

An Overview of Gigascale Antenna Arrays and Electromagnetics for Space Based Solar Power

Timothy Pelham*, Xiaodong Chen, Brain Collins, Clive Parini and Anthony Brown†,

*Communication Systems & Networks Group, University of Bristol, Bristol, UK (t.g.pelham@bristol.ac.uk)

†School of Electronic Engineering and Computer Science, Queen Mary University of London, UK (xiaodong.chen@qmul.ac.uk)

Abstract—Gigascale antenna arrays (3 to 4 orders of magnitude larger than the largest ever built) are a critical component of proposed space-based solar power (SBSP) systems. The transmitting antenna arrays in orbit are expected to be up to $3km^2$, while the receiving arrays on Earth have been proposed at up to $77km^2$. There are many challenges and risks in the design, modelling, operation and deployment of the gigascale antenna arrays in the SBSP system. This paper highlights these challenges and risks, reviews existing solution and proposes novel approaches.

Index Terms—Beamforming, Antennas, Gigascale Arrays, Space-Based Solar Power

I. INTRODUCTION

Space based solar power (SBSP) is re-gaining interests worldwide due to the demands of renewable energy and net zero emission. This technology takes advantage of the higher, continuous solar flux in space to generate consistent solar power in orbit. This power must be transferred wirelessly to ground based receiving stations in order to provide useful power to the national grid, and two different technological approaches are proposed for this, microwave and optical power transfer. Due to the increased atmospheric attenuation for optical frequencies, and the increased power density of optical power transfer, microwave transfer is seen as a more attractive technology, and this review will focus on the challenges and technological approaches to microwave power transfer. The highest power microwave power transfer to date was demonstrated by Brown in 1975, transferring 34kW over 1.55km [1], using a rectenna array with an average collection and conversion efficiency of 82.5%.

Lately, several countries/region have proposed different solar power satellite (SPS) schemes, such as SPS-ALPHA (Solar Power Satellite via Arbitrarily Large Phased Array) in USA [2], SSPS Basic and Advanced Microwave Type models in Japan [3], SSPS OMEGA in China [4] and CASSIOPEIA in UK [5]. Though there are various differences between these schemes, the common feature is the utilisation of a gigascale phased array for beaming RF power to the ground rectenna. The gigascale transmitting antenna array is a planar array in most schemes [2–4], but a 3D array in a helical structure in CASSIOPEIA [5], as shown in Figure 1. There are many challenges and risks in the design, modelling, operation and deployment of a gigascale antenna array in the SBSP system. This paper highlights these challenges and risks, reviews the existing approaches and proposes innovative solutions.

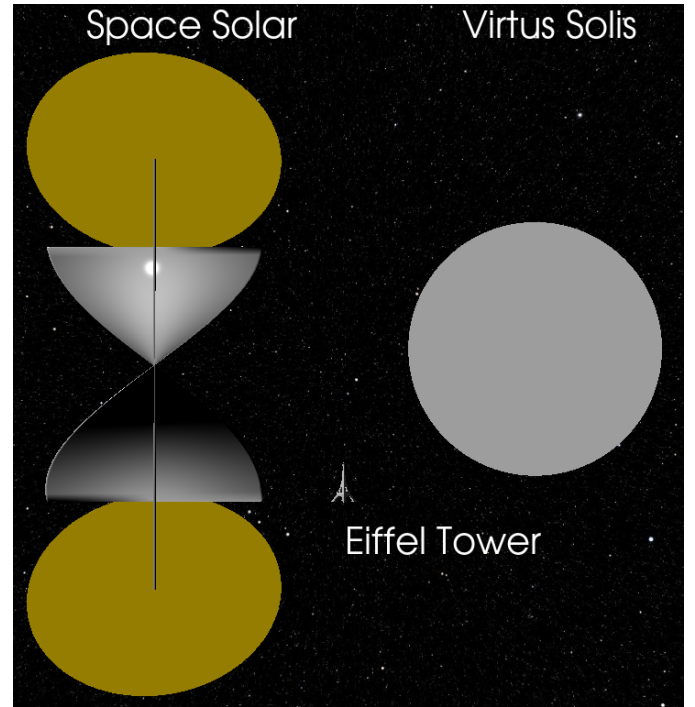


Fig. 1. Space Solar and Virtus Solis concepts for Geosynchronous Orbit, with the Eiffel Tower shown for scale.

II. DESIGN AND MODELLING OF GIGASCALE ANTENNA ARRAYS

The fundamental challenge to the design and operation of gigascale antenna arrays is centred in the scale of operations required. In order to transfer power wirelessly over long distances such as for space-based solar power the antenna arrays proposed are very large scale, with some of the earlier proposals calling for a transmitting antenna array 1km in diameter, with on the order of 16 million antennas, and a receiving rectenna array 10km in diameter with 1.6 billion antennas [6]. While large, this is only the smallest case for a geosynchronous fed rectenna array at the equator, as with higher latitude sites, the beam becomes elliptical, requiring larger elliptical rectenna arrays to capture the full beam. To consider the scale of the problem for design and modelling, merely the position and orientation of each element in the receiving array would require 106GB (using float32), without

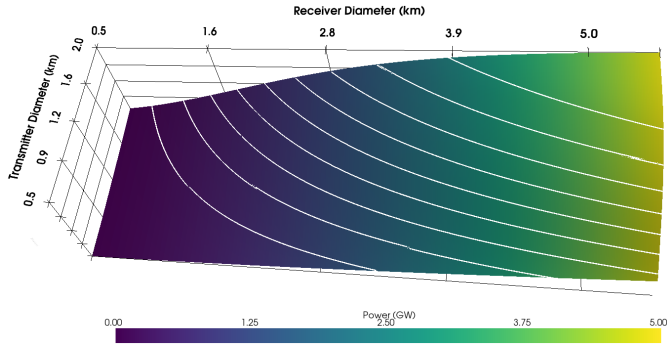


Fig. 2. Maximum Potential Transfer Efficiency and Generating Capacity with Antenna Array Size, showing efficiency as 10% contour lines for a 2.99GHz wireless power transfer system.

the geometry and materials information to design and model the array, together with calculated electric field vectors. One practical modelling approach would be the use of recursive module definition, as the majority of the design elements within the transmitting and receiving antenna arrays would be repeated across the structure.

The motivation for the size of the proposed systems is driven by desired wireless power transfer efficiency, derived by Goubou [7], relating the area of the transmitting (A_t) and receiving (A_r) antenna arrays, their separation (D), and the wavelength of operation (λ) to the maximum potential efficiency via Equations 1 & 2. This can then be used to calculate the maximum possible generating capacity of the system on the ground by relating the area of the receiving rectenna array to the selected radio power density, as shown in Figure 2. This examines the effects of transmitting and receiving antenna array diameter on maximum efficiency and generating capacity for a 2.99GHz wireless transfer system from geosynchronous orbit based upon a surface power density of $245W/m^2$. It is clear that independent of the frequency of operation, one of the critical system drivers is the desired power density of the power transfer beam. A range of potential values have been explored from $1W/m^2$ to $4kW/m^2$, and significant work remains on the implications for power density on the safety and interference potential of wireless power transfer [8].

$$\tau = \frac{\sqrt{A_t A_r}}{\lambda D} \quad (1)$$

$$\eta = 1 - e^{-\tau^2} \quad (2)$$

However, while this illustrates the scale of the issue for the design of Space-Based Solar wireless transmission systems, it is only part of the wider modelling and operations challenges. A key challenge for the design and planning of these systems is an understanding of the expected power density to be expected within the transfer beams, and the effects on the environment and general population, and conventional wireless devices that may be affected by interference. In order to implement these systems modelling capacity is required not merely for the

antenna arrays themselves, but also to predict the propagation of wireless power transfer beams for the wider area around the receiving antenna. LyceanEM is currently under development to support the required problem sizes, but significant high performance compute will still be required to consider the effects of large scale orbital power transfer beam sidelobes [9].

While a number of novel geometries have been proposed there is considerable work to be done moving from the higher level concepts to the detailed design at the module level [2, 5, 10, 11]. There is recognition of the need for in space assembly, and the array modules can be expected to be small enough antenna arrays to be designed and validated with conventional processes, and critically measured in existing facilities.

III. OPERATION AND DEPLOYMENT OF GIGASCALE ANTENNA ARRAYS

The most important technical challenge is maintaining the alignment of the transmitting antenna array so it is accurately directed towards the rectenna during the operation of SBSP system. This is not difficult to be achieved on an ideal planar phased antenna array if the beam steering angle is not too large. However, due to the impacts of gravitation, thermal and space weather, the planar gigascale array will be deformed. One simulation study has shown that the worst deformation of an array panel of $1km \times 1km$ would cause the beam to be shifted around 0.7 degree, which is equivalent to portions of the beam missing the rectenna by a potential 400km [12].

The current de-risking solution is to employ a retrodirective approach. A pilot signalling is transmitted from the rectenna to each transmitting antenna, then it is possible to use this signal to align and focus the down-link beam by adjusting the phase on each transmitting antenna. To further ensure the alignment of the transmitting antenna array, the phase of microwave power on each transmitting antenna is further adjusted by a Rotating-Element Electric-Field Vector (REV) method based on the beam intensity data received, as proposed by JAXA [2]. However, for a severe deformation of the transmitting array panel, this conventional phased array approach is not sufficient to compensate for the adverse effects on the transmitting array.

Another technical challenge in the phased array transmitter is to steer the beam over a large angle, which is required in CassiopeiA [5] and some low orbit SBSP demonstrators. When the beam is steered over a large angle, the gain of the array main beam will drop substantially because the synthesized beam is no longer aligned with the direction of maximum radiation of the individual elements. Also, it accompanies with the increase of the side lobes, which radiate the RF power to unwanted directions. This is a major problem in a solar WPT system adopting a phased array since it will cause a substantial drop of Beam Collection Efficiency(BCE). For example, a 3dB gain drop will cause a 50% BCE drop!

A new concept in antenna technology, the Vector Phased Array (VPA) is proposed to solve these two challenges in the SBSP transmitting antenna array. The basic idea of Vector Phased Array is to dynamically adjust the direction of

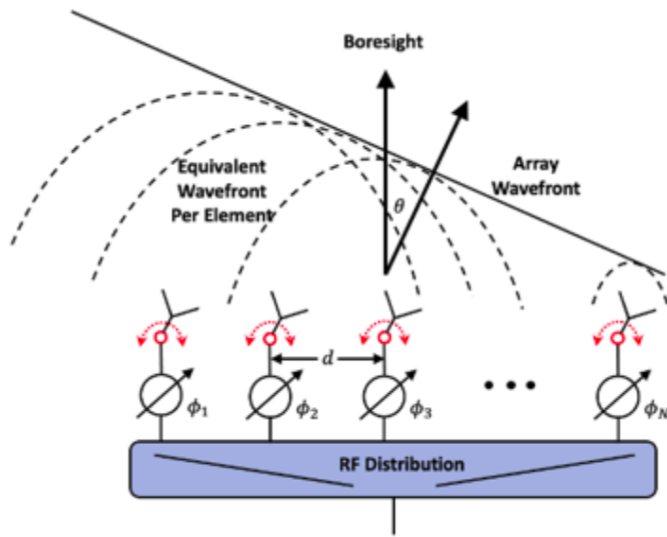


Fig. 3. A schematic of tiled offset fed reflector rectenna panel.

maximum gain of each antenna element, (the beam field vector direction), to align with the steered direction of the synthesized beam, as shown in Figure 3. This creates one more dimension of freedom to use in the antenna array technology. The conventional phased array varies only the phase and amplitude of the signal fed to each element, while the direction of maximum radiation from each element is fixed by its design.

The VPA can be used to compensate any scale of deformation of the transmitting antenna array surface in the space environment. Also, it can be used to maintain the gain of a large angle steered beam by reconfiguring the radiation patterns of the elements to align them with the steered direction of the synthesized beam. The feasibility of a Vector Phased Array is much dependent on the technology readiness of beam steering (pattern reconfigurable) antennas for the array element. Though technically feasible, the mechanical way (stepping motors) of adjusting the antenna element's orientation to steer the beam direction would add much more engineering complexity and challenges in the SBSP system. Therefore, the electrical approaches are much preferred.

There are several classes of electronically controlled pattern reconfigurable antennas (PRA). The first class of pattern reconfigurable antenna is the multiple port antenna with beam direction controlled by switched feeding or phase control. The basic principle is that each of multiple ports input ports excites one branch or one mode in the antenna, generating a particular radiation pattern. RF input to multiple ports can be switched on one by one, or combined to generate multiple patterns in different directions. The second class of pattern reconfigurable antenna is achieved through changing the antenna or its parasitic structures. The common methods for changing the antenna structure is to use PIN diodes, but these introduce unacceptable losses. The third class of pattern reconfigurable antenna is achieved through tuning both phase and amplitude of signals in a mini-array. An example

is the three omnidirectional antenna array (such as dipoles) proposed in CASSIOPEIA. The cardioid shape beam can be steered over azimuthal plane (360 degree) through adjusting both amplitude and phase of driving signals on the antennas. Obviously, adjusting both amplitude and phase of driving signals adds further engineering complexity and challenge. After reviewing a large number of references on the pattern reconfigurable antennas and considering all the engineering factors and the essential need for high efficiency, we have reached the conclusion that at present the first class of antenna is the most feasible pattern reconfigurable element for building the proposed Vector Phased Array transmitter.

Up to now, almost all the SBSP phased array transmitter demonstrators were developed based on the analogue phase shifting networks (RF integrated circuits), that are bulky, complicated and heavy. It poses quite an engineering challenge to deploy this kind of phased array transmitter in the SBSP system. In contrast, digital beamforming is now in widespread use in mobile radio base stations, and this has led to the miniaturisation and a fall in the cost of the associated hardware. Therefore, the digital beam-forming would lead to a solution in which a chip generating the required RF signal in the right phase, using direct digital synthesis, together with an RF power amplifier, would be located at each antenna element feed point. The complexity of digital control to the level of each antenna feed point may be non-optimal, requiring a very complex network operating at the high data rates to control and monitor the very large numbers of elements in the whole array. However, this could be addressed by creating a hierarchical control system such that required data rate is not excessive. It is also possible that the digital control system could be integrated with the DC feeds to the electronic assemblies, avoiding the use of separate subsystems, reducing weight and cost, while increasing reliability. Another advantage of digital beam-forming is that signals fed to the power amplifiers have the appropriate complex weighting (in amplitude and phase) generated prior to final amplification, maximising the efficiency of DC-to-RF conversion.

Since the first wireless power transmission system was developed, the rectenna has been envisaged as a planar array of discrete antenna elements (dipoles or patches) with embedded rectifying circuits, usually one rectifier per antenna element for easy construction. The RF-to-DC efficiency of the patch array rectenna is affected by many factors, such as unavoidable backward scattering, imperfect aperture efficiency (the ratio of RF energy captured to the whole RF energy falling on the array aperture), impedance mismatch due to mutual coupling between elements, and insertion loss of low-pass filters used to block harmonic re-radiation.

Though many efforts have made to improve the RF-to-DC efficiency through using metasurfaces, sub-wavelength antenna elements, etc., no solutions have been proposed to improve the aperture efficiency of patch rectennas. In addition, due to the small aperture of the patch ($< 0.5\lambda$), it requires an enormous number of units (10s of billions) to fill the area necessary to capture the maximum proportion of the total down-coming RF

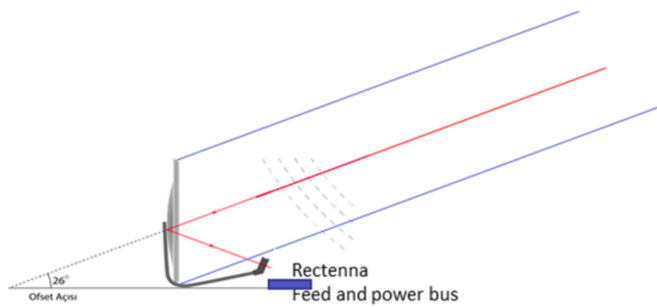


Fig. 4. A schematic of tiled offset fed reflector rectenna panel.

power.

All the drawbacks of patch array rectenna can be avoided or mitigated by the use of a reflector array rectenna. A reflector array rectenna can be arranged in a square panel array layout without gaps, ensuring maximal efficiency with a minimal number of rectenna units. The aperture efficiency of a typical reflector antenna is a trade-off between the feeding spill-over and the edge tapering. However, as the receivers in the ground rectenna, the reflectors do not require a coherent operation since only the DC power is added up at the end. We can minimize the tapering loss through adjusting the D/F ratio of the dish and the feed's beam profile to achieve a higher aperture efficiency. A small open ended waveguide array feed offers the best solution for maximising efficiency.

The aperture of each reflector may be very large (typically 10s -100s λ), being limited by RF rectifier capability and cost. To avoid the aperture efficiency drop caused by the blockage of feeding horn, a tilted offset reflector can be adopted when the rectenna is located in a high latitude site, such as UK, as shown in Figure 4. A ground demonstrator to verify the VPA solution together with digital beamforming in the transmitting array and the reflector rectenna is currently under development in Prof Chen's team at Queen Mary University of London.

IV. SUMMARY

The challenges and risks in the design, modelling, operation and deployment of the gigascale antenna arrays in the SBSP system have been highlighted in this paper. The existing solutions to address these challenges and risks have been reviewed to show their limitations. Several innovative approaches are proposed and under investigation to provide better solutions for the gigascale antenna arrays in the SBSP systems.

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