A Multibeam Lens Antenna for In-Flight Applications Using High Throughput Satellite Systems at V-band

Behzad Koosha* | Omid Manoochehri | Hermann J. Helgert

Electrical & Computer Engineering
Department, George Washington University,
Washington, DC, USA

Correspondence
*Behzad Koosha, 800 22nd street NW,
5000 Science & Engineering Hall,
Washington, DC 20052
Email: bkoosha@gwu.edu

The Q/V band communication systems open new avenues for next generation of High Throughput Satellite (HTS) systems. More specifically, they are attractive due to their high bandwidth for user and gateway links. Having a wide bandwidth at Q/V band makes it permissible to offload the links between the satellite and its earth station hubs (gateway) from the Ka band to the Q/V band. This enables additional bandwidth available for HTS feeder links and user links of specific market verticals, which in turn results in reduction of cost per bit. In this paper, we are going to discuss different aspects of an In-Flight Connectivity (IFC) scheme for HTS. Developing a wideband and multibeam antenna is an essential part of this proposed system, which is also going to be discussed in this paper.
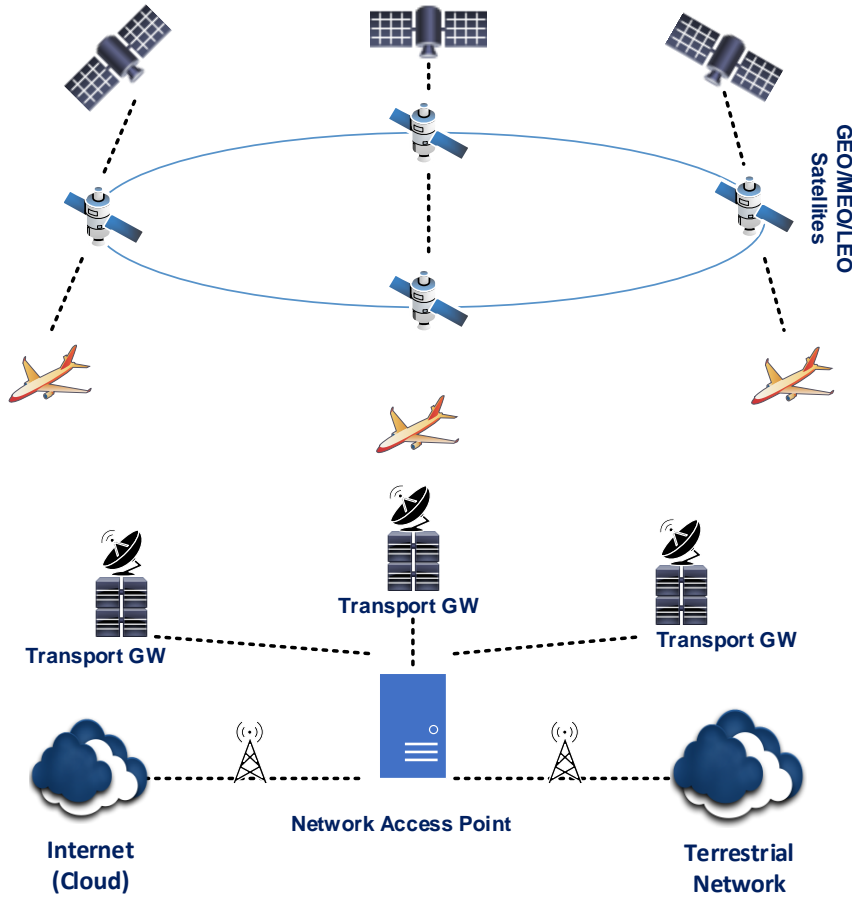
KEYWORDS:
High Throughput Satellite (HTS), In-Flight Connectivity (IFC), Spot Beam, Link Availability

1 | INTRODUCTION

In the last decade, the aviation industry demanded satellite operators to provide reliable and easily accessed WiFi connectivity between aircraft system and passenger devices. In addition to messaging and streaming for the passengers in the cabin, airlines are increasingly interested in the role of WiFi-enabled data transfer for applications such as aircraft health monitoring, safety services, in-flight planning and crew communications[1]. The IFC ecosystem consists of three major components: the satellite technology, the hardware onboard of the aircraft and the service & support on the ground. HTS communications can provide seamless global coverage to support any mission. Today Ku-band (12-18 GHz) frequency is dominantly deployed, while in some regions Ka-band (26-40 GHz) frequency are used. Ka and Ku-bands can deliver peak data rates of up to 50 Mbps through regular and steerable spot beams, answering demands when and where it's required. In recent years, service providers have been advocating for HTS networks to accommodate Terabit speeds. Advancing the feeder links from existing Ka and Ku-bands to Q and V-band would result in raising the overall network capacity and reducing the number of active gateways at the same time. Q/V band can offer greater bandwidths for feeder links to the satellites for future communications and cellular backhaul applications to enhance quality of service with massive throughputs. GEO and NGSO operators use this new frequency for delivering exceptional services to fixed terminal users and mobile users in recent years. Every IFC approach has practical limitations based on the route being served, aircraft type and technology used for that mission. For a specific airline, the flight routes might vary based on the season and traffic demand.

The satellite operator and airline WiFi integrator provide broadband IFC over regions where they have license to use Q-band (33-50 GHz) and V-band (40 to 75 GHz) frequencies. The European commission funded project QV-LIFT, proposes technology awareness in multiple related fields. A proposed solution for network gateway is to deploy stand-by or backup gateways to direct traffic in case of outage or link performance issues due to signal propagation in the frequency bands. The system is designed to

FIGURE 1 System mobility overview with GEO/MEO/LEO constellation

be resilient to any fading that can result in an outage. The common N+P gateway architecture is used where N is the number of active gateways in the system and P is the number of redundant (stand-by) gateways. The redundant gateways join the network once any of the active gateway experiences fading. By deploying this configuration Q-V band feeder links would support remote terminals on the ground or any aeronautical terminals using those frequencies[2].

The main goal for all major airlines that provide IFC is to elevate the vast capabilities of broadband satellite communications and monetize the flexibility of digital steerable spot beams and phased array antennas on the airplane to offer Internet service on-board the aircraft from source to destination. Prior to 2008, Air-To-Ground (ATG) solutions were deployed. This two way communication between the airplane and ground locations had limited coverage and used Ultra High Frequency (UHF) 450-952 MHz and Very High Frequency (VHF) 49-216 MHz that required two antennas installed on the belly of the aircraft to transmit or receive signals from the ground-based cellular towers. The speeds were limited and hand-offs were lengthy and delayed. With the introduction of Ka-band and Ku-band over HTS in early 2013 and the launch of 2Ku antenna technology, a new horizon had emerged for the IFC in the aeronautical industry for commercial aviation[3].

The challenge with user links in HTS is the frequency re-use through the spot beams and on the satellite Earth station gateway is the optical feeder links which will be managed by using Transport Gateway (TGW) located in each regional location. As shown in Fig. 1, a hybrid constellation of HTS system with different links can be considered where it is connected through terrestrial network via the Network Access Point (NAP). Implementing this approach will result in smoother transition between each constellation during the flight duration[4],[5].

Three major achievements could be summarized below:

1. Q/V dual band antenna can deliver seamless speeds up to 400 Mbps total to each aircraft while above 10,000 feet subject to link availability.

2. Improved uploads consisting of very high throughput for up-linking data traffic for applications such as Skype, FaceTime and live streaming.

3. Compatibility with any existing infrastructure from wide beam to steerable spot beam technology.

This study addresses the challenges when adopting a framework for different Earth constellations and how to mitigate those obstacles. The proposed system offers a range of operations for optimized traffic capacity, terminal performance, gateway design and network management as described in the following sections.

A multi-beam, high-gain, wideband and compact antenna is an essential part of a Q/V band communication system. In addition to the previous system analysis, a highly directional lens antenna for a satellite communication system at V band (40 GHz to 50 GHz) is proposed. The antenna is designed based on Luneburg lens structure fed by 16 element spectrum wide-band horns. The septum horn antennas are designed to transmit right and left hand circular polarization (RHCP and LHCP). Each horn has 8 *dBi* gain with -13 *dB* Side Lobe Level (SLL) and less than -10 *dB* S11 in the whole frequency band. By using the lens antenna, the overall gain increases to 26 *dBi* and SLL drops to -21 *dB*. The proposed system can be used for satellite tracking systems in V band. Simulation results are calculated and presented using CST software.

The paper is structured by going over the system architecture and the Network Management System (NMS) involved for aeronautical IFC applications. Then we present the gateway platform used for this solution followed by the Performance Evaluation section for link budget analysis over the flight route.
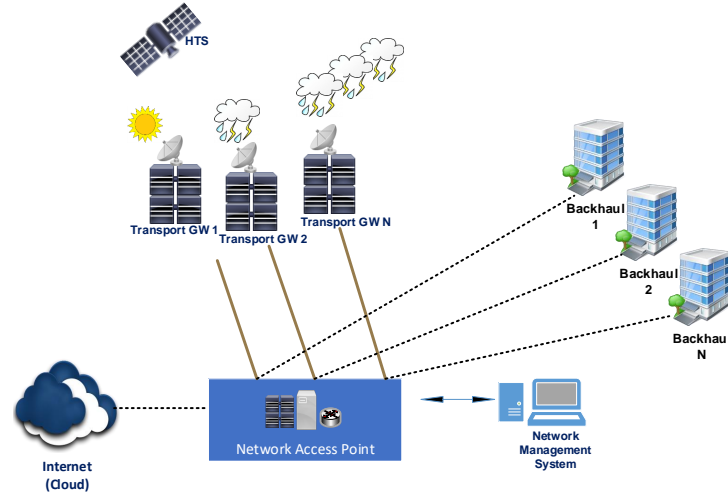
2 | SYSTEM ARCHITECTURE

Some analyses have been proposed for overall architecture design of aeronautical networks and satellite systems. Some studies have focused on the capabilities for these aeronautical networks being compatible for exchanging data between different satellite orbit constellations. Using beam hopping techniques some dynamic traffic allocation has been proposed to enhance the network performance[6],[7]. Nevertheless, the main challenge is the algorithm that assigns the illumination plan and coordinates with the NMS. Studies have shown both non-beam hopping and hybrid beam-hopping HTS systems which use optimization techniques to demonstrate the overall capacity demands and power limitations[8],[9]. In this study, we will be delivering a hybrid architecture design for satellite systems which incorporates high throughput links between satellite gateways and feeder links for microwave backhaul.

With the proposed topology, supporting extremely high data rates for advanced connectivity and tracking purposes could be achieved. GEO, MEO and LEO constellation satellites can smartly communicate and deliver on this promise where they provide Ultra High Definition (UHD) content broadcasting with High Efficiency Video Coding (HEVC) standards which offers improved compression rates. Lately, businesses are investing heavily in MEO and LEO constellations and supporting very latency sensitive applications such as gaming or voice over IP[10]. These constellations can support backhaul networks to comply with low latency requirements and deliver seamless throughput[7].

Canadian-based Telesat has recently introduced the fleet of next generation LEO constellation, Lightspeed, as the most advanced, innovative broadband satellite network ever designed. Lightspeed constellation has been optimized for the fast growing broadband market of fixed and mobility verticals. Another example is SpaceX which is deploying their Starlink global connectivity constellation in the LEO orbit to provide high speed and low latency broadband access. Currently user terminals can receive up to 100 Mbps download speeds with 30 msec roundtrip latency. The future plan is to launch thousands of satellites for providing global coverage and reaching 10 Gbps download speeds. In order to achieve this goal, there needs to be path diversity and routing protocols between Starlink satellites and ground gateways to advance higher throughputs.

Fig. 2 demonstrates how multiple transport Gateways (GW) communicate with backhaul vendors through the NAP and the NMS. The NAP can calculate channel status at different GWs and analyze live and near future weather forecasts for each geographical location. There are techniques proposed that can result in the number of active GWs[6]. In addition, the NMS would determine switching procedures to smartly and efficiently optimize other necessary factors such as inbound/outbound traffic and potential handover durations between the ground GWs.

FIGURE 2 Mobility Ground System with multiple backhauls connected to the Network Access Point

All this data can be distributed on the cloud to geo-graphically compensate rain fade and potential natural disasters. The end to end link is designed to have noise plus interference contributors on the user side of the remote terminals compensated. Uplink power control is used at each gateway to reduce interference from an unfaded gateway uplink into a separate and faded gateway uplink, with very little impact to the clear sky end to end carrier to noise ratio. The proposed solution also can provide backhaul connection to several satellite-based ground networks using a mesh or star topology.

The proposed ground network has multiple gateways scattered across the country and these gateways will be chosen based on geographical diversity and regional landscape. The optimum location of gateways should result in compensating rain fading that can be caused in Q/V band degradation. Having multiple standby gateways in the system will result in network resiliency from unexpected outage or channel degradation. As shown in Figure 3, if there's precipitation close to a gateway, then the stand-by hub could be activated and rolled into the network without interruption to the users.

For instance, we can resemble severe weather conditions or traffic outage over the operating gateway(s) and analyze overall system performance and verify how gateways compensate in the overall network resiliency. Using a hybrid constellation with transport gateways can accelerate switch times between various spot beams[11].
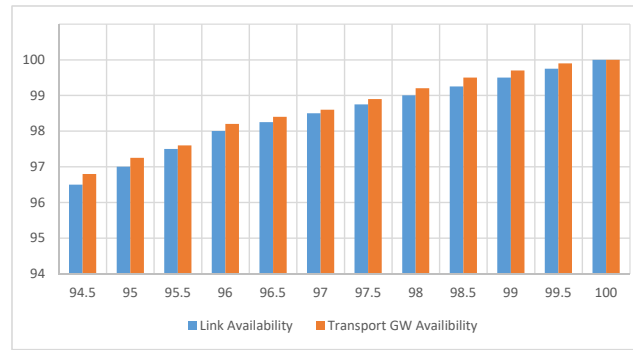
The proposed system could be extended towards N+P model and understand how the stand-by gateway contributes to any weather conditions or failure in the operating gateways. Another advantage of this solution would be to review handoffs between adjacent gateways, while observing mobility applications in the Q/V bands. In the Performance Evaluation section, we have validated this scenario for multiple user beams across the Caribbean for an aeronautical mobile satellite system. The evaluation of link performance in V band frequency using a lens antenna has been presented.

In addition, the delay can be mitigated at the user gateway by using a 5G relay node which is equipped with Global Navigation Satellite System (GNSS) that provides autonomous geo-spatial location position throughout the globe which would facilitate airlines for tracking purposes[12]. As shown in Fig. 3, the target annual remote link availability for V-band varies between 94.5% to 99.5% when a N+P gateway architecture is deployed. In general, this link availability will increase as transport gateway availability expands. For comparison purposes, a 99.5% link availability equals to about 220 minutes (3 hours and 40 minutes) outage per month. In order to achieve higher service level agreement, a higher link availability on the gateway and RF link would be desired.

3 | NETWORK ARCHITECTURE

A high-level network architecture diagram is illustrated in Fig. 4 with major network components and the intercommunication among them. The gateways which can be fully automated or supervised manually in any scenario are located at various geographical locations to provide diversity on the ground infrastructure. Each gateway consists of multiple elements including switches

FIGURE 3 Transport gateway availability % vs link availability %

and routers which interconnects to the backhaul infrastructure. There are outroute and inroute modulators and demodulators in the gateway to handle radio frequency signal conversion from Q/V band to baseband.

The network can support DVB-S2, DVB-S2X as well as legacy DVB-S and DVB-DSNG standards [1]. A range of modulations from QPSK, 8PSK and 16APSK are supported. The backhaul is connected to one or multiple data centers; quantity is dependent on the computation level complexity of the system. Each data center includes two main structure. First the Transport component which operates as a bandwidth manager and second the networking layer which includes all the IP gateways. In this design we have a network IP Gateway (IPGW) in addition to an aeronautical IPGW, which through switching can connect to a public/private network of choice [13].

The IPGWs are structured in a pattern to optimize high-density architecture and minimize floor space noise level which reduces overall power consumption. Each mentioned IPGW provides full automatic redundancy for all traffic-carrying components and is designed for stand-by operations. Each gateway receives user traffic destined for terminals from these data centers via the terrestrial backhaul network and sends the traffic via the satellite links to the user terminals. In the return direction, the gateway receives traffic from user terminals and sends it to the data centers through the backhaul network [14]. In addition to the management traffic switches, another feature that the gateway has to interact with is the element manager for alarm handling. The central NMS configures, balances and optimizes this activity in addition to assessment of the entire protocol stack.
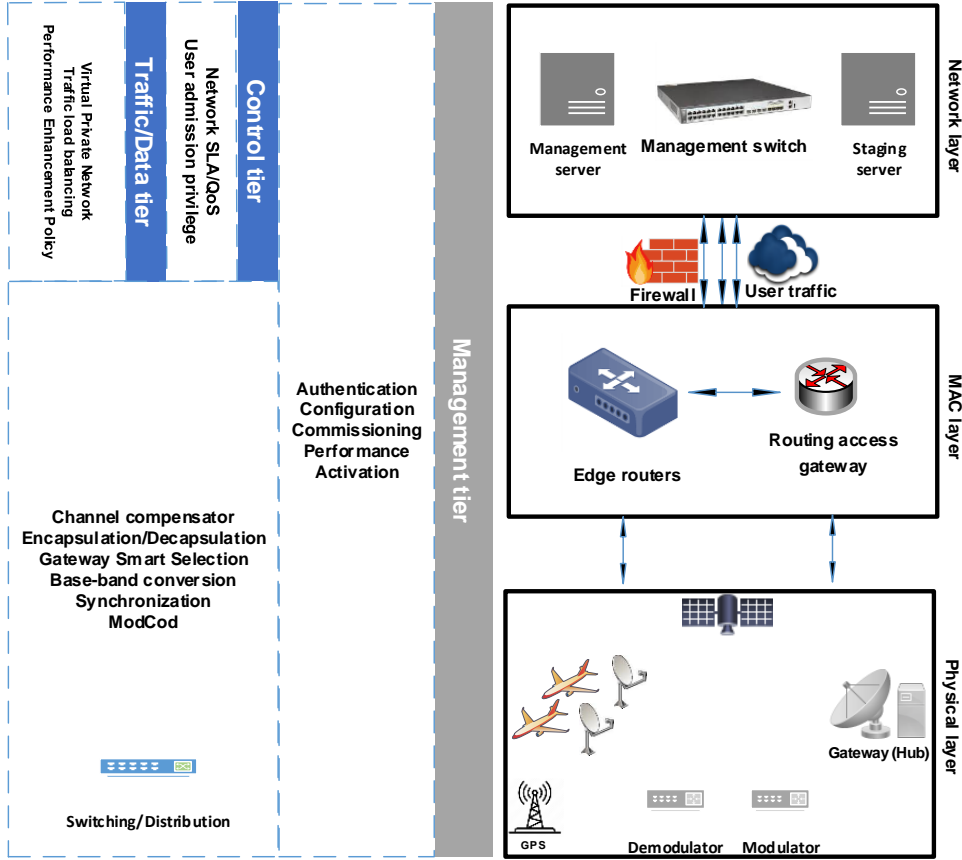
As illustrated in Fig. 4, the NMS provides authentication and security management as well as any configuration, commissioning or performance overview on all the layers shown. The control tier overviews network service level agreement metrics to meet pre-defined and established quality of service. Finally, the data tier would focus on the users (fixed on the ground or mobile over air/water) distributed across the satellite coverage region. This tier contributes to routing, multicast, virtual private network, load balancing and any policies related to performance enhancement.

4 | GATEWAY PLATFORM

The HTS inter-connected data center platforms are designed to use a high-density architecture to optimize physical space and power consumption by utilizing high performance multi-core servers. These data centers provide a comprehensive automatic redundancy for all traffic carrying components and is designed for mobile and fixed user applications. The data center receives user traffic destined for user terminals from the Internet via a terrestrial link and sends the traffic to the gateway illustrated in Fig. 5. In the return direction, the data center receives traffic from the gateways and sends it back via a terrestrial link to the Internet [15].

An approach which can be used to pick the set of active gateways from the pool of potential stand-by gateway is to optimize the ground stations on the existing terrestrial backhaul. The goal is to minimize cost of deployment and data traffic routing while meeting connectivity to all user and making sure latency is minimum across the network. Using Integer Linear Programming (ILP) we have formulated the optimization method discussed below. Two assumptions are considered here: a) maximum

---

[1]https://www.etsi.org/technologies/dvb-s-s2

FIGURE 4 Architecture for the Network Management System

latency is capped at 380 msec one-way and b) each gateway has a maximum capacity of 1500 user traffics that it can handle simultaneously.

The ground gateway constellation is modeled as a graph $G(V,E)$ where links *(l)* and nodes *(n)* $\in E$ whenever a link between the gateway node is established *(l,n)* $\in V$. All sets of nodes for the terrestrial gateway (active and stand-by) are shown by $S \subseteq V$ and $R \subseteq V$ are the set of available and active nodes in the network. The subset node $n \in V$ satisfies the following conditions:
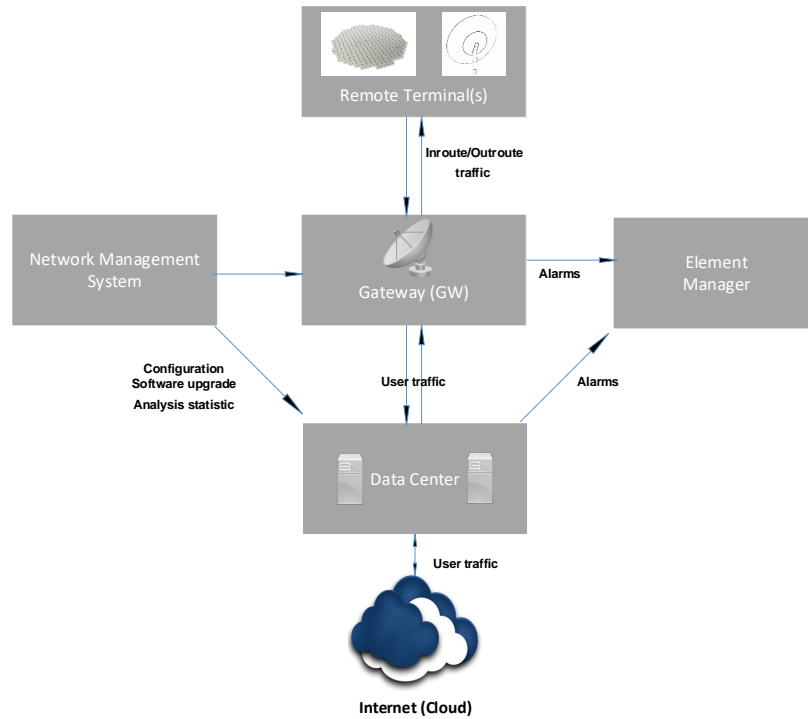
∗ Gateway node *n* is actively connected to the satellite network at a given time

∗ Gateway node *n* sends user traffic of nodes to potential gateways selected by the algorithm

The algorithm will optimize a sub-set of gateways which will be the most cost-efficient in terms of deployment and availability for routing user traffic in the ground infrastructure using any satellite constellation. The ILP function objective is described as:

$$\text{minimize} \quad \sum_{i \in S} C_i X_i \quad \text{subject to} \sum_{i \in S} T_i = 1 \quad T_i \leq X_i \quad \forall i \in S$$

Where T is portion fo user traffic going through the selected gateway. Gateway selection at node i is conditional to traffic passing via sub-set T_i. The optimization minimizes overall cost in terms of a) deployment and maintenance of gateway infrastructure (active and stand-by) and b) achieves network coverage from the source to destination through the terrestrial network. The propagation delays are calculated according to the link distance with propagation speed of $C = 2X10^8$ used in [16].

It's worth mentioning that usually the burst uplink data requests traffic with less bandwidth where the lengthier and steadier user traffic downlink requires a lot more bandwidth. The characteristic of traffic for the proposed solution can be obtained via operational scenarios in the Performance Evaluation section.
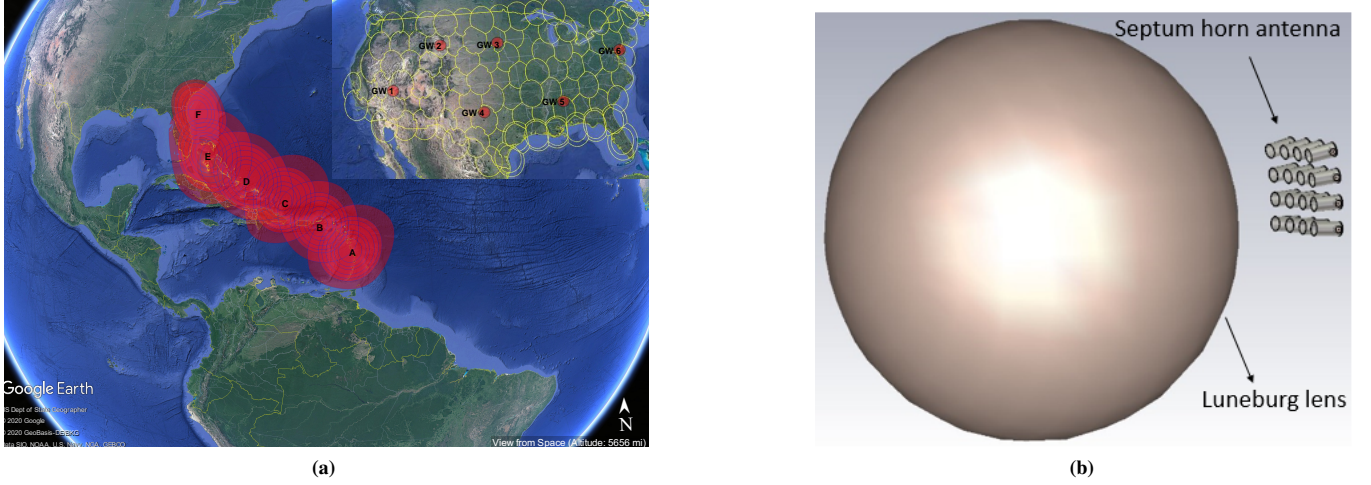
FIGURE 5 Gateway Platform Architecture

5 | NETWORK MANAGEMENT SYSTEM (NMS)

The NMS comprises of a central Manager of Managers (MoM) at the Network Control Center (NCC) with the following services:

- Authentication

- Commissioning and terminal activation

- Comprehensive configuration

- Fault, performance, security and accounting management for remote terminals and gateways

- Distributed management agents within gateways to ensure the autonomous management of terminals subordinate to that gateway

In addition, systems at the NCC provide centralized carrier monitoring and remote terminal performance verification. The NMS can be scaled up to support single or multi constellation networks. It provides browser and provisioning API access for a Host Network Operator (HNO), as well as Virtual Network Operators (VNOs) that use host-provided bandwidth to run their applications. The NMS supports secure access to the Operations Support System (OSS) and the Business Services System (BSS) in parallel.

Enhanced solution of NMS can provide element management for platform components and orchestration for Software Defined Network (SDN) and Network Functions Virtualization (NFV) applications. In addition, it operates as an intermediate solution for integration with an external OSS. The management application provides a comprehensive set of service functionalities towards the provisioning of network level service parameters, service tiers, user terminal location, real-time terminal monitoring and network diagnostics. The dynamic carrier reconfiguration feature adjusts forward and return frequency plan reconfiguration as soon as there's a change of carrier sizes. The NMS interfacing with the gateway platform, communicates scheduled plan updates in real-time. The gateway platform propagates the new carrier plan to the respective gateway control for implementation. This

FIGURE 6 a) user spot beams across the Caribbean and the gateways in mainland US
b) Spherical dielectric with 16 horn antennas for feeding

dynamic carrier sizing feature also provides support for $N+P$ diversity. This method is implemented as part of the overall NMS platform design. Another feature that the NMS is in charge for is the communication between the active gateway stations and stand-by gateways using a mesh type topology as well as a centralized gateway through the satellite for any service to gain access to the shared network/cloud and terrestrial networks. A typical scenario is an Internet access request from a user in a remote location where the baseband level will determine which ground gateway handles the requests based on traffic load balancing and routing optimization techniques discussed in the previous section.
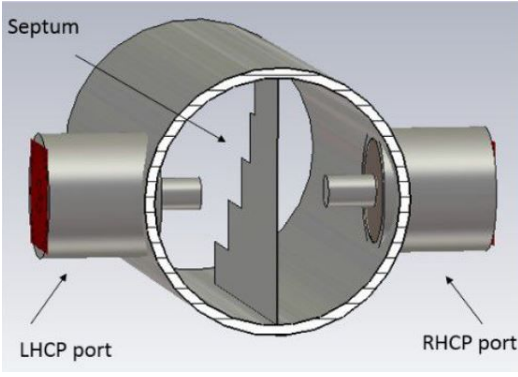
6 | ANTENNA DESIGN

As shown in Fig. 6a link to the gateway is established by multiple spot beams illuminating a relatively large region over the Caribbean. An efficient communication through spot beams needs a re-configurable antenna with selective directional beams and low SLL, which is proposed in this section. The advantage of using re-configurable antenna is light weight, low interference and high C/N for communication systems. High Altitude Platforms (HAPs) are used to deliver various communication systems. Communications On-the-Move (COTM) systems that deploy satellite networks can be considered one of the other applications of the proposed systems because it provides high communication data rates[17].
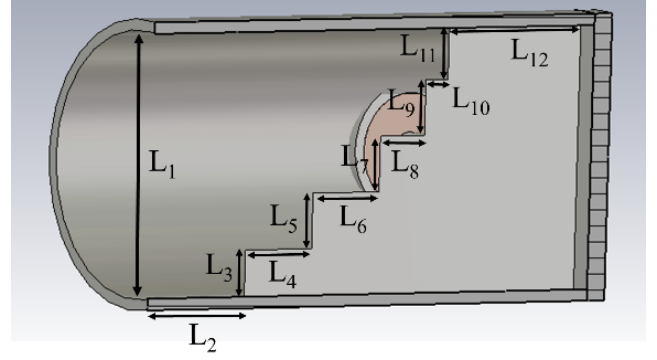
Reflector antenna can be used instead of the lens antennas but the size of reflectors is the main limitation factor versus Luneburg or Rotman lens antennas. Therefore, a miniaturized antenna like a Luneburg lens can be a good candidate for maritime or aeronautical applications in the satellite communications. Many types of lens structures can be used to create multi-beam systems that have their feeding networks placed around the lens. Another advantage of using the Luneburg lens antenna is having pencil or fan beams based on the required applications. A Luneburg lens consist of a spherical low loss dielectric with a gradual permittivity from two at the center of the sphere to one on its surface. Each point of the sphere can be an ideal Luneburg focal point for parallel radiation on another side of the lens. Luneburg lenses have refractive index (n) profiles given by the relation below:
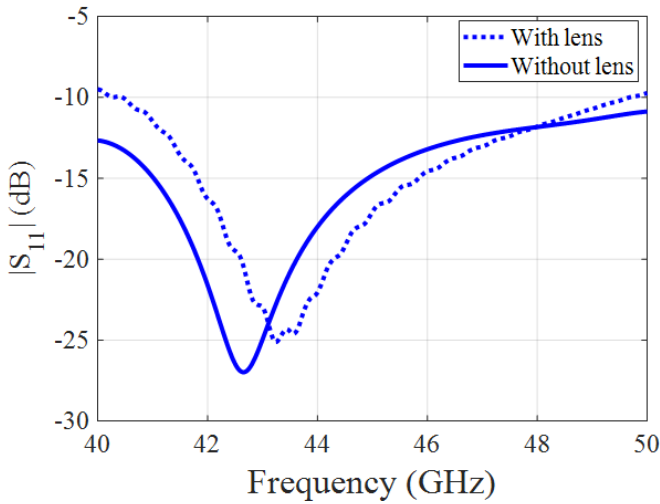
$$n(r) = \sqrt{2 - (\frac{r}{R})^2}$$

Where R is the Radius of the lens sphere and r is the distance from the core center. The lens dielectric is low loss Teflon and has relative permittivity of $\epsilon_r = 2.2$ and loss tangent $\delta = 0.0005$. The cost of fabrication is much less than multi-layer Luneburg lenses. Low loss dielectric can be used to achieve higher gains and lower SLL for the antenna on the transponder of the satellite in any constellation[18].
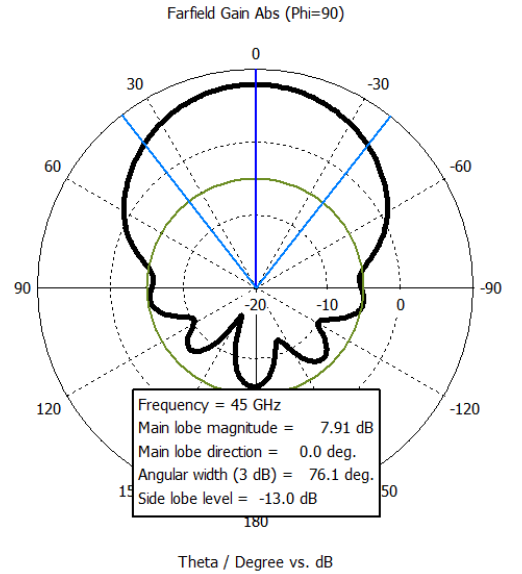
(a) Structure of the septum horn antenna

(b) Dimensions for the septum horn antenna

(c) S11 (dB) with and without dielectric

(d) Antenna radiation pattern in the center frequency (45 GHz)

FIGURE 7 The configuration of the proposed antenna, scattering parameters & radiation pattern

Because of the cost and complexity in fabrication process, a single layer dielectric with constant permittivity is used. As shown in Fig. 6b, to cover both right and left polarization, 16 wide band spectrum horns are designed to feed the lens. The antenna largest size is about 20*cm* x 20*cm* that is smaller than other designs discussed in [17]. The axial ratio is also less than 3 *dB* for 120° on the upper hemisphere space from the main beam as shown in Fig. 9.

Circular polarization is an important factor to consider regarding the EIRP or G/T considered for the link budget requirements. The main advantage of using spectrum horns is generating RHCP and LHCP with symmetric beams simultaneously. The beams can be generated by two orthogonal ports on the antenna (see Fig. 7a- Fig. 7d). The dimension and structure parameters of the spectrum horns are also listed in Table 1. As shown in Fig. 7d the radiation pattern of the septum horn is depicted. The maximum gain is about 8 *dBi* and the first SLL is 13 *dB* lower than the main beam. After placing a single layer dielectric in front of the horn array, the gain increases to 26 *dBi* (Fig. 8b) with -21 *dB* SLL (Fig. 8a).

Parameter	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_{10}	L_{11}	L_{12}
Dimension (mm)	4.85	2.5	0.85	1.5	1	1.5	1	1	1	0.5	1	3

TABLE 1 Septum Horn Antenna Dimensions

	G/T (dB/K)	EIRP (dBW)	OBO (dB)	Polarity (Up)	Polarity (Down)
spot A	18.9	66.9	12.1	RHCP	LHCP
spot B	19.4	66.6	9.1	RHCP	LHCP
spot C	18.6	66.9	12.1	LHCP	RHCP
spot D	20.3	67.8	9.0	RHCP	LHCP
spot E	23.1	66.5	7.3	LHCP	RHCP
spot F	21.4	66.8	9.1	LHCP	RHCP

TABLE 2 Spot beams characteristics

	G/T (dB/K)	EIRP (dBW)
Gateway 1	23.4	65.9
Gateway 2	22.8	66.8
Gateway 3	22.1	67.6
Gateway 4	23.8	69.3
Gateway 5	21.9	66.7
Gateway 6	21.3	66.3

TABLE 3 Gateway characteristics

Moreover, the antennas are placed in defined distances to prevent beam overlapping in two dimensions. The array is designed with a *4×4* septum antenna and each beam has 4° HPBW in the elevation and azimuth planes. 17° spatial angle (or smaller) can select the required number of antennas which could be later modified. The antenna with or without the lens has acceptable return loss. As shown in Fig. 7c, the S11 value is less than -10 *dB* in the whole frequency band. It is interesting to mention that the reflection increases in the presence of the lens, but it is yet below -10 *dB*.

The diameter of the Luneburg lens is 15*cm* and can cover 17° spatial angle. The space scanning angle can be modified based on the application deployment or which region on the planet surface is being scanned for coverage. In the next section we present our findings for the selected beams in the Caribbean airspace.

7 | PERFORMANCE EVALUATION

For the purpose of this study, we have selected six spot beams across the Caribbean in addition to the gateway beams shown in Fig. 6a (top corner). In this simulation, the spot beams are all considered to include 225 MHz available bandwidth (PEB) for each transponder. Table 2 summarizes the characteristic of each spot beam considered in this simulation. This table provides Gain to Noise Temperature (G/T), Effective Isotropic Radiated Power (EIRP), Output Back Off (OBO) and assigned Polarity for uplink and downlink channels. The equivalent G/T and EIRP values for the gateway beams are also provided in Table 3 as reference. All the six spot beams share a common (forward) Traveling Wave Tube Amplifier (TWTA).

Based on the approach discussed in previous section, a gateway is selected based on the optimization method and it illuminates across the spot beams through the satellite. The terminal is placed in four locations for link budget calculation purposes. The terminal location is considered at the center of beam as well as second, third and fourth contour of each spot beam. Using the proposed solution, the following throughputs shown in Table 4 are achieved. We used a 8.1m Q-band antenna at the gateway and assumed 20% roll-off with spreading factor 1. The return links are 5 MHz each at 4Msps and in this simulation the total return links are 16 channels resulting in 64 MHz available bandwidth. The DVB-S2 modulation modes and code rates are presented along the annual link availability for these locations. The link budget considers Crane two-component rain model for the Caribbean region as sub-tropical wet.

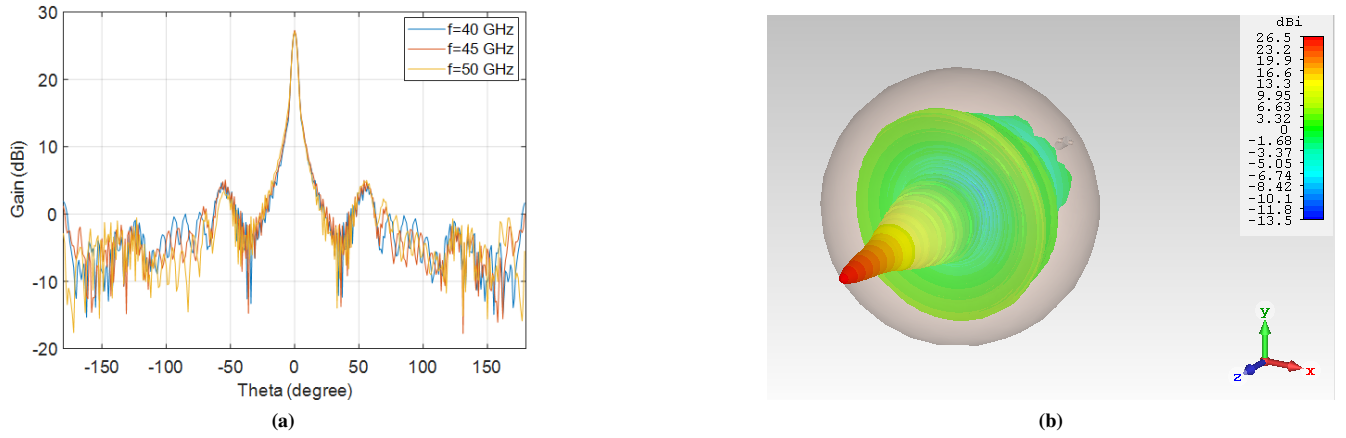| spot beam A	ModCod	Forward Information Rate (Mbps)	Link Availability (%)
beam center	16APSK 8/9	307	99.57
2nd contour	16APSK 4/5	246	99.33
3rd contour	16APSK 3/5	207	99.21
4th contour	16APSK 1/3	179	99.12
spot beam B	ModCod	Forward Information Rate (Mbps)	Link Availability (%)
beam center	32APSK 2/3	367	99.63
2nd contour	32APSK 2/5	321	99.51
3rd contour	16APSK 5/6	296	99.38
4th contour	16APSK 3/5	277	99.19
spot beam C	ModCod	Forward Information Rate (Mbps)	Link Availability (%)
beam center	32APSK 3/5	349	99.61
2nd contour	16APSK 5/6	278	99.49
3rd contour	16APSK 3/4	241	99.28
4th contour	16APSK 1/3	169	99.14
spot beam D	ModCod	Forward Information Rate (Mbps)	Link Availability (%)
beam center	16APSK 4/5	298	99.43
2nd contour	16APSK 3/4	231	99.25
3rd contour	16APSK 3/5	201	99.19
4th contour	8PSK 4/5	166	98.89
spot beam E	ModCod	Forward Information Rate (Mbps)	Link Availability (%)
beam center	32APSK 1/2	307	99.56
2nd contour	32APSK 2/5	273	99.43
3rd contour	32APSK 1/3	249	99.26
4th contour	32APSK 1/4	207	99.13
spot beam F	ModCod	Forward Information Rate (Mbps)	Link Availability (%)
beam center	16APSK 2/3	275	99.39
2nd contour	16APSK 1/2	261	99.23
3rd contour	8APSK 8/9	236	98.83
4th contour	8APSK 3/4	199	98.61

TABLE 4 Link budget summary
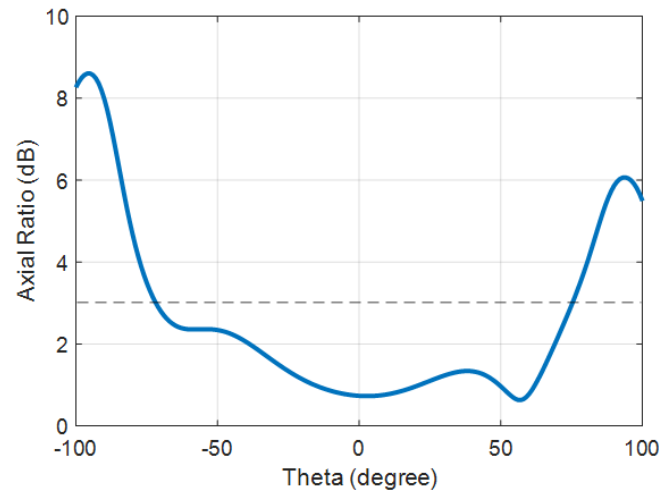
8 | CONCLUSION

In this paper, we have discussed the HTS system gateway platform along a wide bandwidth Q/V-band antenna solution to achieve high throughput over the spot beams. The application for mobile or fixed networks have been examined. This study shows high throughput with efficient spectrum improvement results can be gained by using higher baseband modulation codes using Forward Error Control (FEC) and Adaptive Coding and modulation (ACM) techniques.

Three major use cases for integrating HTS constellations for IFC has been discussed. We reviewed a transport gateway architecture for backhauling connection of a satellite link through a terrestrial network based on the latest 3GPP specifications and the significance of this approach in GEO, MEO & LEO satellite constellations. As an essential part of an HTS communication link, a compact single layer multibeam Luneburg lens antenna system is proposed. This antenna has 16 septum horn antennas to feed the lens and the maximum dimension of the antenna is about 20 *cm* × 20 *cm* and can transmit both left and right circular polarization with 26 *dBi* gain.

(a)

(b)

FIGURE 8 a) 2D Radiation pattern of the Luneburg lens antenna at lower, higher and middle frequency bandwidth (40, 45 & 50 GHz), b) 3D radiation pattern for one of the beams

FIGURE 9 Pattern axial ratio on the elevation angle where the maximum of main beam placed on the $\theta = 0$

9 | CONFLICT OF INTEREST

The authors of this study have no conflict of interest relevant to this article.

References

1. Ercetin O, Ball MO, Tassiulas L. Modeling study for evaluation of aeronautical broadband data requirements over satellite networks. *IEEE Transactions on Aerospace and Electronic Systems* 2005; 41(1): 361-370. doi: 10.1109/TAES.2005.1413768

2. Codispoti G, Parca G, De Sanctis M, et al. Validation of ground technologies for future Q/V band satellite systems: The QV — LIFT project. In: ; 2018: 1-9

3. Zhang J, Chen T, Zhong S, et al. Aeronautical *Ad Hoc* Networking for the Internet-Above-the-Clouds. *Proceedings of the IEEE* 2019; 107(5): 868-911. doi: 10.1109/JPROC.2019.2909694

4. Salcedo-Sanz S, Santiago-Mozos R, Bousono-Calzon C. A hybrid Hopfield network-simulated annealing approach for frequency assignment in satellite communications systems. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)* 2004; 34(2): 1108-1116. doi: 10.1109/TSMCB.2003.821458

5. Tirmizi A, Mishra R, Zadgaonkar A. An Efficient Channel Assignment Strategy In Cellular Mobile Network using Hybrid Genetic Algorithm. In: ; 2016.

6. Koosha B, Helgert H, Karimian R. A Hybrid Beam Hopping Design for Non-uniform Traffic in HTS Networks. In: ; 2019

7. Koosha B, Helgert HJ, Karimian R. A Reciprocal Terrestrial Backhaul Architecture for the Integration of 5G in HTS Networks. In: ; 2019

8. Zhang R, Liang Y, Cui S. Dynamic Resource Allocation in Cognitive Radio Networks. *IEEE Signal Processing Magazine* 2010; 27(3): 102-114. doi: 10.1109/MSP.2010.936022

9. Wang H, Liu Z, Cheng Z, Miao Y, Feng W, Ge N. Maximization of link capacity by joint power and spectrum allocation for smart satellite transponder. In: ; 2017: 1-6

10. Cocco G, de Cola T, Angelone M, Katona Z, Erl S. Radio Resource Management Optimization of Flexible Satellite Payloads for DVB-S2 Systems. *IEEE Transactions on Broadcasting* 2018; 64(2): 266-280. doi: 10.1109/TBC.2017.2755263

11. Fenech H, Roux L, Hirsch A, Soumpholphakdy V. Satellite Antennas and Digital Payloads for Future Communication Satellites: The quest for efficiencies and greater flexibility. *IEEE Antennas and Propagation Magazine* 2019; 61(5): 20-28. doi: 10.1109/MAP.2019.2932307

12. Xu B, Jia Q, Hsu L. Vector Tracking Loop-Based GNSS NLOS Detection and Correction: Algorithm Design and Performance Analysis. *IEEE Transactions on Instrumentation and Measurement* 2020; 69(7): 4604-4619. doi: 10.1109/TIM.2019.2950578

13. Neji N, de Lacerda R, Azoulay A, Letertre T, Outtier O. Survey on the Future Aeronautical Communication System and Its Development for Continental Communications. *IEEE Transactions on Vehicular Technology* 2013; 62(1): 182-191. doi: 10.1109/TVT.2012.2207138

14. Vitusevich SA, Schieber K, Ghosh IS, Klein N, Spinnler M. Design and characterization of an all-cryogenic low phase-noise sapphire K-band oscillator for satellite communication. *IEEE Transactions on Microwave Theory and Techniques* 2003; 51(1): 163-169. doi: 10.1109/TMTT.2002.806931

15. Kota SL, Giambene G, Chini P. A mobile satellite systems frame work for network centric applications. In: ; 2008: 1-8

16. Wang G, Zhao Y, Huang J, Wang W. The Controller Placement Problem in Software Defined Networking: A Survey. *IEEE Network* 2017; 31(5): 21-27. doi: 10.1109/MNET.2017.1600182

17. Thornton J, Smith D, Foti SJ, Jiang YY. Reduced height Luneburg lens antennas for satellite communications-on-the-move. In: ; 2015: 1-4

18. Manoochehri O, Salari A, Darvazehban A, Erricolo D. High-gain V - band Dielectric Lens Antenna for Communication and Direction Finding Systems. In: ; 2019: 181-184

19. Sachdev D. *Recent Successful Satellite Systems: Visions of the Future*. Library of flight / Ned Allen, editor-in-chief, Lockheed Martin Corporation, Bethesda, MarylandAmerican Institute of Aeronautics and Astronautics, Incorporated . 2017.

20. Kyrgiazos A, Evans B, Thompson P, Jeannin N. Gateway diversity scheme for a future broadband satellite system. In: ; 2012: 363-370

21. Werner M, Holzbock M. System design for aeronautical broadband satellite communications. In: . 5. ; 2002: 2994-2998 vol.5

22. Li F, Lam K, Hua J, Zhao K, Zhao N, Wang L. Improving Spectrum Management for Satellite Communication Systems With Hunger Marketing. *IEEE Wireless Communications Letters* 2019; 8(3): 797-800. doi: 10.1109/LWC.2019.2893659

23. Sharma SK, Maleki S, Chatzinotas S, Grotz J, Krause J, Ottersten B. Joint Carrier Allocation and Beamforming for cognitive SatComs in Ka-band (17.3–18.1 GHz). In: ; 2015: 873-878

24. Luis JJG, Pachler N, Guerster M, del Portillo I, Crawley E, Cameron B. Artificial Intelligence Algorithms for Power Allocation in High Throughput Satellites: A Comparison. In: ; 2020: 1-15