ANTENNA SYSTEM DESIGN FOR OLFAR'S INTER-SATELLITE LINK

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Initiatives to perform space-based radio astronomy below 30 MHz have emerged recently, since novel technological developments have increased their feasibility. The Orbiting Low-Frequency Array for Radio Astronomy (OLFAR) project, one of these initiatives, aims to use a swarm of nano-satellites to implement an interferometric array in space. For its astronomical tasks, OLFAR requires that each satellite is able to establish a high-data-rate radio link with any other. We propose a design of the antenna system for these links, in which we present a design approach and describe an antenna configuration, a control strategy and individual antenna characteristics that satisfy OLFAR's requirements.

I. INTRODUCTION

Low-frequency radio astronomy has become increasingly relevant during the last decades, since the scientific drivers for exploration of celestial radio waves with frequencies below 300 MHz [1, 2] become more attainable with recent technological developments. The implementation of long-baseline aperture-synthesis radio telescopes has allowed Earth-based radio observations in the 30 MHz to 300 MHz range with impressive angular resolutions [3, 4], while several initiatives have been developed recently for space-based ultra-long-wavelength radio astronomy [5]. The latter are especially relevant, since celestial radio waves with frequencies below 30 MHz still remain virtually unexplored [6].

The Orbiting Low-Frequency Array for Radio Astronomy (OLFAR) project is one of these initiatives, which aims to develop a detailed system concept for a space-based aperture-synthesis radio telescope implemented with a swarm of autonomous nano-satellites [6]. The swarm will act as a large-aperture interferometric array for frequencies between 0.3 MHz and 30 MHz, and will perfom three main tasks:

1. observation of celestial radio waves;
2. distributed signal processing of the acquired signals;
3. cooperative downlink to Earth of the processed data.

All the elements of the swarm should assist in these tasks, which means that each nano-satellite should be able to perform radio observations, share its acquired data with all the other satellites, process a specific frequency sub-band, and downlink its processed data to Earth. Figure 1 shows the components related to these tasks in each nano-satellite, as well as the flow of the involved signals.

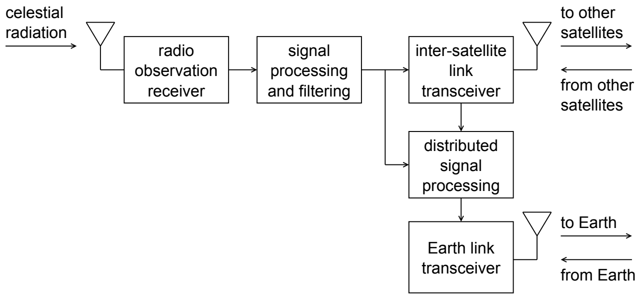

Fig. 1: Radio observation components in each nano-satellite.

In OLFAR, the data sharing among the different satellites will be performed using radio-frequency (RF) links [7]. This implies unique and challenging requirements for the inter-satellite links (ISLs), since the data rate, the element configuration and the satellite properties proposed for OLFAR are considerably different from those present in existing satellite networks with ISLs.

OLFAR's inter-satellite communication system consists of three main components (or layers) that provide the essential functions to establish reliable RF links between different nodes, namely:

1. a data distribution strategy;
2. baseband signal processing;
3. an antenna system.

This work presents a design proposal for the antenna system for OLFAR's ISL.

In Section II we introduce the design considerations used to shape our design approach. We develop our proposal in Section III, including the motivation and details of the different design choices, as well as the expected results. Finally, concluding thoughts and ideas for further work make up Section IV.

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II. DESIGN APPROACH

The design approach for the antenna system involves several considerations, ranging from the configuration of the interferometric array to the dimensions of the individual nano-satellites. We use these to identify our design requirements and limitations, which we attempt to satisfy with the antenna system proposal.

Radio observation considerations

The radio observation considerations involve the amount of information produced by the astronomical measurements and the configuration of the interferometric array.

As shown in Figure 1, the radio observation and the initial signal processing generate a 'raw' data stream with a given rate that determines the minimum required throughput of the ISL. For the observation parameters proposed for OLFAR, this data rate will be around 6 Mbit/s [7].

On the other hand, the configuration of the interferometric array determines the minimum and maximum distances between satellites, as well as the possible directions for the ISLs. For OLFAR, the array consists in a constellation of (slowly) free-drifting satellites, with baselines between 10 km and 100 km [7]. Because of the free drift, the relative location of the satellites with respect to each other changes continuously, even in the presence of attitude control. This means that the ISLs can have –in general– any direction, and each satellite should be able to adapt its link accordingly.

Communication considerations

The communication considerations involve the data distribution scheme and the baseband signal processing of OLFAR's inter-satellite communication system. These basically translate the observation data rate into a signal bandwidth and the constellation baselines into ISL ranges.

In OLFAR, a clustering adaptive topology is proposed for the data distribution, which provides a reduction in the required resources compared to a full-mesh peer-to-peer topology [8]. For this scheme, the cluster heads present the more challenging communication requirements, i.e. longer baselines and higher data rates. Considering a maximum of eight slaves per cluster and the constellation configuration discussed before, the cluster-head communication requirements are 48 Mbit/s over a distance of approximately 90 km.

For the baseband signal processing, we propose 3/4 LDPC coding along with OQPSK modulation and raised-cosine pulse shaping, in order to obtain a good balance between spectral and power efficiency [9]. Then, the 48 Mbit/s data-rate requirement for a cluster head translates into a bandwidth requirement of about 32 MHz.

Other considerations

The size of the nano-satellites is an important consideration for the antenna system design. For OLFAR, satellites based on a 3-unit CubeSat architecture, with dimensions of 10 cm $\times$ 10 cm $\times$ 30 cm [10], are proposed. In such a small device, the inner volume and surface area available for transceivers and antennas for inter-satellite communications are very limited, considering that it must also carry hardware for observation, digital signal processing and downlink, as well as equipment for other systems (navigation, power, thermal, mechanisms, etcetera).

Another important consideration for the antenna system design, specially for the radiating elements, is the frequency band. Although it may not impose system-level requirements or limitations, the frequency band is strongly related to the dimensions and performance of the antennas. Given the restriction on the size of the ISL antennas imposed by the dimensions of the nano-satellite, the frequency band used for OLFAR's inter-satellite communications must be above 2.4 GHz (as is discussed in the next section). Then, considering the required bandwidth of 32 MHz, we can assume that we work with a narrowband system.

A final (although equally relevant) consideration for the antenna system is the available power for inter-satellite communications. In nano-satellites, the energy harvesting and storaging devices are limited in size, and therefore in capacity [11]. For OLFAR, we estimate that the power available for inter-satellite communications for a cluster head will be around 4 W, assuming that it does not participate in the observation, signal processing and downlink tasks.

Requirements and limitations

From the previous considerations, we identify two main requirements and two main limitations for the antenna system design, shown in Table 1.

Requirements	**Limitations**
Transmission of a signal with a bandwidth of 32 MHz over 90 km must be possible	4 W are available for inter-satellite communications
The inter-satellite link must work in any direction	The available satellite inner volume and surface area is limited for radio hardware and antennas

Table 1: Antenna system design requirements and limitations.

Design aspects

Considering these requirements and limitations, we developed our design for three aspects of the antenna system, aiming for *simplicity*, *efficiency* and *flexibility*:

1. antenna configuration: number of antennas and their locations in the nano-satellite;
2. antenna system control: strategy used to ensure that the ISL works in any direction with minimum power consumption;
3. antenna characteristics: type, size, gain, polarization, etcetera of the individual antennas.

III. ANTENNA SYSTEM PROPOSAL

Antenna configuration

Since the ISL must work for any direction, several antennas will be used to cover the whole 4π sr (solid angle) range. Assuming that each antenna has a half-power (3-dB) beamwidth of Θ_{HP} with a circular cross-section and low side-lobes [12], the number of required antennas is

$$N_{\text{ant}} = \left\lfloor \frac{2}{1-\cos\left(\Theta_{\text{HP}}/2\right)} \right\rfloor \quad [1]$$

where $\lfloor\cdot\rfloor$ is the *floor* operator. If N_{ant} antennas are used (in an antenna selection scheme), the minimum gain of the antenna system would be slightly less than half of the maximum gain of the individual antennas, considering the errors produced by attempting to cover a spherical range with circular cross-sections.

Since the beamwidth of each antenna is related to its gain G [12] by

$$G \approx \frac{16}{{\Theta_{\text{HP}}}^2} \quad [2]$$

if more antennas are used, the required beamwidth is lower, which translates in higher individual antenna gain, and thus higher antenna system gain. However, as we mentioned before, the area in the surface of the satellite is very limited, to the point that the number of antennas for the ISL should be minimized.

We propose a configuration of six individual antennas, each with a 3-dB beamwidth of 90° and a gain of 5 dB, placed on the different faces of the satellite. Considering the minimum baseline of 10 km and the satellite size, the transmitter in an ISL can be considered as a point source by the receiver. Then, the exact location of the antennas in each face is not very relevant for the link performance and can be conveniently selected for coexistence with other devices. Figure 2 shows the proposed configuration for the antenna system.

Antenna system control

For the antenna system control strategy we propose a smart antenna scheme [13]. We implement this by multiplying the modulated baseband signal delivered to (or received from) each antenna by a specific complex weight. Then, switching, selecting and combining techniques can be used, along with direction of arrival (DOA) estimation algorithms [14].

For the calculation of the weights, we propose a beamforming scheme that maximizes the antenna system's directivity for any direction of transmission/reception (θ, φ). We assume that for each link direction, at most three individual antennas will participate, namely the ones that 'face' the other satellite. Then, we define a coordinate system centered in the corner of the satellite that corresponds to the faces that hold these antennas. Figure 3(b) shows the definition of the coordinate for the antenna system.

Furthermore, we assume that for each individual antenna i:

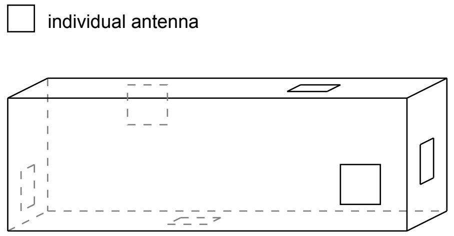

Fig. 2: Proposed antenna configuration.

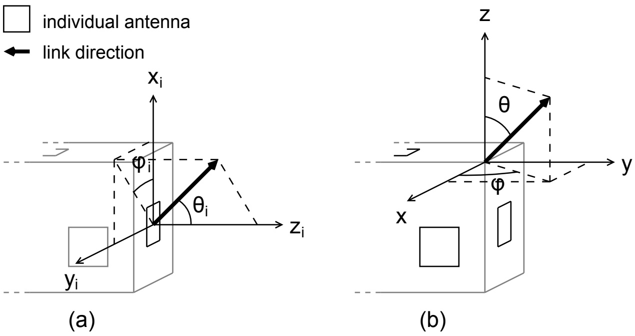

Fig. 3: Definition of (a) individual antenna and (b) antenna system coordinates.

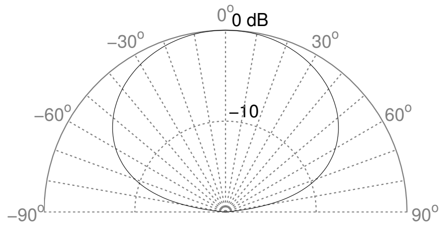

Fig. 4: Normalized 'ideal' individual antenna radiation pattern for all φ.

- the direction of transmission/reception refered to its local coordinate system is (θ_i, φ_i), as shown in Figure 3(a);
- the normalized directivity for this direction of transmission/reception is $D_i(\theta_i, \varphi_i)$;
- the (power) radiation pattern is proportional to $\cos\theta$, as shown in Figure 4;
- the distance from the antenna system coordinates' origin is d_i.

Then, the complex weight for each antenna can be calculated as:

$$w_i = \sqrt{c_i} e^{j\beta_i} \quad [3]$$

where

$$c_i = \frac{D_i(\theta_i, \varphi_i)}{\sum\limits_j D_j(\theta_j, \varphi_j)} \quad [4]$$

ensures that the power is distributed optimally, and

$$\beta_i = k\, d_i \theta_i \quad [5]$$

is the necessary phase change so that the fields from the different antennas add up in phase for a wavenumber k.

Figure 5 shows the resulting normalized antenna system directivity for $0 \le \theta \le \frac{\pi}{2}$, since it is symmetric for other directions. With the proposed beamforming scheme, an increase of up to 3 dB in the antenna system gain (compared to antenna selection) is achieved, which means almost maximal gain for any direction of transmission/reception. Considering the proposed configuration with 5 dB gain antennas, this compensation is a significant improvement.

Using this beamforming scheme along with DOA estimation techniques suitable for real-time systems, link-tracking algorithms can be implemented to provide self-aiming ISLs for a given cluster structure.

Antenna characteristics

The individual antennas for the proposed antenna system may be implemented using single radiating elements

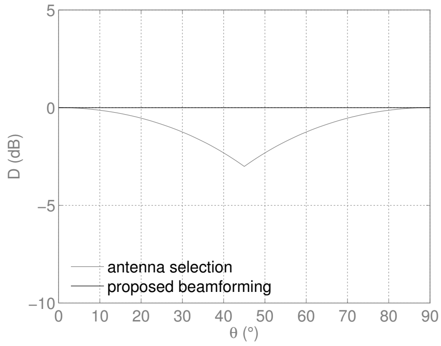

Fig. 5: Normalized antenna system directivity for all φ.

or with planar phased arrays, depending on the frequency band selected for inter-satellite communications. However, we first define the characteristics that are independent of the frequency band:

- bandwidth of at least 32 MHz;
- 3-dB beamwidth close to 90°;
- gain of at least 5 dB;
- right- or left-hand circular polarization;
- area of at most 9 cm^2;
- input impedance close to 50 Ω;
- radiation efficiency of at least 90%, given appropriate matching.

Circular polarization is necessary because there can be any orientation between the transmitting and receiving antennas. However, since the individual antennas have different spatial orientations, an additional phase compensation (with respect to a selected reference antenna) is required in order to perform beamforming for circular polarization. For antenna i and reference antenna r, with respective electric field directions $\mathbf{a}_{\mathrm{E},i}$ and $\mathbf{a}_{\mathrm{E,r}}$ for the given direction of transmission/reception, the phase compensation is given by

$$\delta_{\mathrm{cp}} = \cos^{-1}\left(\mathbf{a}_{\mathrm{E},i} \cdot \mathbf{a}_{\mathrm{E,r}}\right) \quad [6]$$

Single radiating elements, namely microstrip (patch) antennas, are proposed for frequency bands below 5 GHz. The resonance frequency f_{c} of a patch antenna in terms of its dielectric constant ε_{r} and length l is

$$f_{\mathrm{c}} = \frac{c}{2l\sqrt{\varepsilon_{\mathrm{r}}}} \quad [7]$$

so with a standard ceramic patch antenna ($\varepsilon_{\mathrm{r}} \approx 4$), bands as low as the 2.45 GHz industrial-scientific-medical (ISM) band can be used for the ISL antenna system. However, in order to keep a beamwidth of 90°, higher frequencies would require smaller antennas, with less effective area and thus lower gain. Then, the 2.45 GHz ISM band actually provides the best balance between antenna size and gain for the area limitation of 9 cm^2.

If higher-frequency bands are to be used, the individual antennas can be implemented with planar (or even conformal) phased arrays, at the expense of increased complexity and radio hardware. An array would have a narrower beamwidth and higher gain, but would also be able to steer its beam over the same range that a single patch antenna would cover, meaning that the individual elements that make up the array should have a 3 dB beamwidth of 90°. Assuming a linear relationship between the length of these elements and the wavelength, the size of the array would be

$$N_{\mathrm{elem}} = \left\lfloor \left(\frac{f_{\mathrm{c}}}{f_{\mathrm{c,min}}}\right)^2 \right\rfloor \quad [8]$$

individual elements, where $f_{\mathrm{c,min}}$ is the frequency that gives a radiating element area of 9 cm^2 for a given dielectric constant (for our proposal, $f_{\mathrm{c,min}}$ is 2.45 GHz). Clearly, the available area is exploited most efficiently for resonance frequencies that are multiples of $f_{\mathrm{c,min}}$.

For the ISL transmitter, the use of arrays increases the individual antenna gain proportionally to N_{elem}, which improves the antenna system gain (and narrows its beamwidth) for the same factor. However, the use of phased arrays in the ISL receiver implies a reduction in the effective area of each individual element, which compensates for the increased gain, and therefore the resulting antenna system gain will still be around 5 dB.

Antenna system performance

With the proposed design, an antenna system gain of 5 dB is obtained for any direction of the ISL. A link budget analysis for OLFAR's ISL with the parameters presented in Table 2 [9] results in a link margin of 1.2 dB, which we consider sufficient because it considers the worst-case scenario (in terms of data rate and distance) for OLFAR's inter-satellite communications.

Parameter		**Proposed value**
Ambient temperature	T_{amb}	353 K
Center frequency	f_{c}	2.45 GHz
Bandwidth	B	32 MHz
Link distance	r	90 km
Transmitter power	P_{T}	4 W
Transmitter losses	L_{T}	1 dB
Transmitter antenna gain	G_{T}	5 dB
Friis path loss	L	139.3 dB
Receiver antenna gain	G_{R}	5 dB
Receiver losses	L_{R}	1 dB
Signal-to-noise ratio	SNR	6 dB
Receiver noise figure	NF	4.6 dB
Noise floor	N	−107.1 dBm

Table 2: Link budget parameters for the proposed antenna system.

IV. CONCLUSIONS

After an identification of the relevant design considerations, a simple, efficient and flexible antenna system has been proposed for OLFAR's inter-satellite link. The proposal includes the antenna configuration, the control strategy and the individual antenna characteristics, and shows that an antenna system gain that satisfies the link budget requirements can be achieved for any direction of transmission. With the presented antenna system, robust and efficient inter-satellite links that are virtually transparent to the data stream are possible for a constellation of several free-drifting nano-satellites.

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