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HydRON Vision: preparation towards a flight demonstration

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ABSTRACT

European Space Agency (ESA) has been implementing, since 2019, the HydRON (High-thRoughput Optical Network) Project within the ESA ScyLight Strategic Programme Line. HydRON aims to build a network of high-capacity optical inter-satellite links and ground-satellite links that interconnect space assets with each other and with ground networks, and that seamlessly extends the terrestrial optical transport networks into space. Data repatriation from satellite and airborne users, feeder link communications to telecommunication satellite operators, high-capacity connectivity to remote private networks, and dynamic peering to terrestrial network operators are four high-level services that may be provided by HydRON. This paper presents the outcomes of the HydRON Vision Phase-A studies led by Airbus Defense and Space (Germany) and Thales Alenia Space (Italy), completed in 2021. These HydRON Vision Phase-A studies aimed at investigating end-to-end system architectures, and identify key elements of the system architecture such as optical ground-satellite links, high data rate WDMs for optical inter-satellite links, on-board switching and routing in optical and/or electrical domains, seamless integration into terrestrial networks, and control and management protocols. The results of the HydRON Vision from those Phase-A studies described in this paper provided the basis for the definition of the HydRON Demonstration System in the currently running Phase-A/B1 studies, which focus on the in-orbit demonstration of a subset of the key technological elements and the validation of the most relevant operational concepts.

Keywords: Optical satellite networks, free space optical communications, WDM, OTN

1. INTRODUCTION

The relentless drive to reduce the cost per bits per second in the face of ever growing volume of data traffic and the need for secure communications bring to fore free space optical (FSO) communications as a key strategic topic in the European Space Agency's (ESA) Vision. Satellite networks with optical inter-satellite and ground-satellite links may offer Terabits/s grade transmission rates over point-to-point links that are almost impossible to eavesdrop or jam, and that allow by-passing potentially compromised or congested administrative domains in the global terrestrial network. Use of FSO communications in satellite networks not only releases radio frequency bands from satellite feeder links for other uses, but may also reduce the overall CAPEX by decreasing the required number of ground gateways in the network.

This paper presents the outcomes of the HydRON Phase-A studies led by Airbus Defense and Space (Germany) and Thales Alenia Space (Italy), completed in 2021. These HydRON Phase-A studies aimed at investigating end-to-end system architectures, and identify key elements of the system architecture such as optical ground-satellite links, high data rate Wavelength Division Multiplexing (WDMs) for optical inter-satellite links, on-board switching and routing in optical and/or electrical domains, seamless integration into terrestrial networks, and control and management protocols.

The studies, then, provided an overview of the potential enabling technologies required. Finally, the studies defined an in-orbit demonstration mission (or a set of staggered missions spread out in time) in LEO/GEO orbit (or in a mixed LEO/GEO scenario) to demonstrate the feasibility, and to evaluate the communication performances of the critical elements, including the technology development roadmap and associated schedule/cost analysis.

The results of the HydRON Phase-A studies described in this paper provided the basis for the definition of the HydRON Demonstration System in the currently running Phase-A/B1 studies, which focus on the in-orbit demonstration of a sub-set of the key technological elements and the validation of the most relevant operational concepts.

Section-2 provides a summary of the long-term HydRON Vision. Section-3 and section-4 present the selected main results from the HydRON Phase-A studies conducted by consortia that have been primed by ADS and TAS-I, respectively. Section-5 presents the identified way-forward towards the implementation of a HydRON DS. Section-6 presents the conclusions of this paper.

2. HYDRON VISION

HydRON[1,2,3] Vision is a network of satellite nodes at GEO, MEO, and LEO orbits. They are interconnected to each other via OISLs (Optical Inter Satellite Links), and to the ground segment via OGSLs (Optical Ground Satellite Links). HydRON Vision aims to provide a global coverage, offering communication services in the order of Terabits/s. Use of DWDM (Dense Wavelength DiVision Multiplexing) is essential to achieve such high transmission rates.

Atmospheric cloud obstruction is a major problem for OGSLs. In HydRON Vision, a subset of OGSs (Optical Ground Stations) are interconnected via terrestrial optical links to form an OGN (OGS Ground Network). Weather monitoring and prediction techniques coupled with site diversity techniques and switchover protocols are to be deployed to switch traffic to those OGSes in cloud-free sites, and hence, minimise durations of service disruptions caused by cloud blockages.

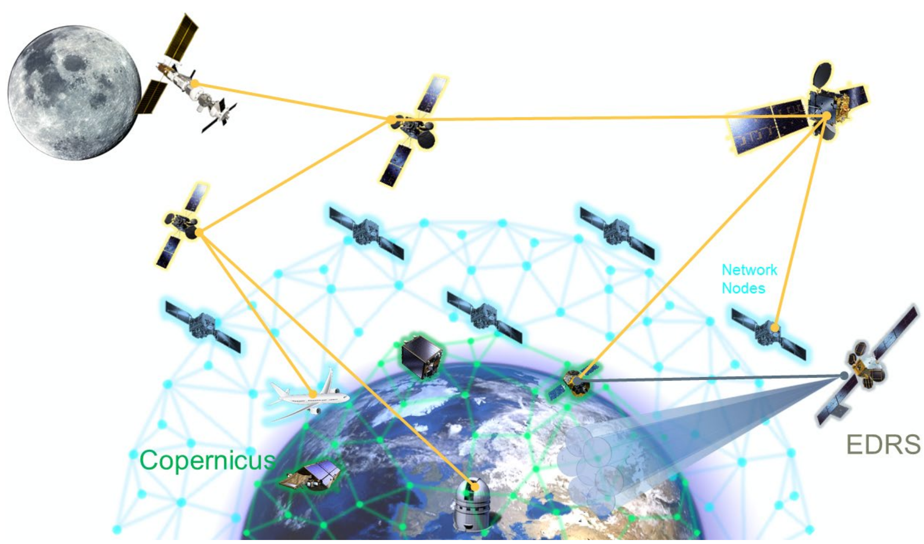

Figure 1: HydRON Vision

HydRON payloads may be embarked on dedicated HydRON spacecrafts, or they may be hosted on spacecrafts owned by other operators. In the latter case, HydRON payload may provide communication services to non-HydRON payloads that are also hosted on the same spacecraft. Four high-level user groups have been identified, so far, for HydRON communication services. These are TSOs (Telecommunication Satellite Operators), SAUs (Satellite and Airborne

Users), PNUs (Private Network Users), and TNOs (Terrestrial Network Operators). TSOs are operators of telecommunications satellites that require to use optical feeder links instead of Radio Frequency (RF) feeder links. SAUs include Earth Observation (EO) satellites, High Altitude Platforms (HAPS), and other airborne entities that send very large volumes of data to the processing centres on ground. PNUs include individual ground users that lack high-capacity terrestrial links to the rest of the terrestrial communication infrastructure due to technical, geographical, political, or security reasons, among others. TNOs are operators of terrestrial networking infrastructure that require high-capacity connections to other TNOs.

Users of the HydRON service – even within the same user group (e.g., PNUs) – may exhibit heterogeneity in terms Quality of Service (QoS) requirements (e.g., latency, jitter, service availability), in terms traffic characteristics (e.g., constant bit rate, variable bit rate), and in terms end-to-end (E2E) connectivity (e.g., Ethernet emulation, IP VPN, multicasting, etc.). For example, EO satellites need high-capacity connections for constant bit rate input traffic with non-stringent latency requirements at pre-scheduled time intervals, whereas HAPS in disaster areas, serving as 5G backhauls, will need continuous connectivity, low latency and jitter performances, and high availability for – at least – the duration of the disaster relief operations. The aggregate traffic generated by PNUs may include flows from delay-tolerant data repatriation applications as well as flows from delay-constrained applications. Some of these applications may need Ethernet or IP VPN services from the provider network (i.e., HydRON). TNOs may use HydRON to directly interconnect to other TNOs by-passing parts of the terrestrial networks for various reasons including security, political, and technical (e.g., shorter latency and jitter than optical fiber in LEO constellations). In this respect, HydRON Vision may be viewed as an Autonomous System (AS) connected to multiple IXPs (Internet eXchange Points) all around the globe (see Figure 2).

HydRON Vision is fully integrated with terrestrial networks. In accordance with the Vision in Figure 2, HydRON is an administrative domain with its own internal routing realm. Transport services may be provided to external networks at OTN (Optical Transport Network) Layer 1, Ethernet, or IP layers. Regardless of the interfaces exposed to external networks, internally to the HydRON, both circuit and packet forwarding may be adopted; depending on the implementation cost/complexity and possible statistical multiplexing gains. It is crucial that HydRON exposes a control-plane API to external users that allows dynamic establishment of connectivity at various QoS levels with a flexible SLA (Service Level Agreement).

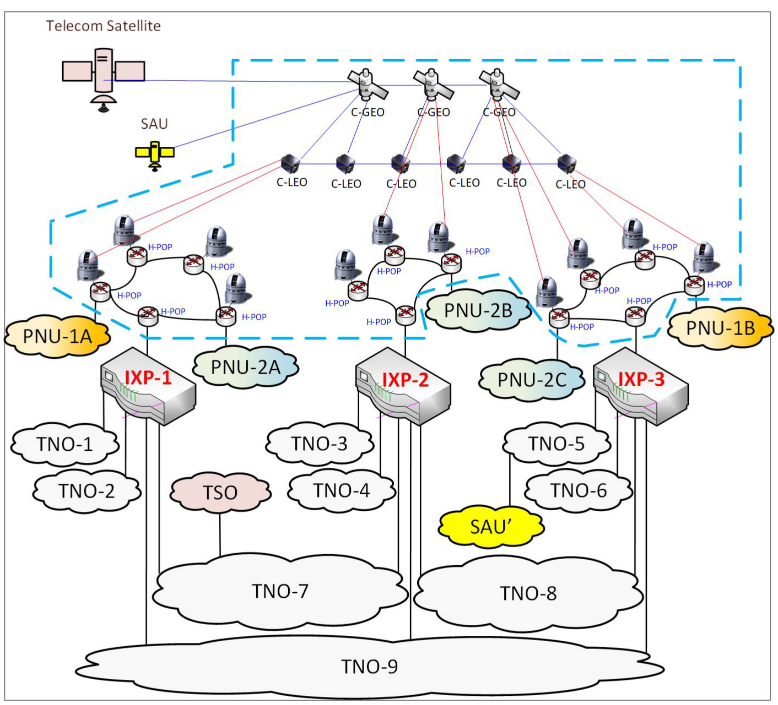

Figure 2: HydRON Vision as an Autonomous System

3. ADS STUDY RESULTS

This HydRON Phase A study was conducted by a consortium primed by ADS, and including TESAT Spacecom, DLR-IKN, ADVA, SODERN and EUTELSAT. Selected results from this study are presented in the rest of this section. After stating the basic building blocks required to meet the HydRON mission objective, the focus is placed on the GEO constellation definition to achieve a global and persistent HydRON network.

Achieving Terabits/s user data rates on FSO links in a mixed terrestrial, and space-tailored terrestrial fiber optical technologies is considered as the main prerequisite. Use of WDM technologies enables significant bandwidth scaling in terrestrial fiber networks. The trade-offs performed in the study indicate utilisation of transceivers supporting 100 Gb/s user bandwidth signals with BPSK modulation as ideal compromise among the required transmission power for link budget closure, the availability of suitable space-qualified client-side interfaces, and the targeted service models. A configuration of ten such transceivers in a DWDM wavelength grid as per in[4] is the selected baseline approach to achieve FSO links of Terabits/s user data rate.

In order to achieve seamless integration with terrestrial optical networks with a largest set of offered service types, the proposed HydRON network implements an OTN following the definitions in[5]. The satellite nodes are all regenerative nodes and capable of routing OTN signals at Layer 1.

Implementation of a GEO ring

This section provides results related to efficiently establishing a HydRON ring network in GEO orbit. GEO platforms are promising hosts for HydRON payloads, because – among other reasons – they usually host other payloads that may be HydRON users for broadcasting and data-relay services. Also the nature of GEO orbit provides easy operation w.r.t. GSL, and coverage of significant volumes of the lower orbits by few ISL interfaces on the HydRON payload.

The E2E system concept foresees a ring of 6 equally distributed satellites in GEOstationary orbit. This paragraph analyses the current distribution of satellites along the GEOstationary orbit and summarises the potential implications. The data source for the locations of satellites in GEOstationary orbit are taken from[6]. The data set is filtered for commercial communication satellites in GEO. Currently, 465 satellites are operational in this category. The histogram of the separation between neighbours of this dataset is shown in Figure 3. It is observed that the usual separation between neighbouring satellites is in the order of a few degrees with a median separation of 0.43 degree and an average separation of 0.775 degree. However, gaps of up to 3 degree are common.

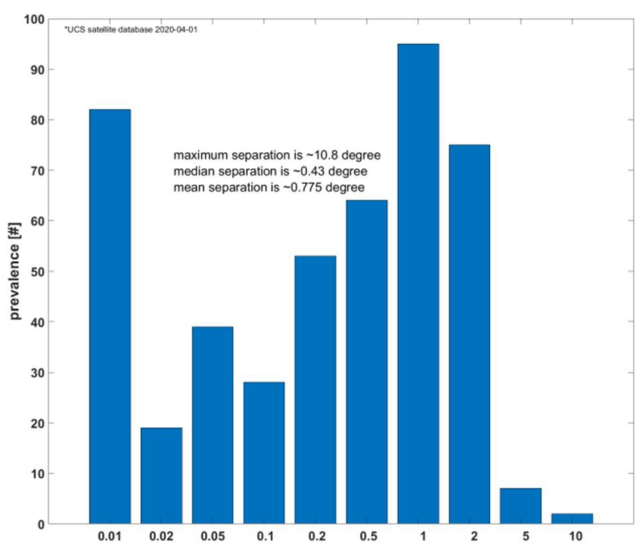

Figure 3: Histogram of gaps between neighbouring GEO telecoms satellites

Next, we investigated if an existing operator has compatible orbital slots in its current operational environment that could be updated with a satellite that hosts the HydRON payload. The analysis was carried out with the dataset in[6]. The distribution of telecoms satellites over the GEO ring was analysed and grouped by major operators. This was compared with the proposed orbital slots of the HydRON Ring with 6 GEOstationary nodes. The result is displayed in Figure 4.

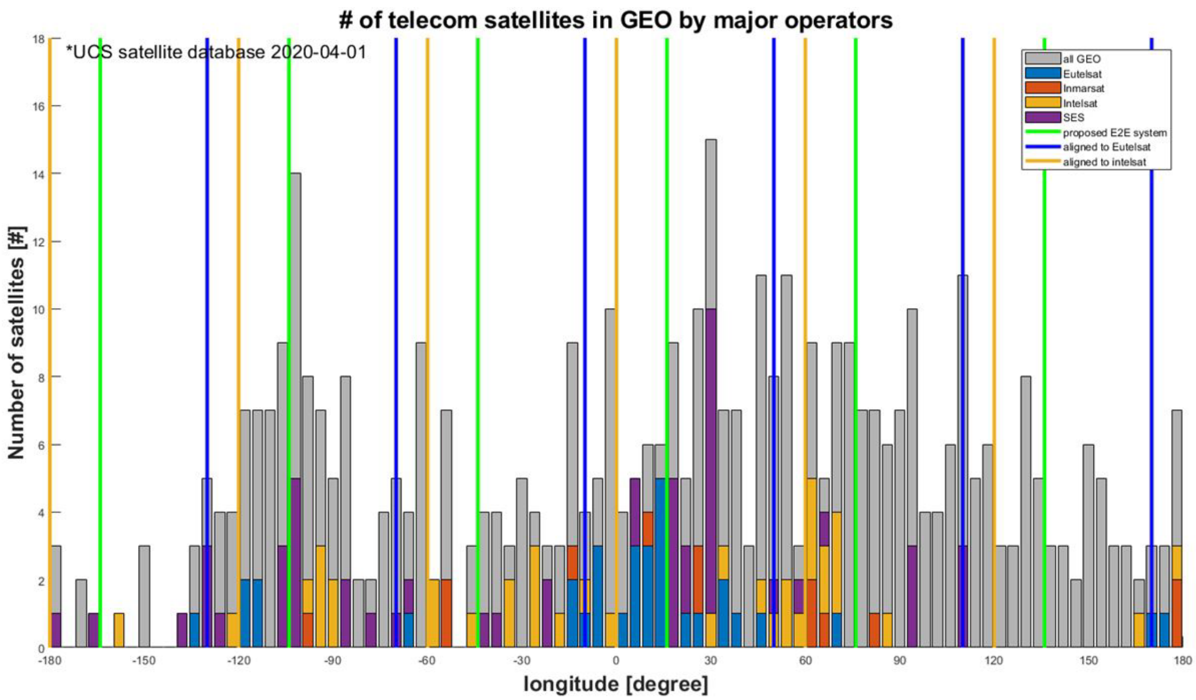

Figure 4: Satellite orbital slots in GEO per major operator

It is noted that currently no operator is operating satellites near all longitudes proposed for HydRON. SES, as the case with the most coinciding satellites, operates close to 4 of the 6 proposed slots. The position of the proposed HydRON slots could be adapted to better fit existing fleets. For instance, slots separated by 60° starting from 128°W would lead to a constellation where 5 slots would be close to orbital slots currently used by Intelsat. A similar constellation starting at 135°W would align with 5 slots used by Eutelsat. These options are indicated in Figure 4 as the lines aligned to the respective operators. Figure 5 shows the number of existing slots for the 6 GEO ring for each operator depending on the position of the most westward node. For most major operators a configuration of 3 slots separated roughly by 120° coincides with existing orbital slots. Figure 6 shows the longitudinal positions for the most westward slot of such a 3 GEOstationary ring at which each operator would have existing orbital slots for all three satellites.

However, these constellations have the disadvantage in regards to the areas reachable by optical GSLs. Specifically, the area over Europe shows smaller coverage, and the most populous area of the world, East Asia, is covered only by one satellite in these cases. Therefore, HydRON will either require an increase in operational coverage by any single existing operator to establish the proposed GEO ring, or a joint venture between several operators, or the use of one or two stand-alone HydRON nodes.

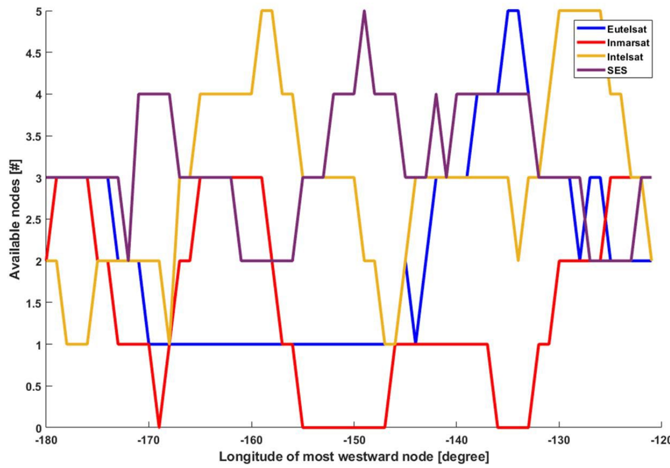

Figure 5: Number of existing orbit positions for 6 GEO ring with 60° [+/- 5°] separated slots per operator

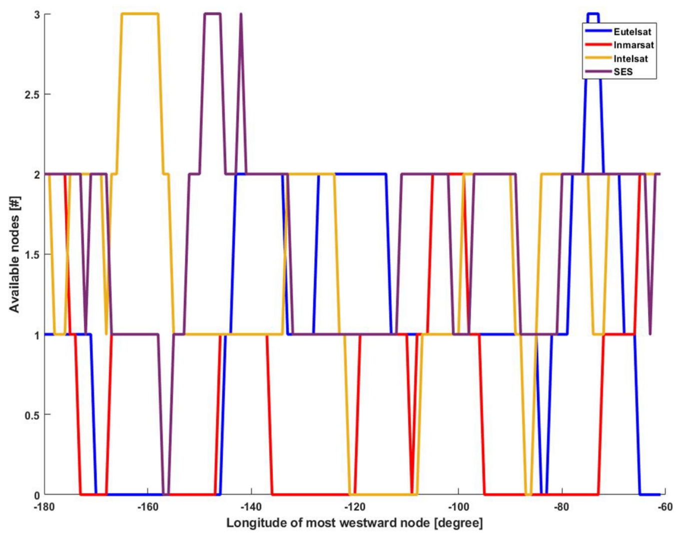

Figure 6: Number of existing orbital positions for 3 GEO ring with 120° [+/- 5°] separated slots per operator

In order to achieve global and persistent coverage, GEOsynchronous orbits may be considered instead of the GEOstationary orbit. This potential implementation is an alternative to constellations of LEO nodes. LEO constellations would require >200 satellites to achieve global persistent coverage assuming GSLs with minimum elevation angles at 30°. The following paragraphs detail the analysis carried out on GEOsynchronous orbits.

Following constraints were assumed for the GEOsynchronous orbits:

- The added inclination should allow the poles to see the satellite with min 30° elevation determines the minimum inclination.
- Since nothing constraints the maximum, the inclination for Molniya/Tundra orbits (63.4°) to stabilize J2 perturbation of argument of perigee is chosen.

The coverage of a single Node with such orbit parameters is shown in Figure 7.

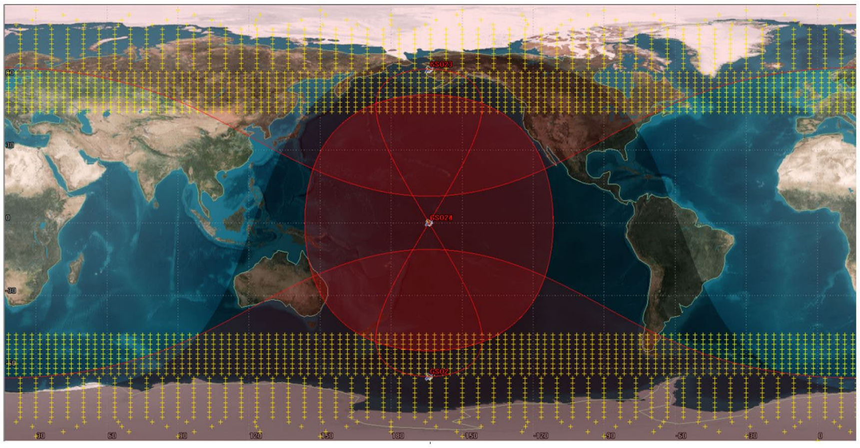

Figure 7: Coverage by a single GEOsynchronous orbital slot (covered areas are shown in red)

Four satellites in this orbit are required to achieve persistent coverage of the entire area shaded in red. The minimum latitude covered is 88° for continuous coverage. As coverage of latitudes >52° is required, a second slot is mandatory. Figure 8 illustrates how the persistent coverage of latitudes evolves for different distributions of satellites over one or two slots. As shown in Figure 8, a minimum of 2 slots with 4 satellites each is required to cover all latitudes >52° persistently. A separation of the longitudinal separation of two slots by 180° ± 3° is required. As an added benefit, each slot will also cover an area in lower latitudes similar to a GEOstationary node. Therefore, it could be considered to replace a GEOstationary slot by a GEOsynchronous slots for HydRON. This leads to a minimum constellation required for persistent and global coverage of 4 GEOstationary satellites and two slots of each 4 GEOsynchronous satellites. If only 3 GEOstationary nodes are used, then areas at low latitudes will lack coverage.

Adding eccentricity to the geosynchronous orbits will lead to changes in the coverage over the northern and southern hemisphere. While this could be used to cover the northern hemisphere with only 2 satellites per slots persistently, it would lead to a significant under coverage of the southern hemisphere.

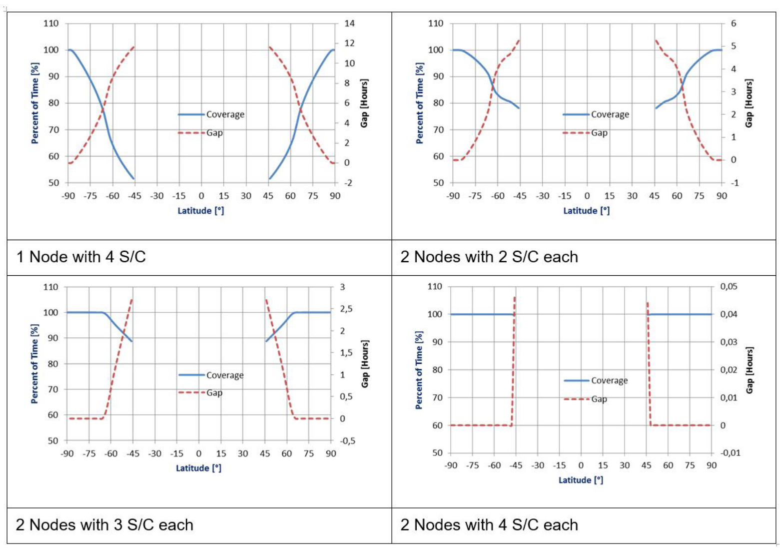

Figure 8: Coverage by different GEO synchronous nodes (i.e., orbital slots)

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A constellation will only be operational once all satellites are launched. Thus, replacing 2 GEOstationary slots with GEOsynchronous slots is unattractive. In addition, this would require more complex networking and space segment management in early phases of the HydRON stage 2. Therefore, the GEOsynchronous slots are added to the 6 GEO stationary slots configuration as separate slot. In order to ensure persistent coverage at latitudes >52°, the longitudinal separation of the GEOsynchronous slots may not be <176°. Therefore, the GEOsynchronous slots are placed symmetrically at 180° apart. In order to reduce the pointing requirements to the adjacent GEOstationary slots, the GEOsynchronous slots are placed in the middle between two GEOstationary slots. The positions of 46°E and 134°W are chosen to optimise coverage over northern Europe and north America as well as utilise the added redundant coverage at lower latitudes in these regions to enhance service capabilities in case sufficient GSL connectivity is available. The coverage of such a constellation is shown in Figure 9. This constellation provides global and persistent coverage of all latitudes. Areas with redundant coverage are shown by brighter shading.

Payload and embarkation implications

GEOsynchronous payload: The HydRON payload on the GEOsynchronous node will require a minimum configuration of four LCTs (Laser Communication Terminal) pointing in the nadir direction to allow for handover of GSLs, and to provide service to airborne users at high latitudes. In addition, at least two OISL LCTs are required to connect to the adjacent GEOstationary nodes for traffic forwarding.

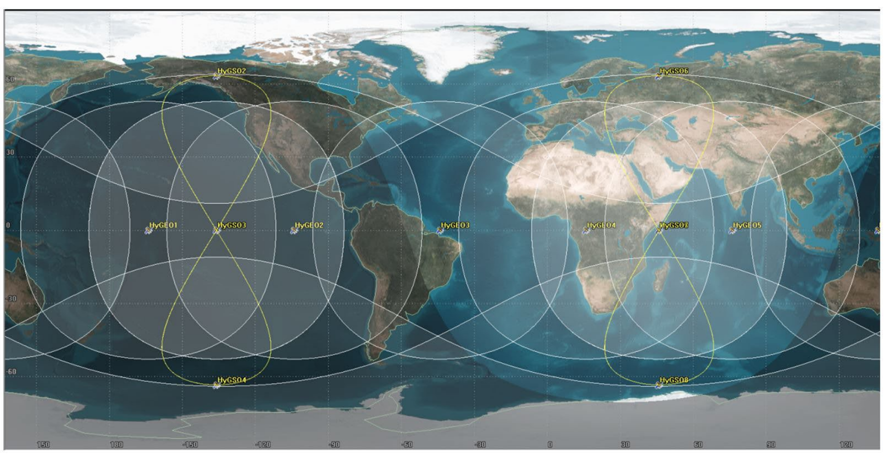

Figure 9: Coverage by 6 GEO stationary and 2 GEO synchronous slots shown in white.

Adjacent GEOstationary payloads will require sufficient LCTs with FOV (Field of View) towards the GEOsynchronous satellites to ensure every one of them has an active OISL at all times. Therefore, either at least one adjacent GEOsatellite is built with 4 additional OISL LCTs with sufficient FOV to cover the complete GEOsynchronous orbits, or both adjacent GEO nodes receive at least three additional OISL LCTs. In the second case, the phasing of the GEOsynchronous satellites needs to be adapted to ensure that only a single handover is required at any time. The required FOV from a GEOstationary satellite to cover the GEOsynchronous orbit in the proposed configuration is shown in Figure 10. Spacecraft coordinate system in this figure is defined as follows: x-axis is aligned with velocity vector of the circular GEO orbit, z-axis aligned with local nadir, and y-axis completes the triad. Azimuth is the angle from x-axis in x-y-plane. Elevation is the angle from the z-axis.

Over the full GEOsynchronous orbit the link distance between the GEOsynchronous satellite and the GEOstationary satellite will vary between 18560 km and 48500 km. As this is well within the designed link range of 60000 km, the full bandwidth foreseen for an individual HydRON OISL link will be available via the GEOsynchronous nodes.

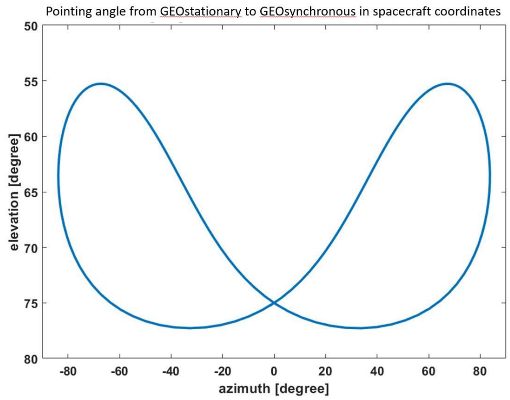

Figure 10: Required pointing angle from GEOstationary node at 16°E to cover a GEOsynchronous node at 46°E.

4. TAS-I RESULTS

Analysis of HydRON benefits and opportunities from the Operators point of view

This HydRON Phase A study was conducted by a consortium primed by TAS-I, including Telespazio, Open Fiber, and Scuola Superiore Sant'Anna. The concept of "fiber in the sky" has been proposed providing preliminary a feasible architecture for the system and the related network implementation. The activity has been started considering and analysing the point-of-view of the possible SNO and TNO. Their representatives in the Consortium have analysed mainly the potential opportunities and benefits that the actual HydRON Network implementation could provide to the market.

The SNO and TNO have identified a set of scenarios and applications in which the HydRON Network can be an interesting and profitable opportunity defining suitable Figures-of-Merit (FoM) that quantify the real benefits (costs performances, complexity end so on). At the end of the study, this has provided a set of recommendations useful for the follow-on and addressing of the future activities to actually implement the HydRON Network. Table 4.1 reports a summary on the benefits and opportunities as above mentioned.

Table 4.1: Summary of the advantages and downsides/grey areas for the SNO and the TNO

Operator	Advantages	Downsides/grey areas
Satellite Network Operator (SNO)	Cost reduction for obtaining and maintaining RF spectrum licenses, also decreasing RF interferences risks with other operators	Latency can be an issue depending on the target service and the HydRON system configuration (orbital position, type of service end so on).
	Cost reduction in the ground segment setup and operations, relaxed availability requirements	Additional complexity on-board and on ground (also including operations) is required, due to technology and Optical Feeder Link/Inter-Satellite Link management.
	Opportunity to use the HydRON feeder link service in place of a dedicated user ground segment, so transforming the relevant CAPEX into a more manageable OPEX	Overall OGS fibre connectivity costs in some ground configurations may be higher than the standard RF approach.
	Opportunity for ground station operators to offer an optical up/downlink ground station (OGS) service to optical satellites	OGS utilization is always very low, meaning that operational costs (maintenance, operations, but also expensive fibre connectivity @ 1 Tbps) have to be sustained even in case the OGS is under-utilized or not utilized at all. Solutions and architectures minimizing the number of required OGS are therefore key for HydRON success.
	Ease of setup of high-throughput long-haul connections.	Limited availability of cheap commercial optical user terminals, especially for MEO/GEO orbits, may have

		impacts on the system design and may limit the adoption of HydRON by end users.
	Increased data exchange security	
	Possibility to perform load balancing and data routing across different payloads, different ground stations and space nodes, even with other operators (federated networks)	
Terrestrial Network Operator (TNO)	Time saving in establishing the physical link between two end-points, due to the fact that the link is not wired but free-space.	Grey area concerning the HydRON system required costs to set up a connectivity service and make it operational.
	Media diversification provided by HydRON can increase the availability of the connectivity service	
	The security on an optical free-space link due to the high link directivity	
	Flexibility provided by the HydRON network in traffic handling can enable to size links not basing on load peaks.	
	New services towards new kinds of final customer and-user represent new business opportunities.	

Proposed HydRON system concept overview

HydRON has been conceived as a space-based optical transport network. As an optical transport network, its main capability is the provisioning of a high data rate communication services TNOs, PNUs, TSOs, and SAUs. In Figure 11, the top level system concept representation summarising the abovementioned system elements is provided. The system architectural solution established for the fulfillment of such capability is composed by:

A HydRON Space Segment including:

- High capacity hybrid (optical-electrical) space nodes, i.e. satellites embarking payloads capable of establishing and maintaining space-to-ground/space-to-space high throughput optical links, and of performing switching/routing at optical carrier level (optical spatial switching); each HydRON space node is characterised by one or more of the following elements: i) optical elements for inter-satellite (including between orbits) optical link connectivity, ii) optical elements for optical feeder link connectivity, iii) optical signal regenerators, iv) on-board optical switching matrix, v) an interface with the Customer payload in case of shared satellite platform (in this use-case, the HydRON payload is a hosted one).
- A management RF link-based network in parallel to the optical one for configuration, control and management purposes of the HydRON space nodes. This dedicated RF infrastructure is implemented by means of the RF Payload Control Link (PCL) subsystem hosted by each HydRON space node.

HydRON Ground Segment including:

- Optical Ground Stations (OGSs) deployed in a set of OGS Networks, each of them behaving as an equivalent single Virtual OGS (VOGS), by applying site diversity schemes to improve GSL availability.
- Interfaces towards the terrestrial Optical Transport Network (OTN) by means of its Point-of-Presence (PoP).
- HydRON Management Control Center implementing all the ground physical/logical entities and functionalities (Site Diversity Control Center, Satellite Flight Dynamics, Optical Link Control Center, Satellite Control Center, OGS Network Control Center, Authentication and Access, Routing Manager) needed to operate the overall HydRON infrastructure.
- RF Ground Stations are needed to feed the PCL on-board each HydRON space node and to gather information from the space segment, interfaced with the HydRON Management Control Center.

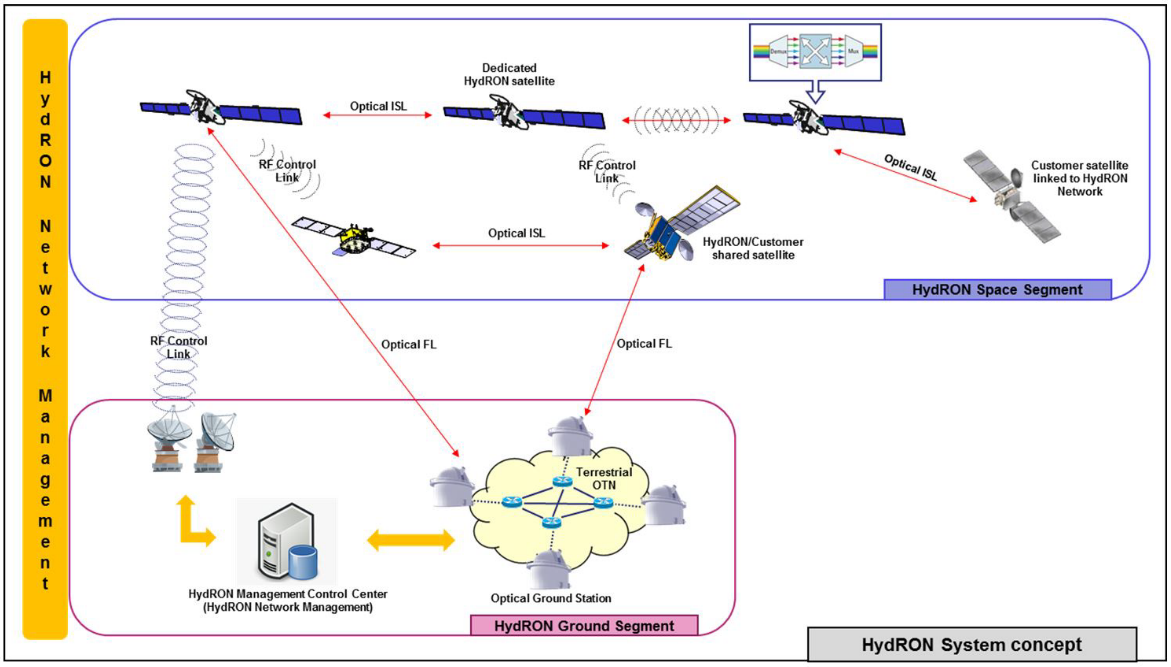

Figure 11: HydRON top level system concept

HydRON baseline architecture

The system analysis addressed during the development of the study led to the identification of a set of possible system architectural solutions differentiated by:

- the space segment orbital configuration; for which the drivers are i) the service coverage to be ensured on ground, ii) the type of customer payloads to be served in space (e.g. customer payloads may be located in GEO, LEO, MEO or HEO orbits), and iii) the user needs and traffic demand (e.g. latency, data rates).
- the payload architecture and capabilities (i.e. optical transparent, hybrid regenerative with optical switching, hybrid regenerative with electrical switching), driven by the optical signal regeneration needs and by the required network functionalities.

The performed architectural trade-offs led to the definition of baseline architecture summarised as in following.

HydRON Space and Ground Segment main outcomes

The space-based OTN service is provided by the HydRON Transport Ring (HTR), a constellation composed by 6 equally spaced satellites in GEOstationary orbit, as represented in Figure 12, connected in a bidirectional ring topology and ensuring a quasi-global coverage between -53° and +53° of latitude, considering that the Field-of-Regard (FoR) of the on-board feeder link optical terminals is characterized by a 7,51° half-cone angle and that the optical feeder link is closed at a minimum elevation angle of 30°.

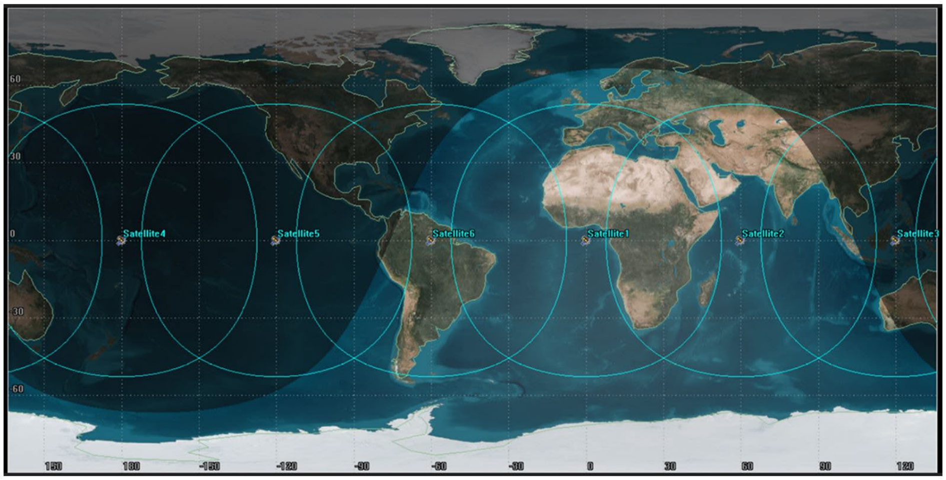

Figure 12: HydRON HTR ground coverage

Regarding the ground segment, the OGS locations have been chosen considering the sites proposed in[7,8] filtered according to their single-site link availability, and the capability to be served by the already in-place terrestrial network infrastructures. The proposed approach for the worldwide deployment of VOGSs is to consider a network of OGS for each continent (Europe, Africa, Asia, Australia, North and South America corresponding to 6 macro VOGSs): the single OGS composing each VOGS are finally selected considering the position of the existing terrestrial infrastructures and the decorrelation of their meteorological conditions. The VOGS dimensioning exercise has been conducted only for Europe case by exploiting the MODIS cloud coverage database retrieved at[9] with 26 OGS placed in moderately weather-correlated locations, a VOGS network availability of 93,33% is achieved (at least 1 OGS is available for 93.33 % of the time in 1 year). However this availability computation suffers from the limits of the considered dataset (i.e. low sample rate, missing samples) and could be highly optimised making use of a more complete/consistent dataset and identifying more weather-decorrelated locations (e.g. in case of optimistic assumption of lowly-uncorrelated OGS locations with a 60% average per-OGS availability, it has been estimated that 8 OGSes suffice to ensure 99.93% of VOGS overall availability).

HydRON satellite and payload main outcomes

Each HydRON GEO satellite comprises a GEO platform, a HydRON GEO payload and a Customer Payload interfaced with the HydRON payload by means of the so called HydRON Piggyback Interface (HPI), a standardised interface providing signal conversion and adaptation from/to the Customer payload.

Focusing on the HydRON payload, the proposed payload baseline architecture is based on a hybrid solution with OEO (Optical Electrical Optical) regeneration and switching performed in the optical domain. As shown in Figure 13, the main payload elements are:

- WDM transparent bidirectional (TX and RX) Optical Heads (OHs);
- Input/Output optical amplifier sections:
  - Low Power Optical Amplifier (LPOA) section (i.e. the low noise pre-amplifier);
  - High Power Optical Amplifier (HPOA) section (i.e. the booster amplifier);
- WDM channels DEMUX and MUX sections ;
- Reconfigurable optical switching matrix (OXC or ROADM);
- Optical harness and fibres to interconnect payload subsystems.
- OEO regeneration stage.

The Section of signal OEO regeneration (2R/3R) is mandatory in order to overcome the issue of the excessive degradation of the OSNR in a multi-hop link propagation and the consequent BER degradation experienced end-to-end.

The OEO regeneration is performed through photonic components (for the O/E and E/O conversion processes) and digital processors (dedicated to the error corrections).

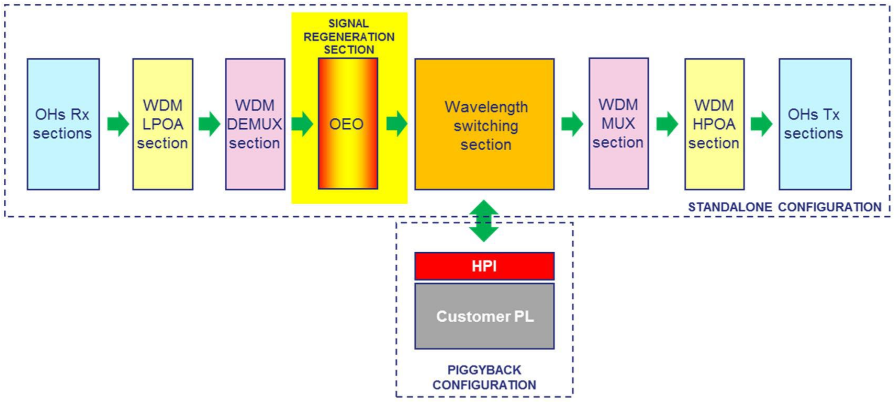

Figure 13: HydRON hybrid payload functional architecture

The multiple on-board FSO communication systems consist in:

- 2 GEO OISL systems, each of one composed by an Optical Head Unit (OHU) and the related Laser Modulator Unit (LMU), for GEO adjacent nodes connectivity;
- 2 GEO OFL systems, each of one composed respectively by 2 OHUs and the related LMUs, for the simultaneous generation of the primary feeder link plus the handover one;
- 1 GEO OIOL system for expandability purposes (i.e. connectivity with satellites at lower orbits, as LEO and MEO).

Communication system preliminary dimensioning

The communication system has been dimensioned in order to be compliant with the wavelength plan defined in the recommendation ITU G.694.1 for terrestrial networks. In particular HydRON will make use of C optical band in order to provide high throughputs and a wide number of optical channels in a DWDM plan equivalent to the one used in the OTN. The optical bandwidth is partitioned in two equal bands, for forward and return wavelengths respectively, with a space bandwidth between these two ones of 15 nm. A 10 Gbps line rate has been selected to reach the throughput of 100 Gbp for each communication direction. Thus, 10 wavelengths (with 0.4 nm of channel spacing) have been considered for each direction (for a total number of 20 wavelengths, corresponding to an aggregated bidirectional traffic capacity of 200 Gbps). An OOK (On-Off Keying) optical modulation together with a BCH coding scheme (at 0.91 code rate) format has been selected as the optical waveform. In order to sustain the above-mentioned data rate, considering an optimized scenario with 0 dB of link margin and a 400 mm satellite Optical Head diameter plus a 600 mm OGS diameter dimensioning, the estimated values of required output optical power at different optical terminals are:

- 55.4 dBm at the OGS terminal;
- 33.7 dBm at GEO OFL terminal;
- 33.5 dBm at GEO OISL terminal.

The choice of 200 Gbps of aggregated traffic capacity is justified by considering the criticalities related to the high optical power levels needed for 1 Terabits/s aggregated capacity scenario (c.a. 60 dBm for the feeder uplink and c.a. 39 dBm for both the feeder downlink and the inter satellite link).

HydRON Management Control Centre (HMCC) main outcomes

HMCC refers synthetically to the whole set of HydRON ground subsystems and functionalities needed to operate the overall HydRON Network. In following all its physical or logical subsystems are listed and developed, explaining for each of them the implemented set of functionalities, while their functional interactions are shown in Figure 14.

- **Site Diversity Control Center (SDCC)**: monitoring of weather and turbulence condition for each individual

OGS, correlating information from different sources (on-site monitoring data, weather forecast, satellite imagery, …). As outcome, SDCC produces the OGS status, continuously updated with the availability and related forecasts for each OGS in the network.

- **Satellite Flight Dynamics (SFD)**: evaluating satellite's position and velocity, visibility with OGS, visibility with other satellites. As outcome, SFD produces OGS schedule (predicts OGS visibility for each satellite) and Satellite schedule (predicts for each satellites its visibility with the others).
- **Optical Feeder Link Control Center (OFLCC)**: it takes as input the real time OGS Status from SDCC and the OGS Schedule from SFD to identify, at any time within the forecast window, the OGS that are/will be available for establishing the OFL (Optical Feeder Link) within a single VOGS (i.e. OGS network). It provides the OFL assignment schedule (renewed dynamically with the real time updates from SFD and SDCC) and allowing seamless handover procedures. For what concern ISL/IOL (Inter-Satellite Link/Inter-Orbit Link) establishment, it considers only the Satellite schedule from SFD and produces the OISL/OIOL assignment schedule to establish the right links (in general the visibility between two satellites to be connected by OISL/OIOL can be time-limited). In both cases, (OFL and ISL/OIOL set up) OFLCC must take in account also the information provided by Routing Manager, communicating the HydRON nodes (VOGS on ground and satellite in space) involved in the E2E lightpath.
- **Satellite Control Center (SCC)**: control and monitoring of HydRON satellites operations via radio TM/TC (TeleMetry/TeleCommand) (space segment configuration) on the basis of the schedules received by OFLCC:

  - Optical terminals configuration

  - Switching matrix configuration

  - On-board optical sources, CODEC and MODEM control;

  - Space interfaces configuration (optical MODCOD configuration)

  SCC provides also satellite ranging and Doppler measurements/evaluation to the SFD. In addition, SCC collects telemetries from in-space network nodes to monitor their health status and failure detection (these collected telemetries are provided to OFLCC and so to Routing manager for recovery and re-routing purpose).

- **OGS Network Control Center (OGS NCC)**: control and monitoring of HydRON OGS Network (HydRON optical terrestrial network/ground segment configuration) on the basis of the schedules received by OFLCC:

  - OGS activation/deactivation and configuration;

  - Monitor and change the setup of the Internal routing functions (within the OGS network constituting the VOGS) in order to forward/collect user data streams to/from active OGS and to/from user on-ground interface;

  - Ground interfaces configuration (optical MODCOD configuration).

In addition, OGS NCC collects telemetries form on-ground network nodes to monitor their health status and failure detection (these collected telemetries are provided to OFLCC and so to Routing manager for recovery and re-routing purpose).

- **Access and connectivity control center (AC-CC)**: it provides access to the HydRON network by means of Users Authentication (only allowed users can access HydRON services and assets) and Authorization (different kinds of users can obtain different classes of services). It gathers information on the user data to be transmitted (end-points of the connection, amount of data to be transmitted, connectivity features or constraints e.g. latency, frame loss rate, …) useful for routing planning. It is in charge of creating and real-time updating of a database (HCDB, HydRON Customer Data Base) containing information about customer and their I/Fs, data coming from accounting process (operations including monitoring the network resource consumption by users, the amount of time attached, the amount of data transmitted and soon, authorization control, finalized to allow billing and to obtain trend analysis, resource utilization and capacity planning activities) for billing and management purposes.
- **Routing manager**: on the basis of the information gathered from Access and Connectivity Control Centre (AC-CC) and Optical Feeder Link Control Centre (OFLCC), the Router Manager selects the E2E lightpath and the assigned wavelengths to implement the user-requested connectivity (User data path), recalculating when needed. It is also

responsible for creating and real-time updating a database, HNDB (HydRON Network Data Base) containing detailed network information. The Routing Manager also is in charge of the E2E network QoS monitoring by gathering measurement and telemetries over the network (provided by OFLCC), evaluating appropriate service performances parameters (KPIs) and processing them to detect underperformances, underservices and faults, and pushing the reactions of the network.

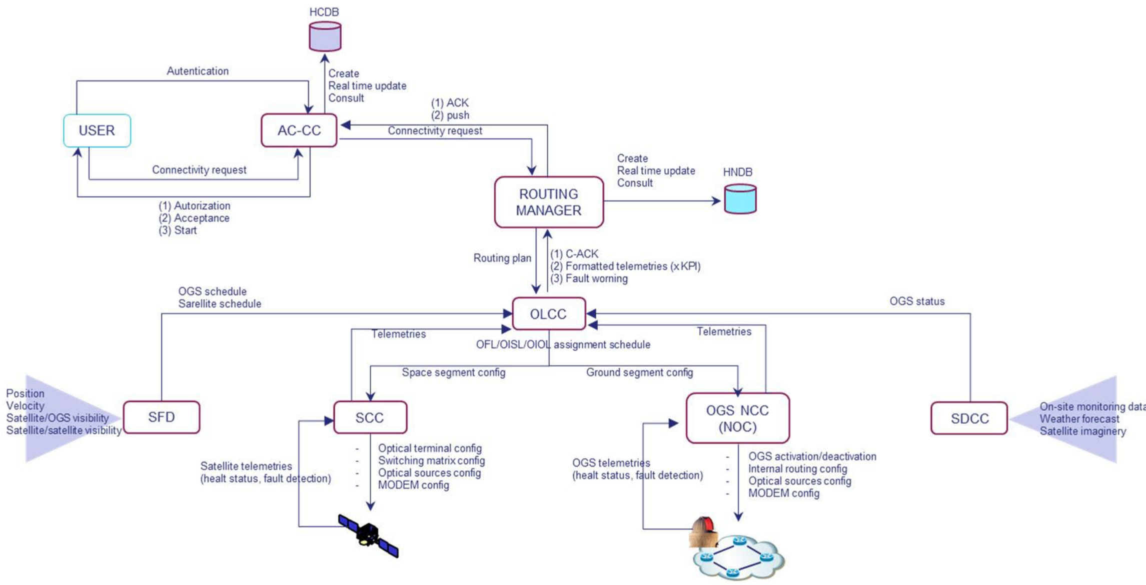

Figure 14: Interaction between HydRON control ground elements

5. TOWARDS HYDRON DS

The implementation of the full HydRON concept (i.e., HydRON Vision) is considered beyond the scope of the HydRON Project. Instead, the objective of the HydRON Project is to define, develop, and validate a representative HydRON Demonstration System (HydRON-DS) reducing the complexity of a full system to a set of key elements. Accordingly, two parallel studies have been initiated with ADS and TAS-I for the Phase A/B1 (Definition Phase) of the HydRON DS in early 2022. These studies are expected to be completed in mid-2023. Then, conditional to the approval from the ESA Council of Ministers in November 2022, Phase B2/C/D/E (Development Phase) of HydRON DS will begin in 2023 with in-orbit demonstrations planned at the end of 2026.

At a very high level, HydRON DS has three objectives. First objective is the in-orbit verification in an end-to-end demonstration of critical technologies and functionalities including on-board routing, WDM OISLs, Virtual OGS concept, OGS switchover/handover, and optimal control and management of all space and ground assets. Second objective is the in-orbit validation of operational concepts in support of a service demonstration. Such validations include network expandability, seamless integration with terrestrial networks, and verification that Key Performance Indicators can be met. Finally, the third objective is the provision of a precursor service demonstration addressing – at least – two types of HydRON users.

The current technical baseline described in figure 15 can be broken down into a Space Segment with payloads in GEO and LEO acting as nodes in a network, embarked on either third-party or on dedicated platforms. A GEO node of HydRON DS will embark optical terminals for GEO-ground connectivity. for space-to-space connectivity as well as for short/mid-distance network expandability to a co-located GEO. Further it will feature a digital interface with a user payload located on the same GEO platform as well as an router for on-board circuit switching. The LEO payload will be similar, with smaller and fewer optical terminals, but an additional mass memory formatting unit with a high data rate interface to serve airborne users or LEO users.

The Ground Segment of the current baseline is composed of four OGS, with three fixed OGS networked to form an Optical Ground Network (OGN) to implements site diversity against detrimental weather conditions (clouds, aerosol, turbulence). The transportable OGS is a low-cost version of the fixed stations, purpose-designed to test and validate future commercial usage and locations. A dedicated Control Centre will orchestrate all the elements of the HydRON-DS space and ground segments, as well as the interface with users for service demonstration.

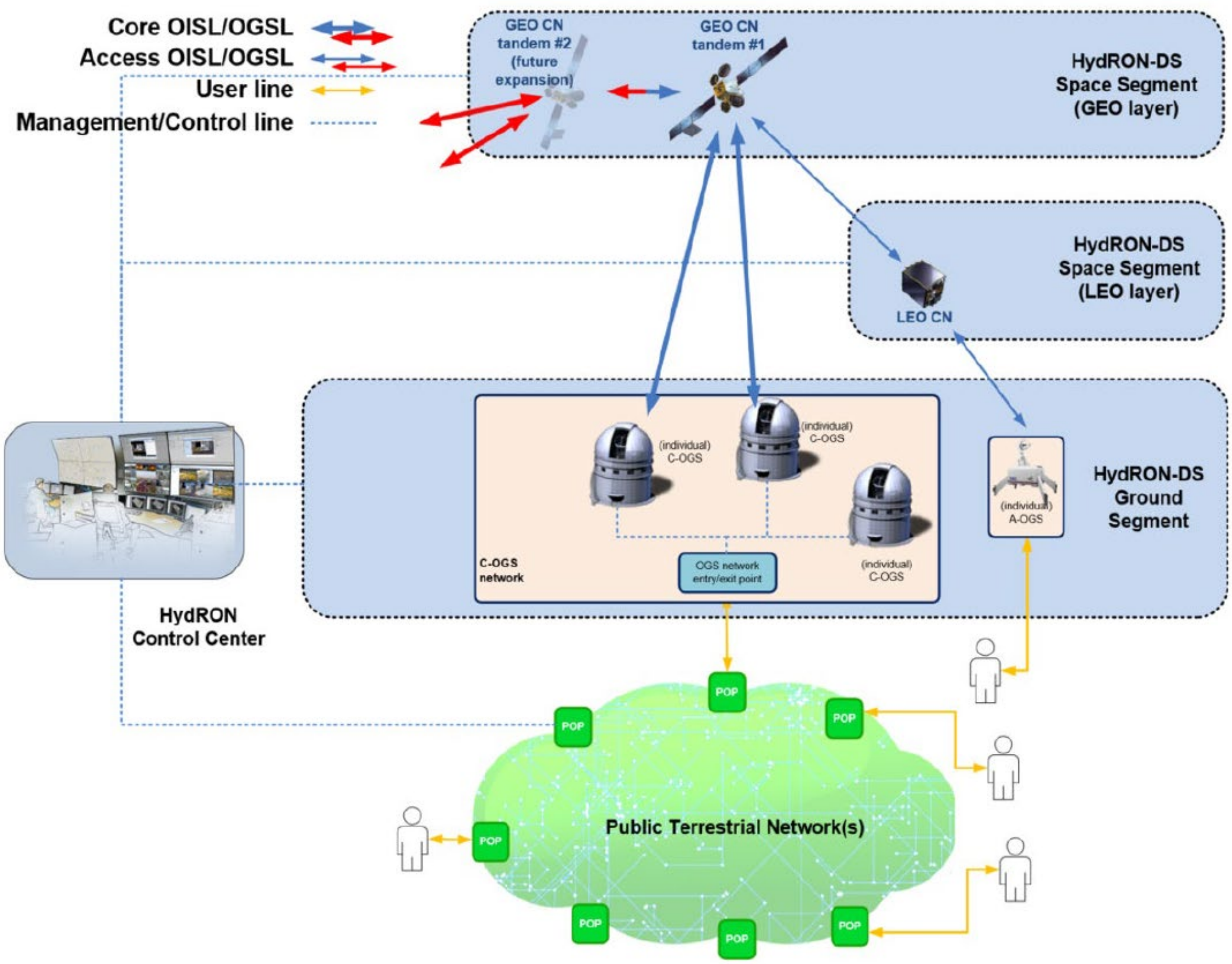

Figure 15: Technical Baseline of HydRON DS Proposal. The Space Segment consists of two co-located GEO payloads, a payload in LEO orbit as well as of Ground Segment with a total of four OGS. The HydRON Control Centre orchestrates all the HydRON DS elements, as well as the interface with users for service demonstration

6. CONCLUSIONS

This paper presented a description of the ESA HydRON Project with emphasis on the high-level description of the HydRON Vision and the outcomes of the two HydRON Phase-A studies, which were completed at the end of 2021. These two studies were conducted by consortia led by ADS and TAS-I, respectively.

The consortium led by ADS derived a potential HydRON system configuration based on Terabits/s transmission rate optical links with a range of up to 60.000km. It is proposed to initially build a GEO ring of 6 nodes, distributed in 60° steps on the GEO ring. In order to implement this ring, collaboration between organisations, acting today as competitors, is required. At a later stage this ring can be extended for persistent coverage, including high latitudes, by either a LEO constellation, or by a adding 2 nodes of 4 spacecrafts each in GEOsynchronous orbits with inclination of 63.4°.

The consortium led by TAS-I defined a baseline system architecture for HydRON that consists of a ring of 6 GEOstationary satellites. It also provided the outcomes of the investigations regarding HydRON benefits and disadvantages from the perspectives of Satellite Network Operators and Telecom Network Operators. The study by TAS-I defined in detail the HydRON network management and control architecture. In addition, a GSL availability of 93.33% has been computed using 26 OGSes selected from MODIS database. Moreover, a preliminary system dimensioning has been conducted concluding it the need for 55.4 dBm, 33.7 dBm, and 33.5 dBM transmission powers at OGS uplink, GEO feeder downlink, and GEO inter-satellite link, respectively, for a 100 Gbps transmission rate. For a 500 Gbps transmission rate, the required transmission powers are c.a. 60 dBm for the feeder uplink and c.a. 39 dBm for both the feeder downlink and the inter satellite link. The consortium also presented a ground segment architecture for the HydRON system.

Based on these studies, ESA consulted with internal stakeholders and participating Member States to the HydRON project to propose a technical baseline of the HydRON DS. This proposal will be subject of funding decisions at the ESA Council Ministerial in November 2022.

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