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Analytic Design Techniques for MPT Antenna Arrays

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Introduction

Solar Power Satellites (SPS) represent one of the most interesting technological opportunities to provide large scale, environmentally clean and renewable energy to the Earth [1]-[3]. A fundamental and critical component of SPSs is the Microwave Power Transmission (MPT) system, which is responsible for the delivery of the collected solar power to the ground rectenna [2]. Towards this end, the MPT array must exhibit a narrow main beam width (BW), a high beam efficiency (BE), and a low peak sidelobe level (PSL). Moreover, reduced realization costs and weights are also necessary [3]. To reach these contrasting goals, several design techniques have been investigated including random methods [4] and hybrid deterministic-random approaches [2][3]. On the contrary, well-established design tools based on stochastic optimizers [5][6] are difficult to be employed, due to their high computational costs when dealing with large arrays as those of interest in SPS [3].

In this framework, a deterministic approach has been recently introduced for the design of thinned linear and planar arrays with low PSLs [7][8]. Such a methodology, which exploits the analytic properties of binary sequences called Almost Difference Sets [9], has provided predictable performances as well as negligible computational costs when designing large apertures [7][8], as well. It has been also proven that ADS arrays overcome random designs in terms of PSL both in the linear and in the planar cases [7][8]. However, their application to the design of SPS transmitting arrays has never been investigated.

In this contribution, the design of MPT arrays by means of ADSs is analyzed. The features of the resulting arrangements in terms of PSL, BE and overall weight reduction are investigated. Moreover, ADS-based techniques are analyzed in view of an improvement of deterministic placements as well as to synthesize different tradeoffs solutions in terms of performances, design simplicity/reliability, and hardware complexity.

ADS-based Design Techniques for MPT

Let us consider a planar uniform lattice of $N = P \times Q$ positions spaced by $s_x \times s_y$ wavelengths ($Q = 1$ stands for the linear case). A thinned array with K active elements ($\nu = \frac{K}{N}$ being the thinning factor) defined on such an aperture exhibits a power pattern equal to $F(u,v) = \left| \sum_{p=0}^{P-1} \sum_{q=0}^{Q-1} w(p,q) \exp\left[i2\pi (ps_x u + qs_y v) \right] \right|^2$, where $w(p,q) \in \{0,1\}$ ($p = 0,..,P-1, \quad q = 0,..,Q-1$) and $\sum_{p=0}^{P-1} \sum_{q=0}^{Q-1} w(p,q) = K$. By exploiting the ADS-technique outlined in [7][8], the design of a thinned array is carried out by the following rule:

$$w(p,q) = \begin{cases} 1 & if\ (p,q) \in \underline{A}\ \ (p \in \underline{A}\, in\, the\, linear\, case) \\ 0 & otherwise \end{cases} \tag{1}$$

where $\underline{A}$ is the (N,K,Λ,t)-ADS at hand (ADS construction algorithms [9] and repositories [10] are available). Thanks to the properties of the arrangement defined in (1), ADS arrays present favorable construction characteristics (all elements are equally weighted) and their synthesis is extremely efficient since any optimization is required whatever the array size. Moreover, thanks to the autocorrelation properties of ADSs, the associated arrays are proveide a PSL, defined as

$$PSL\left(\underline{A}^{(\sigma_x,\sigma_y)}\right) \equiv \frac{\max_{(u,v)\notin R} F(u,v)}{F(0,0)} \tag{2}$$

($\underline{A}^{(\sigma_x,\sigma_y)}$ being the cyclically shifted version of σ_x, σ_y positions of the original ADS and R the mainlobe region [7][8]), below that of random arrangements [7][8]. Furthermore, a single ADS can be exploited to obtain by means of simple cyclic shifts several trade-off array solutions in terms of both PSL values and other relevant parameters for MPT purposes (e.g., the beam efficiency

$$BE\left(\underline{A}^{(\sigma_x,\sigma_y)}\right) \equiv \frac{\int_R F(u,v)}{\int_{4\pi} F(u,v)}, \tag{3}$$

and the BW [2]). However, ADSs have some drawbacks. Indeed, they can provide only sub-optimal PSL performances for a given array size and thinning factor [7][8]. Moreover, they are not expected to provide high BE performances because the thinning and the equally-weights.

In order to improve the performances of ADS layouts for MPT, a computationally efficient approach based on the superposition of a tapering on the ADS layout (i.e., using a Gaussian distribution with edge tapering equal to T) [3] is considered. More specifically, the following weighting is used

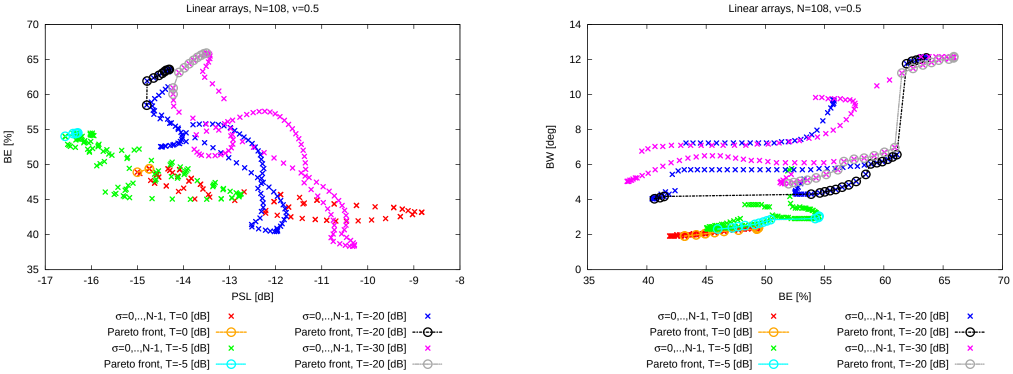
$$w_T(p,q) = \begin{cases} \exp(-D_{pq}{}^2)/\Sigma^2 & if\ (p,q) \in \underline{A}\ \ (p \in \underline{A}\, in\, the\, linear\, case) \\ 0 & otherwise \end{cases} \tag{4}$$

where $D_{pq} = \sqrt{\left[p - \frac{P-1}{2}\right]^2 + \left[q - \frac{Q-1}{2}\right]^2}$ and $\Sigma = \sqrt{\left(\frac{P-1}{2}\right)\left(\frac{Q-1}{2}\right) / \left[\ln\left(\frac{1}{T}\right)\right]}$.

Advantages/potentialities and drawbacks/limitations of "bare" ADS solutions and tapered ADS arrays are analyzed through numerical simulations in the following section.

Numerical Results

The first numerical experiment deals with the linear arrangements resulting from the (108, 54, 26, 27)-ADS with $s_x = 0.5\lambda$ [11]. The behavior of the BE vs. PSL of ADS arrays [Fig. 1(*a*) - $T = 0$ dB] points out that several tradeoffs can be obtained starting from a single binary sequence with good performances.



(*a*) BE vs. PSL (*b*) BW_{1D} vs. BE

Figure 1. (Linear case) – Features of the bare ADS-layouts and tapered ADS-arrangements for $N = 108$ (all cyclic shifts are considered).

However, while several different shifts correspond to good PSL values [Fig. 1(*a*)], the arising BEs are always below 50% because of the thinning factor ($\nu = 0.5$) at hand. In order to improve the *BE*, the effect of the Gaussian amplitude tapering is analyzed in Fig 1(*a*). As it can be observed, small T values correspond to significant improvements of the BE, while moderate T give the best PSL. On the other hand, bare ADSs displacement guarantees a lower beamwidth with respect to the tapered architectures [Fig. 1(*b*)].

Such a behavior is confirmed by the patterns of a representative ADS array and the corresponding tapered solutions (Fig. 2). As expected, the enhanced beam efficiency granted by the tapering is yielded at the expense of wider BWs (i.e., a lower directivity). Similar conclusions also arise when planar ADS arrangements are taken into account. Indeed, the figures of merit for the (529, 265, 132, 264)-ADS array with $s_x = s_y = 0.5\lambda$ ($P = Q = 23$) [11], shown in Fig. 2, confirm that $BW_{2D} = \sqrt{BW_{u=0} \times BW_{v=0}}$ increases as T decreases [Fig. 2(*b*)]. However, a stronger tapering gives a lower PSL as well as a higher BE (up to 65%) also in the planar case [Fig. 2(*a*)].

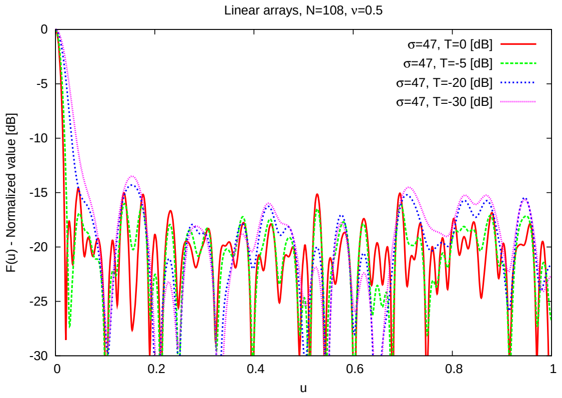
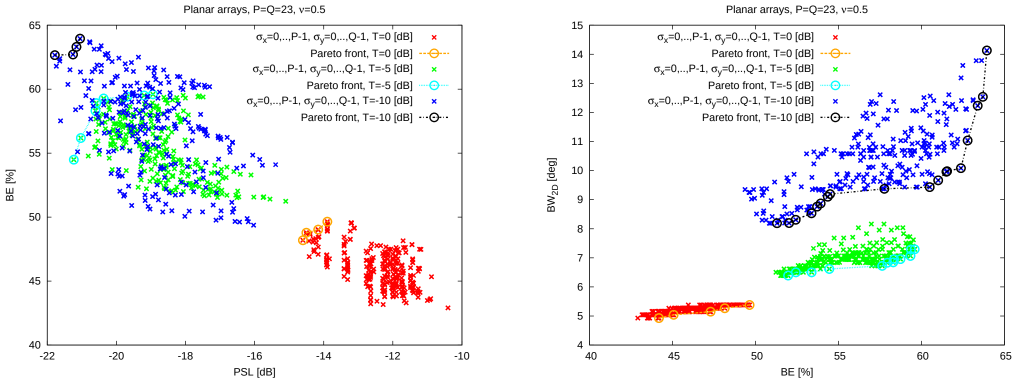


Figure 2. (Linear case - $\sigma = 47$) – Pattern of the bare ADS-layout and Tapered ADS-arrangements for $N = 108$.



(*a*) BE vs. PSL　　(*b*) BW_{2D} vs. BE

Figure 3. (Planar case) – Features of the bare ADS-layouts and Tapered ADS-arrangements for $P = Q = 23$ (all cyclic shifts are considered).

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