the DUs being controlled and managed. However, this could require more distinction for NTN scenarios where a typical MEC approach is not feasible, or unlikely to be available on a LEO satellite or aircraft. The range of latencies that the near-RT RIC needs to work within is very short for GEO scenarios, necessitating that it would likely need to be co-hosted in a flight platform with an onboard gNodeB or DU. The same may be true for MEO and LEO scenarios, since the lower range of tens of milliseconds is still hard to meet just in terms of round-trip delays through a LEO constellation.

This leads to an interesting split between what the non-RT RIC for NTN scenarios can do versus the near-RT RIC, given that the near-RT RIC may by necessity be hosted with less computing resources for NTN operators than would be typical for terrestrial cellular deployments. The xApps using the near-RT RIC are more likely to be based on executing simpler algorithms with parameters that have been trained through more complex models and analysis taking place in rApps at the non-RT RIC, for instance.

Finally, there is the 5G Core Network, and all of the typical functions that it provides for user plane transport between RAN and a Data Network (DN), access management, authentication, policies, and other operator needs.

With the goal to make orchestration possible across such a large and potentially diverse set of elements in different NTC networks, and support the needed flexibilities, a number of different components of the Non-RT RIC can be designed, using a microservices type of model (as exemplified by ONF's SD-RAN, for instance), and services similar to those that have been described for Minkowski [9].

Topology Model Datastore

One key result from experiences with TS-SDN published by Google/Loon is that in addition to assembling and serving a holistic view of the logical network topology, the system must also keep track of the physical relationships between relevant network nodes. This can be accomplished by encapsulating the persistent storage of the history of the logical and physical topology within a platform service called here the Topology Model Datastore. This includes capability to track the current state and projected state of each physical platform's:

- Position - As coordinates that can be expressed using different types that are best suited to particular types of platforms or rApps (e.g. cartographic points using latitude, longitude, and altitude on the Earth based on WGS84 or other reference spheroids, cartesian x/y/z coordinates in some given reference frame, or other types of coordinates or areas such as S2 cells).
- Orientation - Giving the needed attitude information to determine how the platform is facing.
- Motion - Using means appropriate for the platform to

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[8] This is a confusing case for backhaul, transporting fronthaul, but is technologically possible, despite the illogical terminology.

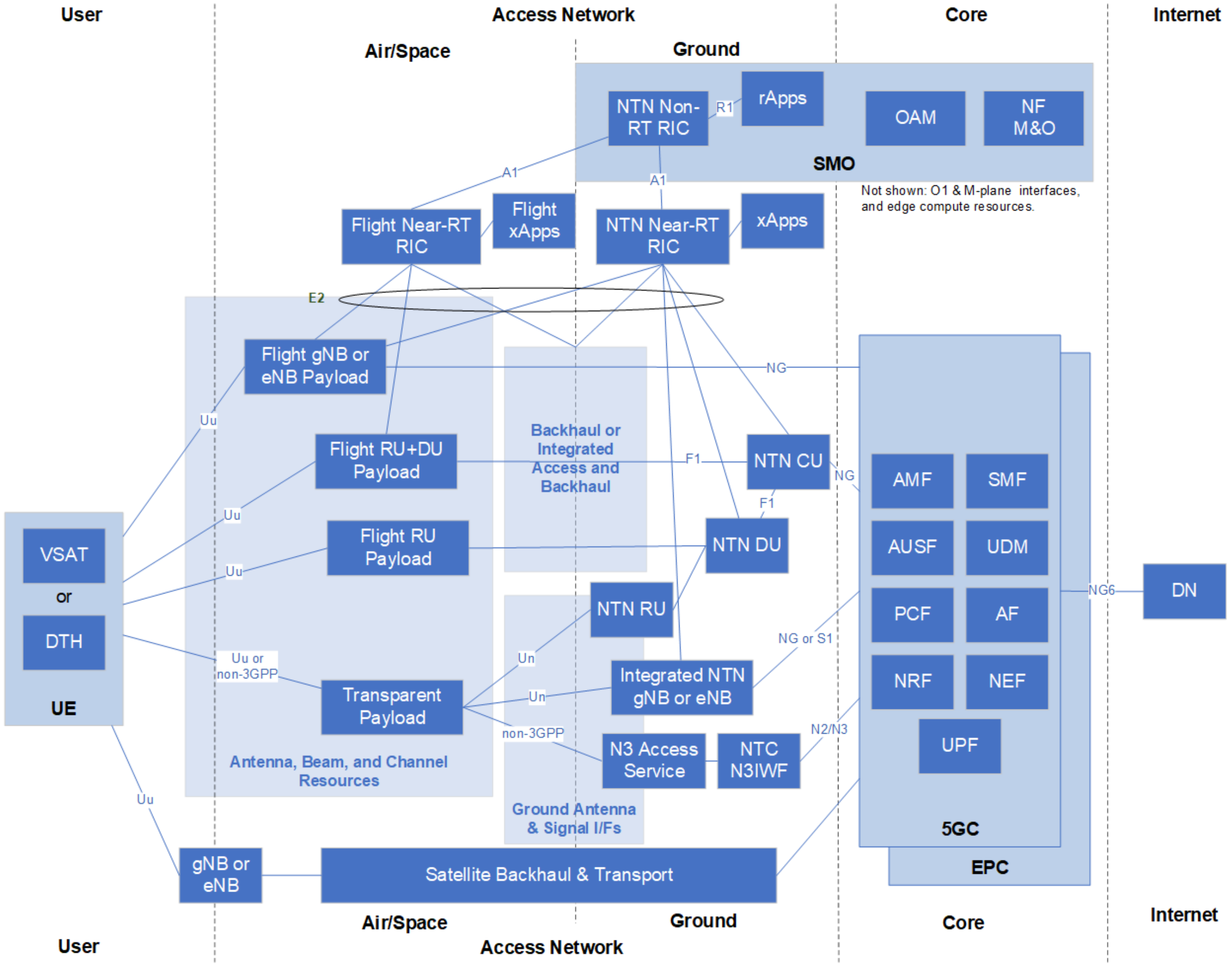

Figure 5: **Possible elements of non-terrestrial communication architectures.**

indicate its changing position and any rotations changing the orientation. This might include orbital elements of different types for satellites, waypoints or other means of indicating airborne platform mobility, or the motion could even be null for fixed ground station platforms.

Antenna apertures are treated as extensions of the physical platforms. They can have their own positions, orientations, and motions relative to the host platform.

Wireless Signal Propagation

Another shared service provided by the Unified SMO platform is the Wireless Signal Propagation Modeling Service (aka digital twin). This is a stateless service that rApps or other services may leverage to query or request proactive computation of the forecast wireless channel conditions for candidate backhaul links or access layer coverage. The modeling approach used will differ depending on the candidate link vector under consideration. For the candidate links and coverage within a terrestrial urban environment, or other types of settings, there are many different loss models available that the service should include a set of, and select appropriately from them.

Prior publications [9] discuss implementation of a wireless signal propagation service as part of a TS-SDN controller. This work showed that the needed functionality can be built up from existing software libraries that support aircraft and satellite motion and RF or optical link modeling. This type of service can also easily be adapted to the non-RT RIC operating environment and software interfaces.

Non-RT RIC

The Non RT RIC takes as input the top-level goals of the network, which are expressed by rApps through the R1 interface defined by the O-RAN Alliance. The RIC can enable subscription to the state of the network provided by the topology model datastore and configuration of the wireless signal propagation modeling service to proactively compute the forecast channel state information for all candidate backhaul links and coverage are computations of interest (which may contain millions of data points). It can them provide rApps access to the set of access coverage areas, planned or otherwise feasible backhaul links, radio channel and bandwidth configurations, and forwarding paths for the S1 interfaces.

There are many different algorithms and approaches that rApps might employ for optimizing aspects of the network and performing intelligent radio resource management. These may be monolithic (optimizing across all aspects of the network at once) or factored into a pipeline or set of rApps that optimizes particular aspects within an envelope created by decisions made in other rApps. Using rApps and a non-RT RIC approach allows many different types of implementations and problem solving techniques to be employed and experimented with either over time or in parallel since multiple rApps can subscribe to the same information streams through the RIC. For instance, in-development algorithms could be using real network monitoring data, but producing only notional outputs while training, while other stable rApps control the actual network parameters. There is a wide range of potential algorithms that operators may be interested in trying for different purposes, including brute force approaches, heuristics, constrain-based optimization, greedy algorithms with backtracking, inference (e.g. mapping to a contextual bandit problem in ML), and others.

No matter what algorithms or factorings across rApps are used for decision-making, the output of the Non-RT RIC represents a high-level blueprint for the intended network state over time, which is compiled by the Unified SMO platform to orchestrate the required control plane signaling over the southbound interfaces. The actual state of the network over time can then be tracked and compared to the intended planned state in order to detect deviations, isolate faults, and contribute towards rapid problem resolutions.

Network Planning and Operations User Interface

Human network operators will be faced with new challenges in planning and operating 5G IAB and NTN networks. Planning and debugging a terrestrial IAB will be similar to those already experienced in the Terregraph program – human operators will need the ability to visualize the state of the backhaul mesh topology at historical periods of interest when debugging connectivity problems reported by their users. The coherent visualization of the physical network topology in the context of the logical network topology takes on increasing importance with NTN given the constraints imposed by terrain, weather, and geometric obstructions.

For Minkowski, Loon developed a network operations user interface that offered a number of different views of the network data and other information stored within the TS-SDN[9]. Figure 6 shows a view that was developed for LEO constellations in order to be able to quickly understand the areas of the globe being covered by different satellite beam footprints, visualize current connectivity within the network, see relevant weather information, and select elements to navigate through to other views. Figure 7 shows another view that was developed in order to summarize the state of network control attempts either completed, planned, or in-progress, to see how nodes in the network are interconnected, and to help in isolating and solving network problems.

The network operations UI is like any other rApp in the proposed Unified SMO architecture; it can subscribe to the present and historical logical and physical topology and access the wireless signal propagation service to provide network operators with additional insights about hypothetical links. Human operators should also be able to access perfomance metric dashboards and interfaces to view and modify parameters of other rApp algorithms. The user interface capabilities are crucial in complex NTN systems in order to make the massive amounts and diverse types of information useful and actionable for people. Experience has shown that the user interface capabilities are critical to aid in network planning, to understand the state of the network when troubleshooting, and should also be important for generating counterfactuals for the decisions made by the rApps.

Spectrum Allocation Service

The physical platform entities stored in the topology model datastore need not be limited to platforms employed in the network being orchestrated. It may also contain 3rd party platforms, which may constrain the operation of the network as potential victims of interference that need to be avoided by the RIC. This is an especially important feature for 5G NTN given constraints that HAPS and NGSO satellite constellations avoid interfering with incumbent systems like radar installations, radio astronomy, terrestrial cell towers, or geostationary satellites.

The Unified SMO platforms' ability to store and model the position and orientation of antennas from multiple parties, and to model wireless signal propagation over space and time, allows it to also participate in federated Spectrum Allocation Services (SAS) for Dynamic Spectrum Access Networks (DySPAN). This is shown in the architecture diagram as an east/west interface to the Unified SMO. This can be an important future contribution, since existing SAS solutions do not support networks with directional, steerable beams like those that will be used in 5G IAB and NTN. The lack of sharing and coordination of link direction vector pointing information and associated dynamic interference modeling is currently a major impediment to the efficient use of spectrum on non-terrestrial networks and would otherwise significantly limit the total number and aggregate capacity of commercial HAPS and satellite constellations.

FCAPS, Core, and SDN

The proposed architecture will also facilitate the necessary evolution of FCAPS, Core, and SDN-based forwarding functions to support 5G IAB and NTN.

Network operators rely on Network Management System (NMS) software in order to support typical functions related to fault management, configuration management, accounting, performance management, and security (FCAPS). NMS systems can use the interfaces provided by a unified SMO in order to benefit from the centralized view and prediction capability that it provides for air and space networks. The terrestrial IT industry YANG models and other information representations that NMS software has typically used are not always able to deal with these dynamic network elements in an accurate way, but the TS-SDN experience can be leveraged in enhancing APIs for NMS products intended for air and space networks.

For the core, the core network orchestrator will need to schedule changes to the S1 tunnel interface that are used to forward packets for a given user to be coherent with the changes to IAB mesh topology, since the donor gNB used to reach a given UE may be changed frequently to account for varying coverage in highly-dynamic topologies. Scheduling the enactment of these changes in an SDN-like model (rather than reactively detecting and responding to fades and failures) will be important to major avoid packet loss and throughput degradation events in the user plane.

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[9] The screenshots included here are from the Loon Library https://x.company/projects/loon/the-loon-collection/.

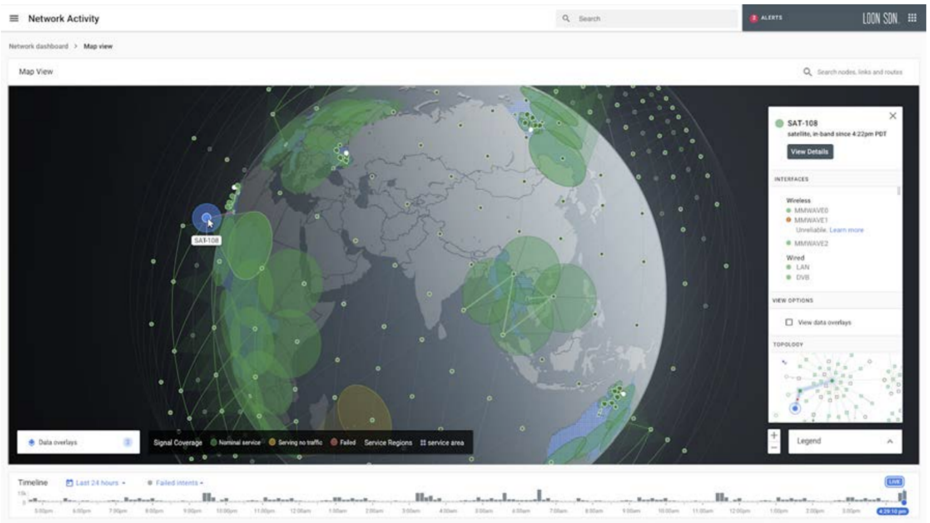
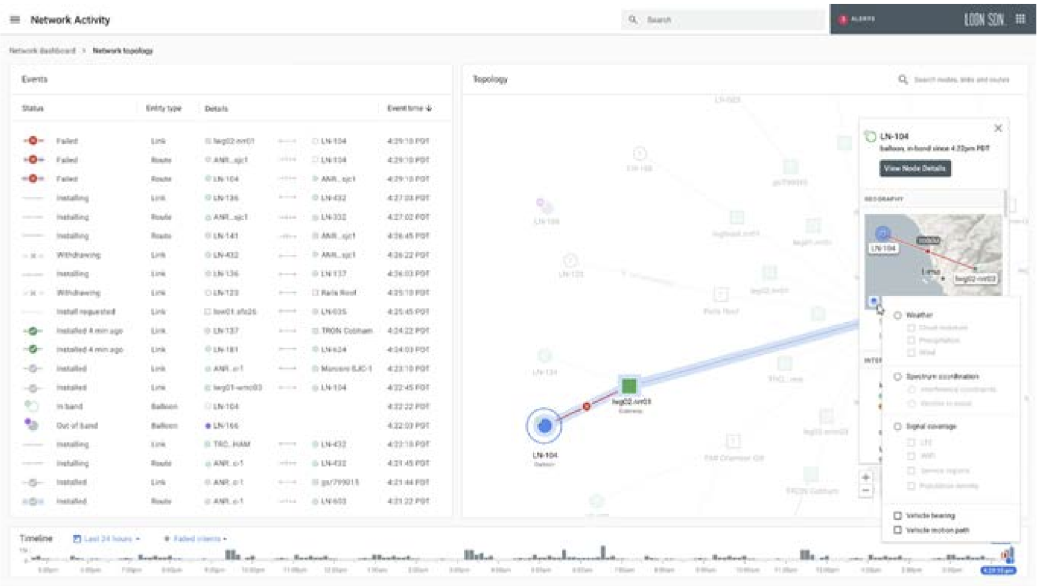


Figure 6: **Loon's Minkowski network operations user interface showing the geospatial positions, orientations, RF coverage, and other information useful for NTN systems.**



Status	Entity type	Details		Event time
Failed	Link	legg02-nrt01	LN-104	4:29:10 PDT
Failed	Route	ANR...sjc1	LN-104	4:29:10 PDT
Failed	Route	LN-104	ANR...sjc1	4:29:10 PDT
Installing	Link	LN-136	LN-432	4:27:03 PDT
Installing	Route	ANR...sjc1	LN-332	4:27:02 PDT
Installing	Route	LN-141	ANR...sjc1	4:26:45 PDT
Withdrawing	Link	LN-432	ANR...sjc1	4:26:22 PDT
Installing	Link	LN-136	LN-137	4:26:03 PDT
Withdrawing	Link	LN-123	Raila Roof	4:25:10 PDT
Install requested	Link	low01.afo26	LN-035	4:25:45 PDT
Installed 4 min ago	Link	LN-137	TRON Cobham	4:24:22 PDT
Installed 4 min ago	Link	LN-181	LN-624	4:24:03 PDT
Installed	Link	ANR...c-1	Manzano ILJC-1	4:23:10 PDT
Installed	Link	legg01-wmc03	LN-104	4:22:45 PDT
In band	Balloon	LN-104		4:22:22 PDT
Out of band	Balloon	LN-166		4:22:03 PDT
Installing	Link	TRC...HAM	LN-432	4:22:18 PDT
Installing	Route	ANR...c-1	LN-432	4:21:45 PDT
Installed	Link	ANR...c-1	gs/799015	4:21:44 PDT
Installed	Route	ANR...c-1	LN-603	4:21:22 PDT

Figure 7: **Loon's Minkowski network operations user interface showing the state of network elements, control attempts, and relevent context.**

Finally, for SDN forwarding within the network, the capabilities of unified SMO are well suited to make use of programmable network hardware and continued advances in the state of support for programmability through different table types, protocols, and other SDN features becoming more commonplace. The SMO can properly orchestrate configurations across the specific hardware, software, and virtualized network functions and elements, as well as providing accurate abstractions of these and their logical and physical relationships to the rApps that manage them or manage services through them.

5. STANDARDS AND INDUSTRY

Within the Telecom Infra Project (TIP)[10], the Non-Terrestrial Connectivity Solutions (NTCS) Project Group (PG) has been rechartered[11] in mid-2021 in order to address the needs of satellite and HAPS operators. The NTCS PG has an operator-oriented approach, including the network operators and service providers from the outset in developing requirements that cover necessary features and functions for their specific environments. The NTCS PG is chartered to deliver requirements documents and test suites for continuous integration / continuous delivery (CI/CD) that enable the development

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[10] https://telecominfraproject.com/

[11] https://telecominfraproject.com/tips-non-terrestrial-connectivity-solutions-project-group-relaunch-new-partnerships-new-scope/

of multi-vendor and cross-vendor interoperable end-to-end systems. TIP uses a badging process to enable easy and effective identification of products and solutions that are recognized to meet the requirements, streamlining the processes for operators to acquire and deploy validated hardware and software products.

Among the NTCS PG deliverables are:

- Base Station Requirements - covering both near-term 4G services, as have been provided by HAPS or for NB-IoT via satellite, as well as longer-term 5G NR capabilities that might be delivered through different operator architectures.
- Backend Requirements - covering the SMO needs discussed in this paper, plus core network capabilities and the N3IWF.
- Interfaces - describing the usage and adaptation of 3GPP and O-RAN interface standards for the NTCS operator needs.

The NTCS PG has participants from over 100 member organizations, is being co-chaired by leadership from two major satellite services operators, has workstreams led by the European Space Agency and a rising LEO constellation operator, has a collaboration agreement with the HAPS Alliance, and welcomes all types of operators, and ecosystem hardware and software vendors, and other organizations to participate. We at Meta Connectivity are also making significant technical contributions, and see this as important work for our goals in improving connectivity.

6. CONCLUSIONS AND FUTURE WORK

In summary, there are major new NTN capabilities coming into the 3GPP specifications, yet there remains a lot of work to be done within the management and control systems, and we have shown that a Unified SMO based on the TS-SDN approach is viable and can meet the industry needs. Through our prior work on Minkowski, TS-SDN has been shown to work well for operating early NTN-precursor type of services, including building and maintaining a mesh network among RAN components, similar to what new IAB capabilities require.

Unified SMO incorporates the services from a TS-SDN controller and then leverages the O-RAN Non-RT RIC in order to provide those services through to rApps. The R1 interface between Non-RT RIC and rApps might in the future be extended or enhanced to support this more directly in the O-RAN architecture. As future work, we are bringing contributions to the TIP NTCS PG, which offers a promising avenue for further developing the unified SMO concepts described in this paper.

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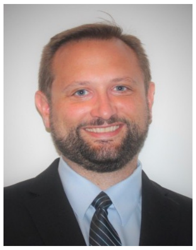
BIOGRAPHY

Brian Barritt *received his B.S., M.S., and Ph.D degrees in computer engineering from Case Western Reserve Univ and an M.B.A. from the Univ of Minnesota. He supports open source cellular software as an engineering manager at Facebook Connectivity. Before that role, he spent 6+ years as a software engineer at Google and its affiliates on non-terrestrial connectivity solutions.*



Wesley Eddy *received his B.S and M.S. degrees in Computer Science from Ohio University in 2002 and 2004. Since then, he has worked on development of novel networking technology for air and space communications systems, and deployment of networks supporting spacecraft and aircraft mission operations, as a contractor at the NASA Goddard Space Flight Center, Glenn Research Center, Google X / Loon, Facebook, and with other government agencies. He has served as an area director in the IETF, and co-chaired several working groups, as well as contributing in several other standards organizations.*