Smart Apertures for In-Flight Electronically Steerable Antennas in LEO/MEO/GEO Satellite Constellations

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Abstract—**In-Flight Connectivity services through satellite systems is expected to grow exponentially throughout the 2020 decade. The deployment of high throughput satellites and mega-constellations in low and medium earth orbits will result in higher demand and lower running costs. However, in addition to harsh environmental conditions, antenna systems must overcome important challenges derived from heterogenous scenarios and the associated regulations. This paper focuses on these aspects and proposes smart apertures based on electronically steerable antennas to enable multiple beam and fast steering capabilities and to mitigate the restrictions of emission in the geostationary arc.**

Index Terms—**In-Flight *Connectivity*, IFC, electronically steerable antennas, ESA, multibeam, LEO, megaconstellation, Clean Sky 2 Joint Undertaking.**

I. INTRODUCTION

In-Flight Connectivity (IFC) is expected to have an impressive growth during the 2020 decade. The predictions highlight that the market will benefit from a wide deployment of high throughput satellites (HTS) in geostationary Earth orbits (GEO) and the advent of mega-constellations with satellites in low/medium Earth orbits (LEO/MEO) [1]. In this scenario, higher capacity/bandwidth is offered by satellite operators at a lower cost per bit. In addition to increased passenger demand for connectivity and entertainment, airlines and airplane manufacturers are expected to exploit applications and services in other areas like flight operations and maintenance.

The process to develop, install and operate satcom systems on aircraft requires intense work until approval is granted. Regulatory institutions, aviation administrations and satellite operators impose important restrictions that satcom terminals must observe. The aviation industry standard ARINC-792 [2] compiles the most recent guidelines for manufacturers and confirms the trend to deploy Ku-band and Ka-band electronically steerable antennas (ESA) to match the predicted scenarios.

II. IN-FLIGHT CONNECTIVITY VIA SATELLITE

A. Scenarios

With GEO and LEO/MEO systems, global coverage and high capacity will be offered to enable, among others, superior connectivity not only to in-flight services but also to ground operations, called gate-to-gate (G2G) operations. In these scenarios, airplanes get coverage from different satellites and service operators and must manage the configuration of the communications system (see Fig. 1). Satellites can be classified into two types with the following characteristics:

- High Throughput Satellites: geostationary, static coverage, small cells, frequency reuse per cell, hand-over between cells, Ka-band, high capacity.
- Mega-constellations: low/medium orbits, hundred/thousands of orbiting satellites, small cells, hand-over between satellites, Ka-band, high capacity.

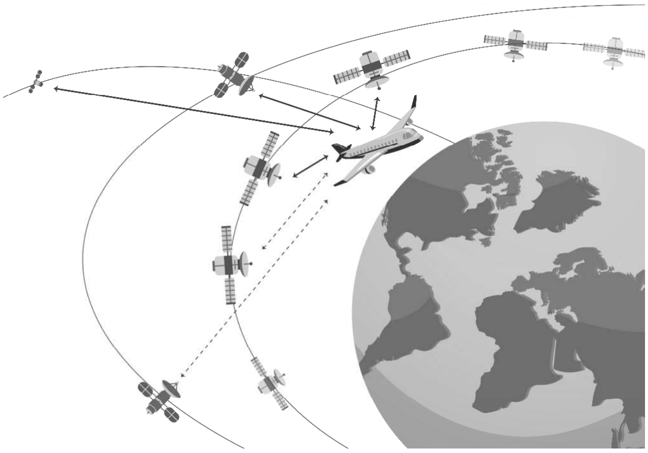

Fig. 1. Simplified IFC scenario.

The presence of a large number of satellites in both GEO and LEO/MEO systems makes it necessary to carefully observe regulatory aspects in order to prevent interference in adjacent and distant satellites as well as guarantee the interoperability [3] [4] [5].

B. Actual solutions

Aware of the market potential, airlines, aircraft manufacturers, service providers, satellite operators and satellite communication terminals manufacturers have collaborated in recent years to develop the antenna systems. A variety of solutions to provide the onboard connectivity is available, from gimbaled to electro-mechanical, lens-based or fully electronic systems. Brief details are presented below:

- Gimbaled terminals correspond to the migration of ground on-the-move equipment to airborne systems. They are characterized by medium profile and highly asymmetric apertures with mechanical steering in two axes. E.g. TECOM or Viasat. Medium performance, single beam, and scan angle agnostic.

- Electro-Mechanical by ThinKom with VICTS patented technology. Flat antenna with moving parts in a low profile. High performance, single beam, and highly scan angle dependent.
- Metamaterials-based flat panel from Kymeta.
- Lens-based plus digital beamforming terminals by Isotropic.
- Full-electronic based on RF beamforming. E.g. Phasor.

C. *Key requirements and challenges*

Next, the key requirements are considered for Ka-band satellite communication terminals for in-flight scenarios:

- 70 deg scan range in GEO systems
- 50 deg scan range in LEO/MEO systems
- EIRP > 50 dBW (boresight)
- G/T > 18 dB/K (boresight)
- Multibeam for seamless handover
- Radiating pattern, FCC - 47 CFR § 25.218
- Low profile/drag
- ARINC-792 compatible
- MTBF > 100,000 hours

Inherent challenges are associated with airborne applications, in particular the environmental conditions [2][6]. In addition to the temperature range involved (-55 ºC to +74 ºC), power consumption and heat management are two other key challenges in ESA systems with all the active electronic installed with the outdoor equipment.

III. SMART APERTURE

Smart aperture can be considered as a general concept to reconfigure the aperture in size, in shape and in operational mode, depending on the working conditions. Typically, ESAs have some limitations when working to very low elevation angles due to scan losses and the increase of the beamwidth in the axis of the scan which can mean limitations due to the applicable pattern regulations. In a smart aperture the radiating elements used to create the beam can be reconfigured to optimize these features. The same process is applicable when multibeam is required – typically when a seamless handover is needed. Several approaches can be used for multibeam that will affect the system complexity, and smart apertures is a feasible approach for it.

A. *Concept 1 – Split aperture*

The split aperture concept is applied in reception when one aperture is divided into 'n' smaller apertures, in an equal or asymmetric way. Each one can operate independently to generate multiple beams or some of them can be combined to improve the figure of merit. For example, full aperture combination can target GEO scenarios. However, with split apertures it is possible to track multiple LEO/MEO satellites where a handover is more commonly needed. Consider the case where the receiver operates in full aperture mode (see Fig. 2 – left), during the moment when the handover is made, the aperture can be split into two equal apertures (see Fig. 2 – right). So, each side is pointed to a different direction and creates two beams able to deal with the seamless handover with minimum impact on the communications. After handover, full aperture mode can be recovered with maximum performance.

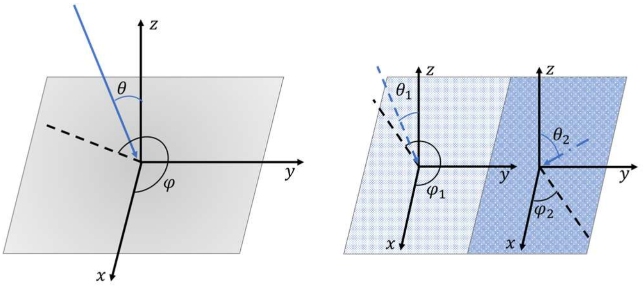

Fig. 2. Split aperture concept. Full aperture (left) and split aperture in two equal apertures (right) approaches.

A reference aperture of 620x620 mm^2 in reception can provide a G/T of 18 dB/K at boresight with a theoretical degradation of 1.92 dB at 50 degrees scan and 4.66 dB at 70 deg scan. When this aperture is split in two equal apertures (50% of the total area, 620x310 mm^2 each), boresight G/T is reduced by 3 dB approximately considering effective aperture area and temperature contributions from sky. Therefore, each aperture delivers 15 dB/K at boresight with analogous degradation depending on scanning angle. Asymmetric split would lead to a different G/T balance, in example, 67%-33% would result in boresight G/T theoretical reduction of 1.8 dB and 4.8 dB, respectively.

In GEO scenarios, a high variation in G/T is expected due to high coverage in elevation, hence continuous adaptation in link budget is required while handovers are infrequent in continental flight. Antenna size is designed to meet the requirements in the worst case, that is, at maximum scanning angle.

However, in LEO/MEO scenarios with multiple satellites in the field of view (+/- 50 degrees cone) the G/T does not vary dramatically, but handovers occur very often. Based on the reference aperture, full aperture approach will exhibit superior performance according to effective aperture size and suffer several interruptions in the communications during the transitions from one satellite to the next. With the split aperture approach, two beams with sufficient and low variation G/T can be generated to access two satellites simultaneously during the handovers.

Further advantages are identified within this concept in equally and asymmetrically split apertures. Among others: to increase the downstream bandwidth by targeting two satellites in the same constellation with coordinated handover; and, to address two different constellations depending on the service parameters.

B. *Concept 2 – Adaptive aperture*

Electronically steerable antennas are typically limited in EIRP due to regulations related to off-axis limits. The limit is mainly at high scan angles due to the increase of width in the main beam due to the smaller effective aperture size in that condition. The adaptive aperture concept is based on the reconfiguration of the active aperture for optimizing aperture shape and avoiding an undesired increase of the beamwidth in a certain axis (typically the GSO arc projection on the antenna). Applying this concept in transmission, it will allow a higher acceptable emitted power by limiting the interference produced to adjacent satellites in the GSO.

As reference, a circular aperture is assumed (Fig. 3). When this aperture is steered to a satellite in the boresight direction, any GSO projection onto the antenna (skew angle) corresponds to the maximum dimension of the aperture, i.e., the antenna diameter (Fig. 3 - left). However, at oblique incidence (scan angle) that effective aperture is decreased and may limit the equivalent aperture dimension that is aligned to the GSO projection (Fig. 3 - right). This reduction impacts directly on the beamwidth, increasing it, and on the radiating pattern, increasing the sidelobe levels. Both parameters are key for satellite communications since regulations [3] prevent interference with the adjacent and distant satellites.

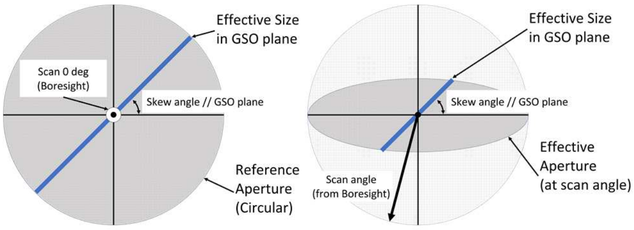

Fig. 3. Effective aperture size in a circular antenna versus scan angle.

Fig. 4 presents the study of the effective aperture size at boresight and at 70 deg scan angle. The reference aperture is circular (diameter 360 mm) and GSO plane (skew angle) at 45 deg is considered.

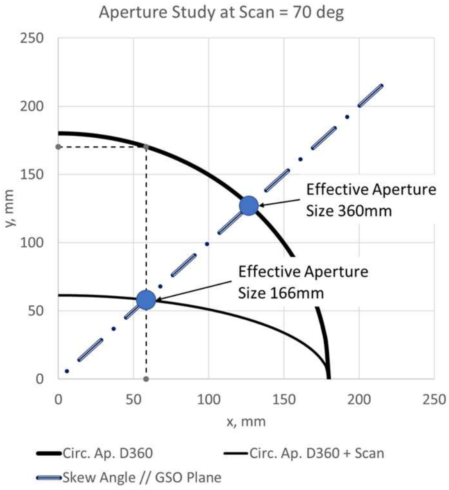

Fig. 4. Effective aperture size study for reference aperture.

The effective aperture size in the GSO plane is 360 mm when the satellite is at boresight direction. However, at 70 deg scan, the electrical equivalent aperture is reduced by projecting the surface at the scan angle. In the particular case of 45 deg skew angle, the effective aperture is 166 mm, which means beamwidth is roughly doubled. The worst-case analysis shows that when skew angle is 90 deg the new electrical equivalent aperture size is around 123 mm. Consequently, beamwidth is three times larger compared to boresight direction in that plane.

To mitigate the significant impact on maximum permissible radiated power in the terminal, the adaptive aperture concept is proposed. Radiating elements and active elements are enabled on demand to reconfigure the antenna with two objectives: first, to match the GSO plane to the most appropriate shape; and second, to maintain the required EIRP. A larger circular aperture is considered with the ability to be reconfigured in elliptical shape. The major axis of the ellipse is aligned to skew angle/GSO plane, thus the effective aperture size is maximized. The area of the elliptical adaptive aperture is equivalent to the reference aperture and provides the same gain and power. In other words, EIRP is constant as well as the number of active elements and the power consumption. Fig. 5 depicts the concept in boresight direction and 45 deg skew angle.

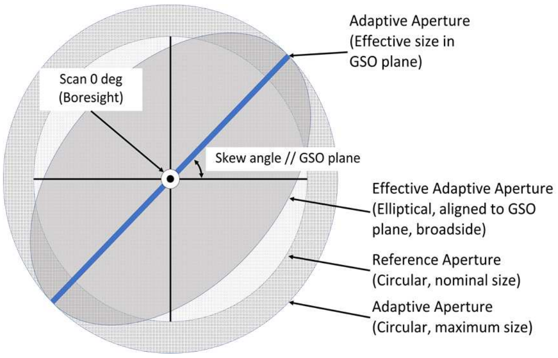

Fig. 5. Adaptative aperture concept in boresight direction.

In high scan angles, to get maximum advantage of the adaptive aperture concept, an optimization can be made. To perform this optimization, in addition to the alligment between GSO plane and the major axis of the ellipse, the adaptive aperture is further ‘rotated’ to consider the scan angle. Therefore, an optimal adaptive aperture shape is defined as a function of skew angle and scan angle. Fig. 6 presents the proposed concept.

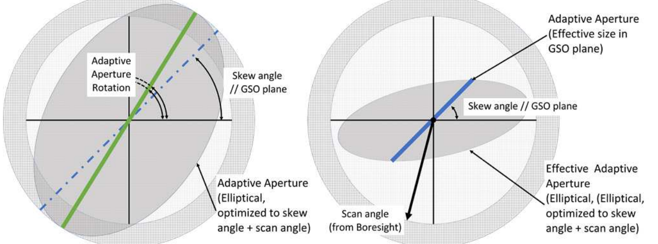

Fig. 6. Effective aperture size when adaptive aperture concept is optimized as a function of skew angle and scan angle.

The suggested aperture optimizes the effective aperture size in GSO plane at the desired scan angle and achieves the same EIRP, without any mechanical movement of the aperture. The application of this concept requires increasing the nominal size of the circular aperture, resulting in a larger number of active elements and higher CAPEX of the system. Nevertheless, this drawback is mitigated when considering that the adaptive aperture allows a higher acceptable emitted power which would mean higher capacity and efficiency in the satellite link with lower running costs (OPEX).

Fig. 7 compares the adaptive aperture concept with the reference case, at skew angle 45 deg and scan angle 70 deg. The optimized shape is an ellipse (Da = 440 mm, Db = 280 mm) whose major axis is rotated 71 deg.

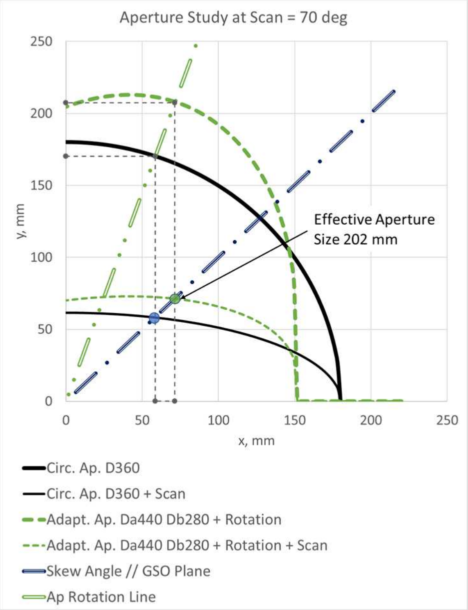

Fig. 7. Effective aperture size comparison between reference aperture and adaptative aperture.

According to this study, in this configuration the effective aperture size is increased up to 202 mm. In the worst-case at 90 deg skew angle and 70 deg scan angle, the effective aperture size would be around 150 mm. In comparison to the reference aperture, both cases show a significant increase of 21.5 % in effective aperture size. Hence, the resulting narrower beamwidth and lower sidelobes would allow higher emitted power with the same power consumption. Following this approach, it is estimated that EIRP is improved by 1.62 dB.

IV. IMPROVEMENTS AND APLICABILITY

The application of the proposed concepts may support significant advantages to the satcom systems. Improvements and applicability of both concepts are presented next.

Although the split aperture concept is highly suitable for LEO/MEO constellations, it should be noted that it is also applicable to GEO systems. In the first scenario, multiple satellites, high frequency reuse techniques and handover are presented. A limited scanning range is required (typically 50 deg) and the degradation of performance from boresight to maximum scan is lower. In the second scenario, the antenna must operate as a single aperture to maximize the G/T performance and allow higher scanning ranges up to 70 deg.

The adaptive aperture concept is more focused on transmitting towards GEO satellites, while being fully compatible for LEO/MEO constellations. The demanding requirements in GEO scenarios, including the case of high throughput satellites, and the regulation will require approaches that maximize efficiency and performance. The use of adaptive apertures improves the beamwidth and radiating pattern in the GSO plane. Consequently, the limits associated with regulations are fulfilled with higher EIRP, which provides higher capacity and efficiency to the satellite link. Further benefits are obtained, the high reconfigurability of the aperture maintains a constant number of active elements and power consumption.

V. CONCLUSIONS

Satcom terminals for the next generation of In-flight Connectivity services will be based on electronically steerable antennas. This paper approaches the demanding antenna requirements and regulation in LEO/MEO/GEO satellite constellations. Smart solutions, based on split aperture and adaptative aperture concepts, are proposed to improve the performance and to enable multibeam and seamless handover. This extra level of flexibility is opening the door to different levels of connectivity and architectures.

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DISCLAIMER

The present work reflects only the authors' view, and the European Commission and Clean Sky 2 Joint Undertaking are not responsible for any use that may be made of the information contained in this paper.

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