Compact Switchable RHCP/LHCP Mobile Ka-band Antenna

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Full Paper — This document describes a new concept of a mobile Ka band antenna for satellite communications. The antenna shows a low profile and can cope with the stringent specification of polarization switching required in the handover from cell to cell. Transmit performance is discussed in detail and compared with an equivalent reflector antenna.

In the same time, a new generation of modem allowing transmission with low power density (spreading feature) so that high bit rate return link can be achieved with compact terminal, suitable for aeronautical domain.

Keywords: Satcom, slotted waveguide, method of moments, mobile antennas

I. INTRODUCTION

Multimedia services via satellite are becoming possible thanks to a new generation of satellites recently launched operating in Ka band. Thanks to the usage of a cellular coverage, these satellites offer a dramatic increase of the capacity available, lowering cost and consequently extending the market to consumer broadband applications [1]. However, the drawback of a multi-spot coverage is the extra complexity required for the ground segment in contrast to existing platforms in Ku band: in order to achieve larger capacity, frequency reuse as well as two circular polarizations is used in the cellular scheme. Therefore, mobile terminals will have to cope with the handover from one cell to another. In addition, these terminals must be compliant with the off-axis EIRP density regulation, and compact design.

Even though antenna pointing systems, either fully mechanical or hybrid electronic-mechanical are very mature technology and can be found in the market for Ku band, the additional implementation of the circular polarization switching subsystem needed for the spot-beam handover requires a dedicated design which was barely attempted in the past, even for X or Ku band antennas [2].

This paper will show the joint effort of Thales Alenia Space in France and Universidad Politécnica de Valencia (UPV) in Spain to design an efficient panel antenna able to cope with circular polarization switching in a cellular environment, and at the same time compliant with ETSI EN 303978 regulation rules [3]. The basic radiating structure consists of a slotted waveguide array and a polarization screen above to provide the required circular polarization. A number of screen switching procedures have been devised and patented [4]. In the next section the basic procedure for obtaining the circular polarization will be briefly described pointing out its potential for polarization switching, then several practical implementations of screen switching mechanism will be discussed in section II. In section III overall panel antenna specifications are considered for compliance with existing off-axis EIRP density regulation. In section IV. New generation of modem developed by TAS is presented in section V. And finally overall system performance for such compact terminal are shown in section VI. Conclusions are drawn in section VII.
II. SLOTTED WAVEGUIDE ARRAY WITH CIRCULAR POLARIZATION

Slotted-waveguide array antennas have been widely used in many radar and communications applications because of their geometric simplicity, efficiency, reliability and light weight. One of the most common configurations consists of longitudinal shunt slots located in the broad face of the rectangular waveguide. Such configuration is able to radiate linear polarization only. However, circular polarization is also possible by resorting to lineal-to-circular polarization converters. It has been demonstrated [5] that it is possible to obtain circular polarization by mounting a parasitic dipole array approximately at \( \lambda/5 \) above the slotted waveguide array. The two orthogonal field components are achieved by tilting the parasitic dipoles a certain angle \( \alpha \) with respect to the slots while the phase quadrature is achieved through the distance between the slots and the dipoles (See Fig. 1). Interestingly, the orthogonal polarization is obtained by merely flipping the parasitic dipole so that the tilting is \(-\alpha\). This property will be exploited through a number of mechanisms to achieve the desired switching capability.

![Figure 1. Basic radiating element for circular polarization](image)

There certainly exist other approaches to obtain circular polarization from a basic slot radiator; those are beyond the scope of this paper. This one has been chosen because it gathers the merits of switching capability, modeling simplicity and ease of fabrication, which are particularly attractive at millimeter-wave bands, where the manufacturing tolerances are critical.

Detailed description of the performance of a basic slot-dipole radiator can be read in [6]. For the purpose of this work, let us point out that the achievable axial ratio (AR) beamwidth is 73º in the cut containing the slot and it is practically omnidirectional in the upper hemisphere for the transverse cut. In addition, an AR relative bandwidth of up to 4% can be attained using one parasitic dipole, while two parasitic dipoles can even double this bandwidth.

In this paper attention will be drawn to the switching mechanisms and the rest of challenging specifications a SATCOM antenna has to cope with in Ka-band.

III. POLARIZATION SWITCHING MECHANISMS

As mentioned in the introduction, polarization switching, required for the spot-beam handover constitutes one of the major challenges Ka-band planar array antennas have to face in contrast to Ku-band antennas where polarization is mostly linear.

One last procedure recently patented in [9] enables the polarization switching by simply rotating the whole panel antenna, as depicted in Fig. 4.

This last mechanism is probably the most robust and reliable of all since both faces of the antenna are adjusted in advance to radiate the corresponding circular polarization. This is the option selected for the antenna proposed in this work.

![Figure 2. Double face panel antenna. The antenna shows two radiating sides providing RHCP and LHCP polarization respectively.](image)

IV. SATCOM ANTENNA

Polarization switching is certainly a challenging constraint but it is not the only one. Another major constraint is also the maximum allowable height, which in turn will have an impact on size and on the type of antenna to be chosen. Total height shouldn’t be more than 30 cm. This leaves reflector antennas out of the list of candidates. Array panels are then the preferred choice.

Regarding the pointing system, a common approach for mobile terminals combines mechanical movement for the azimuth axis with an electronic scanning in elevation. This alternative may turn out to be more expensive in Ka band than in Ku band due to the higher cost of phase shifters. A
fully mechanical pointing system on the other hand is a robust and less expensive alternative and it will be adopted for this antenna.

Another key issue is the required EIRP. Reaching the required EIRP with the smallest possible antenna, force us to seek for highly efficient antennas. Among the available technologies, slotted waveguide arrays are well-known as antennas with high efficiency. They are definitively superior to solutions based on microstrip technology, in particular for Ka band. On the other hand, resonant slotted waveguide arrays are not particularly wideband radiators. However, using detuning techniques [10] and conveniently dividing the antenna panel into smaller subarrays can provide a solution within the specifications for this system.

In the following, the selected antenna aperture illumination and size will be shown and the compliance with applicable regulations highlighted.

A. Aperture illumination and size

Over the years UPV has developed a full-wave code based on the Green’s function/Method of Moments technique to deal with 2D slot arrays in rectangular waveguides. This code can model not only the slots but also the presence of parasitic dipoles above them in an arbitrary multilayer environment. The code details can be read in [6] and [8]. This code is integrated into an efficient optimizer to fine-tune the slot array by adjusting dimensions of slots and dipoles to compensate for mutual coupling effects.

An accurate determination of slot length, dipole length and dipole tilting of a basic radiating element within the array requires taking into account mutual coupling with surrounding elements. Since the final arrangement of these elements is not known a priori, a uniform infinite array is commonly adopted for this task. This is indeed a reasonable approximation because little variation on physical dimensions of nearby elements is expected. However, in our case a uniform finite array model is adopted to reach more accurate results. A finite array model is certainly slower computationally speaking but it allows to use the actual amplitude and phase distribution of waveguides and radiators and to take into account edge effects. The implementation of the above design method gives as a result the full arrangement of antenna elements, which is completely defined by offsets and lengths of each slot and tilting angle and length of each parasitic dipole. With this initial placement, however, the desired performance of the antenna is not completely achieved. Notice that the design method necessarily considers identical antenna elements, which does not correspond to the actual antenna. This disagreement affects all mutual couplings very markedly, altering antenna parameters.

Hence, an iterative tune-up procedure is carried out. It is started from this initial design, which can be considered as an acceptable starting point. In order to meet all requirements, three corrections are performed successively for each array element: 1) slot offset adjustment to assure the required aperture illumination; 2) slot length correction to achieve proper matching for every waveguide and 3) dipole rectification (both length and orientation) to improve the AR figure. Notice that each adjustment somehow distorts what is attained in previous corrections. For this reason, an iterative procedure is required to accomplish all above antenna parameters in the end. The stopping conditions for this process are a threshold level for the AR and the sum of row admittances, since it is a measure of waveguide matching. Only a few iterations are needed to reach convergence.

The proposed antenna will consists of two panel arrays next to each other one for transmit in the 29.5 to 30 GHz band and the other for receive in the 19.7 to 20.2 GHz band. Both panels are designed in a 2x2 subarray configuration. For the transmit panel, subarrays are made of 15 hollowed center-fed rectangular waveguides having 16 slots in each. The dipoles layer is 2 mm above the slots, etched in a copper-cladded substrate of 127 μm and permittivity εr=3.5. The spacer used is a foam layer of εr=1.05. In the receive panel, subarrays comprise 10 waveguides with 15 slots per waveguide. Materials used to set up the dipoles layer are the same as for the TX panel except for the spacer, which is now 3 mm in thickness. Slot arrays are of the standing wave type. Transmit aperture has been designed to show a 25 dB Taylor distribution in both main planes, while receive panel shows a uniform distribution. The area of the radiating panels is approximately 24x24 cm (HxW) for the transmit antenna and 24x32 cm for the receive one.

The most significant parameters of transmit and receive panels are summarized in Tables I and II.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>29.5</th>
<th>29.75</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Ratio (dB)</td>
<td>0.86</td>
<td>0.03</td>
<td>0.72</td>
</tr>
<tr>
<td>Directivity (dB)</td>
<td>37.37</td>
<td>37.47</td>
<td>37.48</td>
</tr>
<tr>
<td>Aperture Eff (%)</td>
<td>80</td>
<td>80.4</td>
<td>79.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>19.7</th>
<th>19.95</th>
<th>20.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Ratio (dB)</td>
<td>1.15</td>
<td>0.03</td>
<td>1.07</td>
</tr>
<tr>
<td>Directivity (dB)</td>
<td>35.76</td>
<td>36.08</td>
<td>36.0</td>
</tr>
<tr>
<td>Aperture Eff (%)</td>
<td>89.4</td>
<td>93.7</td>
<td>89.8</td>
</tr>
</tbody>
</table>

Losses has been estimated to be around 0.3 dB for the transmit antenna and 0.2 dB for the receive one, including ohmic as well as mismatch losses.

In Figs. 5 to 7 the radiation patterns of the transmit antenna are shown with certain detail because the transmit antenna is subject to off-axis EIRP emission density limits, which will be analyzed later in the section. Fig. 5 shows the pattern cuts at the lower frequency, Fig. 6 shows those same cuts for the center frequency of 29.75 GHz, and finally Fig. 7 depicts the patterns for the higher frequency of the band.
Figure 3. Transmit antenna radiation patterns at 29.75 GHz for several azimuth

As can be seen, the Taylor distribution is achieved for the center frequency while for the band limits this performance deteriorates.

B. Analysis of transmit performance

In order to ensure protection to other satellite systems in the uplink, regulation EN303978 [3], established by ETSI (European Telecommunications Standards institute) for Ka band mobile satellite communications with ships, trains and aircrafts in Europe must be met. This regulation establishes the off-axis EIRP emission density limit within the band of 29.5 GHz to 30 GHz.

Any antenna off-axis direction may be defined by a pair of values \((\alpha, \phi)\) where \(\phi\) is the off-axis angle of that direction with the antenna main beam axis and \(\alpha\) is the angle of the plane defined by that direction and the antenna main beam axis with any arbitrary plane containing the antenna main beam axis. The range of values of \(\phi\) and \(\alpha\) is from \(\phi_{\text{min}} - \delta\phi\) to 180 ° for \(\phi\), and from -180 ° to +180 ° for \(\alpha\), being \(\phi_{\text{min}}\) the minimum elevation angle declared by the applicant, and \(\delta\phi\) the antenna pointing accuracy.

Therefore, the maximum EIRP in any 40 kHz band within the nominated bandwidth of the copolarized component in any direction \(\phi\) degrees from the antenna main beam axis shall not exceed the following limits:

- \(19 - 25\log_2\phi\) dBW for \(2.0° \leq \phi \leq 7.0°\);
- \(-2\) dBW for \(7.0° < \phi \leq 9.2°\);
- \(22 - 25\log_2\phi\) dBW for \(9.2° < \phi \leq 48°\);
- \(-20\) dBW for \(48° < \phi \leq 85°\);

These limits apply to any off-axis direction \((\alpha, \phi)\) within \(\pm 3°\) of the visible part of the geostationary orbit (GSO) and may be exceeded up to 3 dB in any other direction. In Fig. 8, a schematic view of the sectors associated to the EIRP limits is shown for clarity.

Table III herebelow summarizes the In-axis EIRP density limit performance for the proposed antenna panel.
<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>29.5</th>
<th>29.75</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>In Axis EIRP limit (dBW/40 kHz)</td>
<td>18.42</td>
<td>18.21</td>
<td>18.56</td>
</tr>
<tr>
<td>Limiting $\phi$ (°)</td>
<td>2.02</td>
<td>2.02</td>
<td>2.02</td>
</tr>
<tr>
<td>Limiting $\alpha$ (°)</td>
<td>45</td>
<td>135</td>
<td>135</td>
</tr>
</tbody>
</table>

Table III. IN-AXIS EIRP DENSITY FOR THE TRANSMIT ANTENNA PANEL

Therefore, the 24x24 cm transmit panel for the proposed antenna, allows a EIRP density of 18.21 dBW/40kHz compatible with ETSI regulations for off-axis EIRP density.

It is pertinent now to bring up a comparison with an equivalent reflector antenna, which is an alternative for this type of applications. A 24 cm in diameter, center-fed, paraboloidal reflector antenna in Gregorian form has been chosen for the comparison. Fig. 9 illustrates a few details of the reference reflector antenna. The reflector has been selected so it shows the same height as the panel antenna therefore complying with the same criteria for aerodynamic impact in a mobile antenna.

Reflector surface has been shaped using ray tracing techniques to provide reduced side-lobes. Fig Figure 7. shows the ray tracing associated to the reflector designed and Table TABLE IV. summarizes its main dimensions.

<table>
<thead>
<tr>
<th>Main reflector</th>
<th>Parabolic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>240 mm</td>
</tr>
<tr>
<td>Focal</td>
<td>50 mm</td>
</tr>
<tr>
<td>Auxiliary reflector</td>
<td>Gregorian</td>
</tr>
<tr>
<td>Diameter</td>
<td>50 mm</td>
</tr>
</tbody>
</table>

Table IV. MAIN DIMENSIONS OF SYNTHETIZED REFLECTOR

In-axis EIRP density compatible with ETSI regulations is 17.68 dBW/40kHz as shown in Fig. Figure 8. This value has been obtained following the same procedure as for the panel antenna which consists in “pushing” the antenna pattern up until it touches the template in a given point. Then the magnitude of the main beam is read in the vertical axis giving the maximum EIRP density sought. This procedure is applied on a representative set of pattern cuts to retain the worst case of all.

As can be seen, this result is approximately 1 dB worse than that obtained for the panel antenna which is very encouraging having in mind that no particular pattern synthesis procedure has been used on the panel antenna pattern and a standard Taylor distribution has been used.

V. MODEM

Thales Alenia Space proposes solution for broadband transmission over satellite. It is ideal for large private networks, or shared hub services. In this scope TAS developed a complete mesh SCPC system called HDR. To provide airborne broadband access TAS declined the HDR modem in an aeronautical solution.

For this purpose, the HDR modem is hardened to support aeronautical demanding constraints in term of environment but also in term of doppler and emission
regulatory constraints. An extended patented version of DVB-S2 modulation has been developed by TAS.

This new waveform is capable to deal with the following constraints

- C/N as low as $-17 \text{ dB}$
- Spreading as much as 52 times
- Doppler shift of 33 kHz and doppler variation of 1962 Hz/s

Despite of this hard constraints, this waveform kept the advantages and performances of DVB-S2 original waveform bringing a total adaptation range of more than 30 dB.

![Figure 9 A total adaptation range of more than 30dB.](image)

VI. SYSTEM PERFORMANCE

The following section deals with the link performance achievable through Athena Fidu Theater coverage.

Clear Sky Return Link Maximum Throughput

(Satellite G/T=10dBK)

<table>
<thead>
<tr>
<th>PIRE</th>
<th>Symbol Rate</th>
<th>Waveform</th>
<th>Spread Factor</th>
<th>IP Throughput</th>
<th>BW</th>
</tr>
</thead>
<tbody>
<tr>
<td>49.95 dBW</td>
<td>22 Ms/s</td>
<td>QPSK 1/3</td>
<td>1</td>
<td>13.252 Mbps</td>
<td>26.4 MHz</td>
</tr>
</tbody>
</table>

Clear Sky EOC Throughput (Satellite G/T=7dBK).

<table>
<thead>
<tr>
<th>PIRE</th>
<th>PIRE density</th>
<th>Symbol Rate</th>
<th>Waveform</th>
<th>Spread Factor</th>
<th>IP Throughput</th>
<th>BW</th>
</tr>
</thead>
<tbody>
<tr>
<td>48.65 dBW</td>
<td>17.47dBW</td>
<td>5.247 Ms/s</td>
<td>QPSK 1/3</td>
<td>3</td>
<td>8 Mbps</td>
<td>52.47 MHz</td>
</tr>
</tbody>
</table>

VII. CONCLUSIONS

In this paper a compact terminal design dealing with aeronautical constraints with a new concept for switchable RHCP/LHCP antenna has been described, as well as improvement in waveform domain made by TAS.

REFERENCES


