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Configuring a Large Formation of Communication Satellites for Optimal Electrical Power Generation and Antenna Beamforming

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Abstract

Formation-of-arrays (FoA) distributed antenna technology has recently been proposed to provide 5G-like mobile satellites services in the context of the integration of non terrestrial with terrestrial networks. This large distributed array configuration (resulting from the formation of many satellites each carrying its own small antenna) must be carefully engineered to provide the desired benefits. In this paper, we tackle the issue of optimal formation configuration to improve the performance in terms of system power generation and beamforming design. To this aim, we propose an algorithm based on a *formation thinning* approach with sparse random placement of satellites on a grid, to optimize both beamforming and power generation.

1 Introduction and motivation

Recently, satellite-based infrastructures have gained momentum thanks to the official introduction of non-terrestrial networks (NTNs) in Release 17 of the 3rd generation partnership project (3GPP) specifications for 5G standards [1]. Satellite technologies are already quite mature for backhauling and Internet of things (IoT), not so much for 5G-like services [2], so that a number of research activities have been recently launched to fill such gaps. This renewed interest has also been stimulated by ambitious private ventures, including Space X's Starlink, OneWeb, and Amazon's Kuiper [3] mega-constellations. A novel technology to achieve integration of NTN into 5G networks is the geostationary-orbit distributed very large antenna introduced in [4], called formation-of-arrays (FoA). Ref. [4] performs a system-wide analysis from a communication performance perspective (with special emphasis on end-user available bit-rate), and computes the benefits of this technology, based on phased array technology [5]. However, two relevant issues in the design and optimization of the FoA structure are not fully addressed in [4], namely: *i*) optimization of the power generation subsystem to feed each satellite array, and *ii*) configuration of the satellite formation to optimize the antenna beam pattern. The first aspect affects the fundamental function of providing electrical power to the satellite as well as the generation of radio signals for communication. Ref. [4] addressed the simplest arrangement of equipping the satellite with a single, two-faced array with radiating elements on one side and solar cells on the other. However, this solution is strongly suboptimal for power generation, since the array is forced to always point towards the Earth to sustain the communication link, instead of pointing towards the Sun for optimal power generation. To improve the performance in terms of power generation, in this paper we present a more conservative design, wherein the functions of radiating antenna and solar arrays are decoupled to optimize them individually. On the other hand, adopting a side-mounted steerable solar array introduces further constraints to the configuration of the formation of satellites that need to be considered when (also) evaluating the beam pattern. In fact, introducing an intra-formation large intersatellite gap may be favourable for power generation (to allow for the adoption of large, deployable solar arrays), but it may introduce undesired issues related to the generation of additional secondary beams (akin to the grating lobes of a conventional array alignment) [6]. The motivation of this paper is therefore clear: finding a jointly optimal formation configuration that provides high power yield and sufficiently good multibeam phased array pattern.

Many optimization techniques to solve the issue of secondary lobes have been investigated in the literature involving the thinning or displacement of radiating elements in an array, the main issue being the large number of optimization parameters when the number of radiating elements (for an array) and/or satellites (in our FoA) is large. In what follows, we will show how a simple probabilistic design approach [7, 8] can lead to good results. In particular, we will focus on the technique of *thinning* an oversized formation of satellites (keeping the structure of each satellite antenna unchanged) according to a certain probabilistic rule, so as to come to a final desired number of satellites in the FoA, as well as to place them at a desired minimum distance to consistently suppress emission sidelobes. Other issues arising in this context, such as coordination across the satellites in the FoA, impact of location and synchronization errors across the satellites, etc., are considered in [4, 9] (with solutions that may be adopted to reduce the impact in terms of architecture complexity with minimum performance reduction) and are outside the scope of the present study. After this introduction, Sect. 2 presents the methodology considered to jointly optimize power generation and array formation. Sect. 3 introduces some numerical results, whereas Sect. 4 draws some conclusions and outlines future directions for this area of research.

2 Methodology

The FoA architecture investigated in [4] makes use of a large number of satellites, each hosting one array antenna of the same size, that we will call sub-array (SA), as an elementary component of the (virtual) large active antenna for signal generation(/reception). Due to the large demand of power required by the direct to hand-held 4G type of application, the electrical power supply represents a very challenging task. As already mentioned, the simplest arrangement is integrating the solar cells and the radiating elements in a dual-face antenna/solar generator panel, with radiating elements of the SA side facing the Earth, and with solar cells on the other side. This arrangement, dubbed *body-mounted*, turns out to be *inefficient* since a geosynchronous earth orbit (GEO) satellite using this configuration would always point towards the same spot on Earth, therefore periodically changing the solar panel pointing with respect to the Sun. In so doing, the solar panel mounted on the back side of the SA will be completely shadowed from the Sun rays for roughly half of its daily orbit. We can compare the body-mounted arrangement above with that of a conventional GEO communication satellite adopting *i*) off-body solar generators (SGs) following the Sun orientation by means of a dedicated solar array drive mechanism (SADM), plus *ii*) a body-mounted fixed antenna pointed towards the Earth. It turns out that the body-mounted SGs go through an extended eclipse period of about 12 hours per day as compared to the much shorter eclipse lasting no more than 70 minutes (and only occurring during three weeks before and three weeks after the summer and winter solstices [10]) of the conventional Sun-facing GEO satellite. The longer and more frequent total eclipses would call for a much larger battery capacity (hence much larger on-board weight) to power the satellite payload during the longer eclipse time. In addition, the much higher (daily) number of charge/discharge cycles would tend to reduce battery lifetime unless the depth of discharge (DoD) is reduced. In other words, being the satellite platform attitude dictated by the communication requirements, a body-mounted SG solution is largely sub-optimal in terms of the solar array surface yield.

A way out of this impasse is to assume a more conventional configuration for each FoA satellite, in particular placing the SG at the side of the main (fixed) array antenna, with the capability to keep the panel always oriented towards the Sun by means of an appropriate SADM, so as to limit the duration of daily (partial) eclipses. Of course, this approach leads to specific constraints on the placement and orientation of spacecrafts in the FoA. To better understand the FoA eclipses' specific issues one can refer to [9], providing a detailed analysis of the phenomenon. In a nutshell, even when using a SADM for the FoA, any FoA satellite will experience a (longer or shorter) eclipse twice per day. This happens when some other FoA's satellite body or SG sufficiently close to the SG of interest is shadowing the Sun rays. The duration of the eclipse is clearly depending on the selected FoA geometry: worst-case shadowing occurs when one SG is masking the adjacent SG. This is because the (inclined) satellite body casts a smaller shadow on the SG of interest than the (parallel) nearby SG. To limit the duration of the SG-induced eclipse, it is necessary to ensure a sufficiently wide inter-satellite gap between two adjacent SGs in the formation. In addition, to keep the solar radiation as orthogonal as possible to the SG plane, the SADM should rotate it along the Earth north-south axis. The considerations above apply to a GEO FoA – the case of a low earth orbit (LEO) FoA is somewhat less critical: it is true that at LEO we have one eclipse per orbit, but its overall duration is much shorter than for the GEO case, requiring a relatively small battery capacity (independent of the kind of mounting of solar arrays) – as shown in [11] the maximum eclipse duration is 35 minutes, and its fixed solar array power conversion efficiency is reduced by the time-variant sunlight incidence angle. In the following, we will concentrate on the criteria to optimize a GEO FoA only.

As stated above, power generation is just one facet of the problem. The very reason of deploying a FoA is in fact being able to implement a very large equivalent antenna array, with very high overall radiated power and very nice features of beamforming/beam steering. A very large FoA may in fact generate a very narrow beam with a footprint size similar to that of a cell of a cellular terrestrial network. Unfortunately, as noted in [4], the introduction of gaps between the SA carried by each formation satellite creates undesired *grating lobes* in the FoA radiation pattern. To mitigate this issue, we adopt an approach akin to the well-known concept of *statistically thinned arrays* [7, 8], applied to the satellite formation: a thinned FoA (TFoA). We start from a very large number of potential satellite locations on a regular grid (what we called before an oversized FoA), and we perform thinning (i.e., sparsification, pruning) of the oversize formation to come to a desired number of satellites. Since the diverse satellites of the TFoA are (still) distributed across the original oversized area, we obtain a remarkably narrow beam size, and a total radiated power proportional to the number of actually deployed satellites. In particular, the thinning principle, while not affecting the direction of peak gain value, allows us to use a very small inter-satellite gap in the underlying (un-thinned) regular grid. Using configurations where the spacing across spacecrafts is in the order of the spacecraft size itself [4], FoA thinning provides almost the same behavior in terms of adjacent grating lobes as compared to the hypothetical un-thinned FoA with the same number of satellites, while significantly reducing the main lobe width, hence increasing the flexibility in terms of network planning and frequency reuse strategies. It is also true that adopting a very small inter-satellite gap may by un-

Figure 1. Possible elementary configurations of a 2-spacecraft box in the TFoA.

feasible when assuming off-body SG configurations as envisaged above, unless suited compatibility rules are added to a purely probabilistic thinning criterion - the subject of the next section.

3 Modified thinning algorithm and results

A customized TFoA approach can be derived to accommodate the constraints placed by the power generation issues mentioned in the Sect. 2, in particular to "allocate" satellites into the oversized grid. We assume that each spacecraft features a SG mounted on top of the satellite body and rotating along the Earth north-south axis, with the SG having the same size as the SA. Therefore, two adjacent SGs must keep a distance greater than the established inter-satellite distance Δ along the axis orthogonal to the previous one. According to this design assumption, we consider a "box" populated by 2 adjacent spacecrafts as the actual elementary unit for our allocation algorithm, so that the location/orientation of spacecrafts must follow one of the 6 possible configurations illustrated in Figure 1, where red and blue boxes depict the SAs and the SGs, respectively. Any configuration may or may not be acceptable according to the configuration of neighboring boxes, since *i*) the SGs can only sit on the top or on the bottom of the SA to be able to correctly operate the SADMs, and *ii*) the SGs of the current satellites box must not be immediately adjacent to any other SGs from other occupied boxes to prevent shadowing.

An overall TFoA configuration has strictly to enforce all of the constraints above – a practical algorithm to make sure of this has to be developed. The pseudo-code of our satellite thinning/allocation algorithm is shown in Algorithm 1, where S is the desired number of spacecrafts, Δ is the spacing across adjacent satellites, and q is the *thinning factor*: the actual position of each satellite in the TFoA belongs to a virtual grid of $N \times N$ locations, with $N = \lceil \sqrt{2S/q} \rceil$, where the factor 2 is used to accommodate room for the corresponding SG per each SA, and q serves to *thin* the virtual array, by discarding $(1-q)S$ box locations.

As can be seen in Algorithm 1, the possible box locations are selected randomly, and, for each selected box, the possible configurations compatible with the neighbouring boxes

Algorithm 1 Pseudocode for TFoA configuration.

Inputs:
- S, desired number of spacecrafts in the TFoA
- q, thinning factor
- Δ, spacing across spacecrafts

Output:
- $\mathscr{P}^\star$, coordinates of selected SAs

Code:

compute the number of SAs per row $N = \left\lceil \sqrt{2S/q} \right\rceil$
compute the set of $N \times N$ potential SA positions $\mathscr{P}$, each spaced by Δ along horizontal and vertical directions
map the $N \times N$ potential positions into $\frac{N}{2} \times \frac{N}{2}$ box positions $\mathscr{B}$, each box hosting 2×2 adjacent SAs
select a random permutation $\widetilde{\mathscr{B}}$ of box position indices
initialize the set of selected SA positions $\mathscr{P}^\star$
for $1 \leq \ell \leq (N/2)^2$ **do**
  identify $\widetilde{\mathscr{B}}(\ell)$-th box's neighbouring boxes
  compute the set $\mathscr{A}$ of box configurations compatible with such neighbouring boxes
  if $|\mathscr{A}| \neq 0$ **then**
    select randomly one configuration $a^\star \in \mathscr{A}$
    identify selected SA positions based on $a^\star$
    add $\widetilde{\mathscr{B}}(\ell)$-th box's corresp. positions to $\mathscr{P}^\star$
    if $|\mathscr{P}^\star| \geq S$ **then**
      break
    end if
  else
    ▷ do nothing, as $\widetilde{\mathscr{B}}(\ell)$-th box is not available
  end if
end for

are computed. If there exists at least one such configuration, a random pick is assigned, and the algorithm goes on until the desired number of spacecrafts S is reached. Note that due to the random nature of thinning, the actual final number $S^\star$ of allocated satellites is not necessarily exactly equal to S – the smaller is q, the wider are the satellites spaced apart, and so the closer is $S^\star$ to S since the probability that all constraints will always be satisfied for each random draw of satellites location will be higher.

An example of the outputs achieved by Algorithm 1 is shown in Figure 2, reporting the worst-case cut of the TFoA pattern (in which the azimuth angle φ equals the elevation angle θ – see [4] for further details) for different values of the thinning probability q. The plot is obtained with a constant desired number of satellites $S = 1089$ (each equipped with a SA with 49 radiating elements), and always assuming a final spacing of around 4.6 m between the spacecrafts (see [4] for further details). This means that the original grid of virtual positions is of different size for each q value (note that the case $q = 1$ implies no thinning, and hence the original FoA configuration considered in [4]). The im-

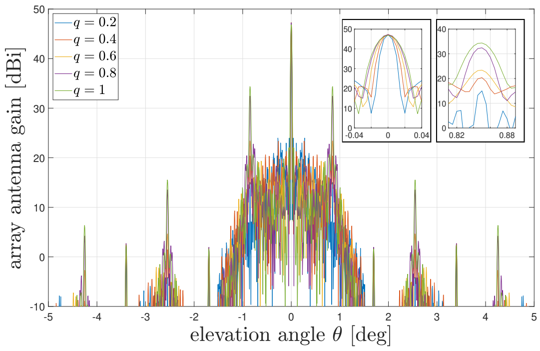

Figure 2. GEO TFoA worst-case ($\theta = \varphi$ plane) array factor for different values of the thinning probability q, $S = 1089$, and $\Delta = 4.6\,\text{m}$.

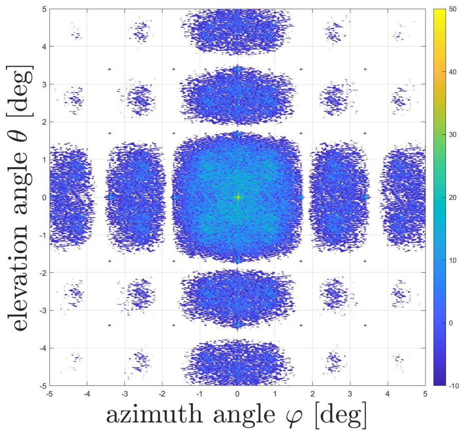

Figure 3. 2D map of the antenna gain for the GEO TFoA array factor for $q = 0.6$, $S = 1089$, and $\Delta = 4.6\,\text{m}$.

provement in terms of grating lobes and more in general of sidelobes is apparent compared to the unthinned version of the FoA, as can be seen in the magnification around the first grating lobe. For the reader's convenience, Figure 2 also contains a magnification around the main lobe, to emphasize the impact of thinning in terms of the main lobe width – which decreases as q decreases. The whole array pattern as a function of φ, θ is also shown in Figure 3 for $q = 0.6$, to appreciate the behavior of the array pattern across all directions.

4 Conclusion

This paper proposed a method to optimize the FoA architecture based on power generation and beam optimization criteria. This is achieved by an algorithm to design a thinned-FoA configuration, to obtain high gains using a limited number of satellites while considering room to accommodate the solar generators aboard the spacecrafts. Numerical results showed that, thanks to narrower beams and limited secondary lobes, the network area capacity can be significantly increased with respect to the FoA configurations considered in [4]. Further work is needed to investigate the impact of the proposed technique within a more detailed system modeling, considering realistic traffic distributions and radio resource management strategies.

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