Low-Profile Antenna Package for Efficient Inter-CubeSat Communication in S- and V-band

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Abstract – Even space-borne deep space observation missions such as OLFAR require very large apertures (>10km). A CubeSat cluster is the only practical and affordable method of achieving such a large aperture in orbit, for the foreseeable future, but cannot be used until certain inter-CubeSat communication challenges are addressed. In this Paper, we review the challenges, focusing on the size limitations of CubeSats, but also on the radiofrequency allocation spectrum, and show that the 60GHz band is the best compromise, when high bandwidth is needed. So as to facilitate 60GHz inter-CubeSat communication, we propose a double V-band antenna design, expecting to reach more than 5GHz of bandwidth, a moderately high gain of 18dBi and a high efficiency (95%), using two orthogonal polarisations for the transmit and receive antennas. Each antenna is fixed as transmit or receive, only due to the 60 GHz chipset that is currently available to us. This antenna package is completed by an omnidirectional 2.4GHz-modified Planar Inverted F Antenna (PIFA) suitable for a reliable low-data-rate link over which channel management data can be exchanged. The full antenna package is readily integrable onto a 0.5U face of a CubeSat with a total thickness of 6.4mm. We evaluate the 60GHz link budget and expected performance of such a system, based on commercially available V-band transmitter and receiver modules.

I – INTRODUCTION

CubeSats have been under intensive investigation for the last decade or so [1]. The concept of constellations has emerged in response to increasing CubeSat capabilities, especially in altitude and positioning control [2]. A constellation will most likely consist of CubeSats distributed across a finite planar region, perhaps a few hundred metres or a kilometre across (depending on numbers). Besides spreading the risks and the costs of a mission, constellations can be far larger from edge to edge than the arms of even the largest conventional satellites (typically a handful of metres). For example, the OLFAR (Orbiting Low Frequency Array) mission is designed for radio astronomy observation below 30MHz [3]. At those low frequencies, large aperture of over 10km is needed to achieve the required spatial resolution, operating as a distributed aperture synthesis array. A schematic diagram of a possible distributed aperture swarm makeup is shown Figure 1. Assuming Nyquist sampling at 8-bit resolution, real-time uncompressed transmission will nearly 500Mbps data rate per detector and compression will be undesirable so as to retain precise time relationship between all received signals. Hence, high-data rate communication is key for the success of such a configuration. The 60GHz band provides 12GHz of bandwidth for inter-satellite communication (59GHz to 71GHz), typically in channels of 0.5-1.5GHz each. Yet the communication system must respect the mechanical and electrical requirements of the CubeSat platform, such as the trade-off between radio power and communication distance. In this Paper, we will first discuss current limitations for CubeSats then justify choosing the 60GHz band. We will then describe the design and simulation of a very low profile antenna package including two 60GHz Bull’s eye antennas and a low frequency antenna for channel control tasks. We have high confidence in the feasibility of this antenna package because we previously experimentally demonstrated an individual Bull's eye antenna with good agreement to simulated results [4].

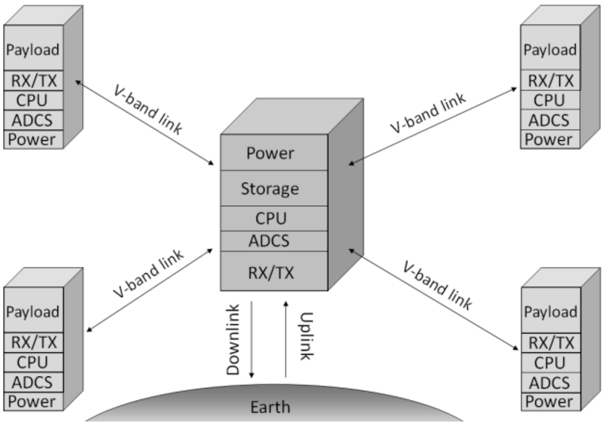

Fig. 1: Schematic view of a distributed aperture based on a swarm of CubeSats and using a central member to maximize downlink capabilities and avoid CPU and storage redundancy. Four payload members are shown; in practice swarms may have 30 or more.

II – CURRENT LIMITATIONS FOR INTER-CUBESAT COMMUNICATION

In order to take advantage of the CubeSat platform for scientific missions, particularly in a distributed aperture scenario, an efficient inter-CubeSat communication system will be required. Ideally, such configuration would require a high data rate system in order to handle the transfer of a large amount of data to the central member. Such a communication system would require compact and directive antenna in order to avoid interferences with other paths and increase the S/N ratio. Currently, UHF/VHF and S-band communication system are the most used and provide up to 256kbps (for the S-band) [5]. Those systems are reliable, cheap and efficient for long distance communication but suffer from important drawbacks. They have a limited maximum data rate and the large wavelength makes the design of fixed directive antennas highly impractical for a CubeSat platform.

In order to tackle this problem, this only solution is to go higher in frequency, offering both the possibility larger bandwidth and small and directive antennas. To this extent, the V-band (around 60GHz) is particularly interesting for multiple reasons. First of all, the band between 59 and 71GHz is available for primary usage in inter-satellite communications. Second, such a large total bandwidth (12GHz) could offer data rates of over 1Gbps per channels. Third, at those frequencies, the wavelength is about λ=5mm. Hence the dimension of one face of a CubeSat (1U) is 20λ, which offers enough space to accommodate the design of an efficient directive antenna. Finally, the 60GHz band is also available for terrestrial use (ISM) and commercial technology is emerging for high data rate, short distance communication. Hence, CubeSats can benefit from those affordable Commercial Off-The-Shelf (COTS) components, increasing reliability and reducing the price.

III – V-BAND AND ANTENNA DESIGN

In the previous section, we listed the reasons why the V-band is a good compromise for inter-CubeSat communication. Common antennas are available at those frequencies but are usually not well adapted to the physical limitations of CubeSats. For example, a horn antennas provides a high gain (>20dBi) but is too voluminous for a CubeSat chassis. An array of patch antenna can provide the directivity and the very-low profile required but suffers from important loss due to the use of dielectric substrate.

We previously designed a Bull’s eye antenna that provides the low-profile, high directivity and high efficiency required for CubeSat missions [6]. This Bull’s eye antenna consists of a subwavelength aperture, fed by a WR-15 waveguide, creating free wave radiation and surface waves travelling away from the centre aperture. The central aperture is surrounded by a corrugated plate, in the form of rings from which surface waves couple to free space. This approach enhances the directivity because the rings increase the effective size of the aperture. Increasing the number of rings increases the directivity up to a certain number of rings (about 7 rings). The enhancement is limited by the maximum propagation distance of the surface waves. The prototype in [6] was 3.2mm thick, providing a gain of 19.1dBi using 7 rings, a bandwidth of 5GHz and a total efficiency of 97%.

IV – DOUBLE V-BAND BULL’S EYE ANTENNA AND S-BAND PIFA

In this section, we present a double V-band Bull’s eye antenna allowing TX and RX links over orthogonal polarizations. Most of the commercially available 60GHz modules, developed mainly for terrestrial applications, are only able to transmit or receive. An orthogonal polarization-based link is a good solution to provide a full-duplex transmission. To do so, we designed a single 0.5U module, comprised of two Bull’s eye antennas with two linear polarizations, orthogonal to each other, as shown in Figure 2. It was decided to limit as much as possible the size of the Bull’s eye in order to have the two antennas fir over a 0.5U plate.

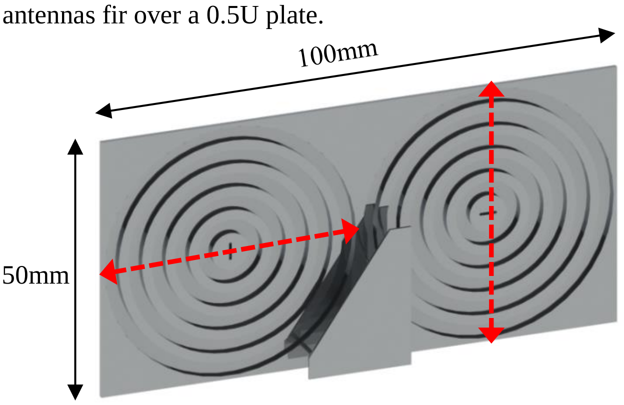

Fig. 2: Antenna package with the two V-band Bull’s eye antenna and the S-band PIFA, with polarization planes indicated with dash line.

We modelled all the antennas using CST Microwave Studio. The 60GHz antennas simulations used the transient solver, the 2.4GHz antenna the frequency domain solver. As, shown in Figure 3, each antenna has five indented rings which provide a maximum gain of 18.0dBi.

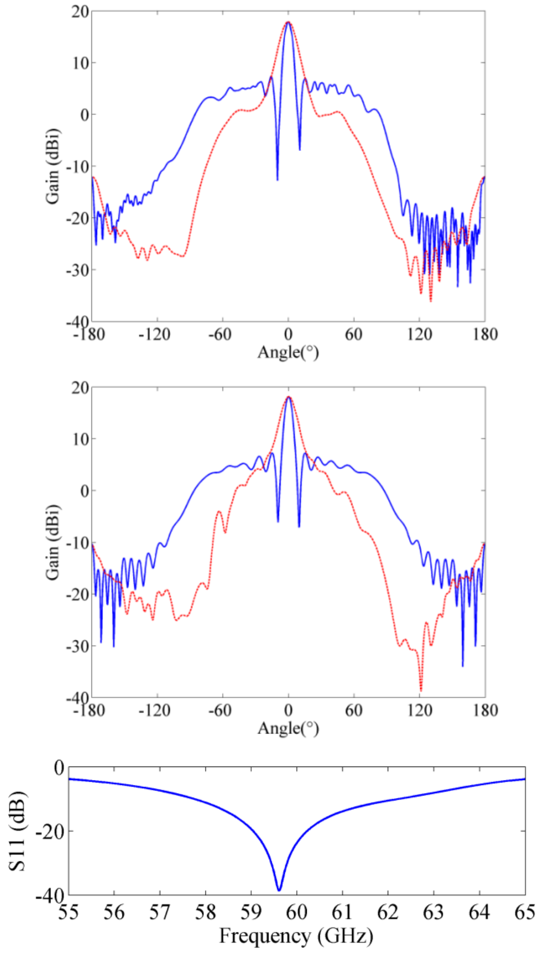

Fig. 3: Plot of simulated data for each 60GHz antenna. E- and H-plane (respectively solid and dotted line) for the left (top plot) and right (middle plot) Bull’s eye antenna. S11 parameter, identical for both Bull’s eye antennas (bottom plot).

The bandwidth (S11=-10dB) is 4.5GHz and the S11 parameter for both antennas is very similar. We can notice the slight asymmetry in the back lobes due to the position of each of the antennas on the 0.5U plate.

In case of misalignment during manoeuver phase, or as a low data rate backup link, a 2.4GHz PIFA antenna was designed and integrated onto the same Bull's eye aluminium plate. This antenna, based on the design described in [7], provides an omnidirectional radiation pattern and is not directly influenced by the 60GHz antennas' corrugated structure, whose profile is much smaller than the wavelength at 2.4GHz ($\lambda_{2.4GHz}$=12.5cm). Figure 4 shows the 3D radiation pattern and S11 parameter between 2 and 2.8GHz.

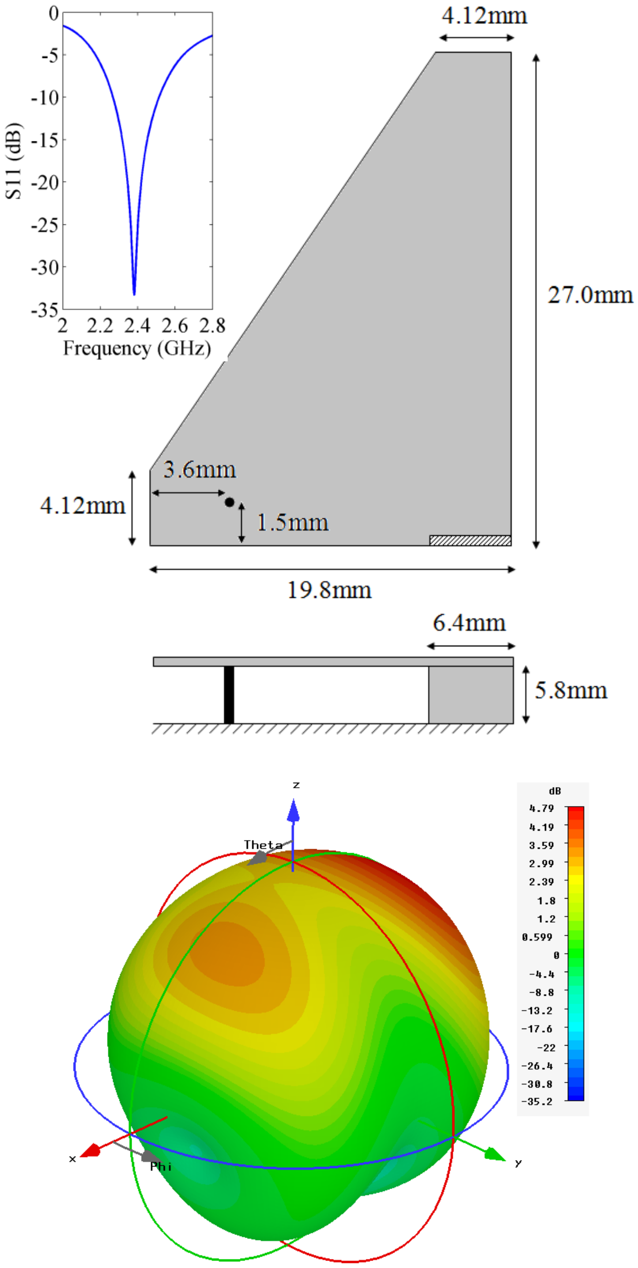

Fig. 4: PIFA dimensions, with S11 parameter inset (top) and 3D radiation pattern showing gain for the 2.4GHz PIFA antenna.

The 2.4GHz PIFA provides an omnidirectional pattern, with maximum gain of 4.79dBi. It is expected the CubeSat chassis will have only a minor effect on the radiation pattern (full simulation with the chassis was not run because of the large space domain leads to excessively high memory requirement).

V – INTEGRATION ON A CUBESAT CHASSIS AND PERFORMANCES

Figure 5 illustrates the integration of the proposed antenna package on the side of a CubeSat chassis. V-band modules are already available for terrestrial application such as the RX and TX waveguide modules from VuBiQ Inc.

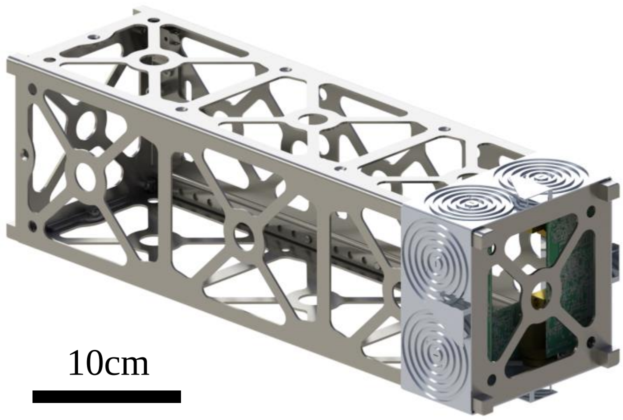

Fig. 5: Illustration of antenna packages attached to the four sides of a CubeSat chassis.

Using those modules' features, the maximum expected distance transmission, with a 10mW transmitter and a 6dB noise figure receiver, is about 300 meters to reach a desired BER of 10^{-6} in BPSK modulation, with a potentially achievable data rate of 500Mbps, as shown in Figure 6.

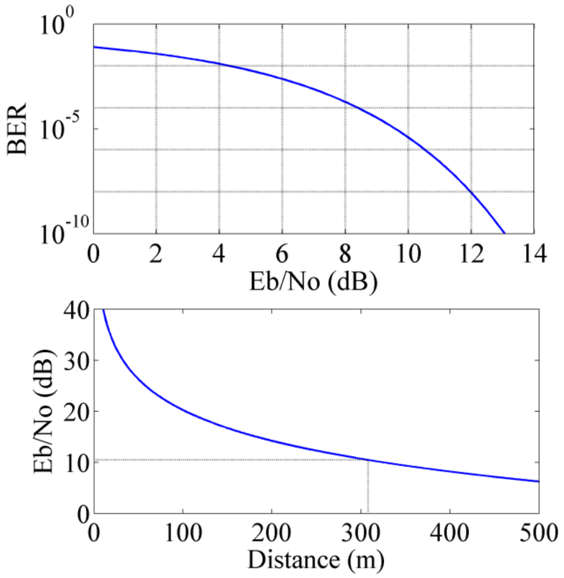

Fig. 6: Standard curve showing BER as a function of Eb/No for a BPSK modulation scheme (top) and calculated Eb/No as a function of the distance.

We can note that effect of the error in the polarization orientation is only noticeable for values >30°, yet ADCS operate with accuracy <1°, hence it was not taken in account [8]. We can notice that the maximum distance of 300 meters has to be improved in order to suit interplanetary CubeSat missions such as OLFAR, requiring several kilometres between members of the distributed aperture. Because of the limited available space, the maximum communication distance can be enhanced by increasing the output RF power and using a receiver with a lower the noise figure. For example, a RF power of 100mW and a receiver with a noise figure of 3dB can help to increase the maximum transmission distance up to 1700 meters.

CONCLUSION

We presented the design of a very low profile double V-band Bull eye module with 2.4GHz omnidirectional PIFA antenna. This module provides a baseline for high data rate inter-CubeSat communication, using directive, V-band Bull's eye antennas. A maximum gain of 18dBi at 60GHz is obtained, offering a maximum transmission distance of about 300 meters, with 500Mbps transmission rate and BPSK modulation using 10mW COTS radio modules. Full-duplex communication is obtained with orthogonal polarisation-based channels.

Additionally, a 2.4GHz PIFA antenna (providing omnidirectional pattern) is integrated into the module to provide a reliable low data rate link in case of a major misalignment during a manoeuvre phase.

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