1. Introduction

Current and next satellite telecommunication services require the radiation of multiple high-gain, steerable and possibly reconfigurable, spot beams, in order to guarantee a flexible coverage of the areas of interest.

In this context, arrays whose elements are independently fed represent an appealing alternative to conventional array fed reflector antennas [1]. Within this class of arrays, which are referred to as Direct Radiating Arrays (DRAs), arrays having a non-periodic layout and a reduced number of elements, with excitations of equal amplitude (*isophoric*), are particularly attractive, since they exhibit remarkable advantages with respect to standard periodic architectures [2]-[5]. Indeed, the adoption of aperiodic layouts is particularly attractive in terms of both cost and physical feasibility, since they allow to achieve practically the same performances of the periodic ones, with a significantly smaller number of control points. Moreover, in the isophoric case, all the feeding solid state power amplifiers may operate at the same (and thus optimal) working point, thus allowing to optimize the overall power efficiency.

There are essentially three possible architectural choices for such kind of arrays, namely: *thinned* arrays, *clustered* arrays and *sparse* arrays. Thinned arrays are obtained removing a subset of elements from a standard periodic array. Clustered arrays are DRAs whose layout is fixed *a-priori*, but the elements are clustered in subarrays, in order to reduce the number of control points. In the case of sparse arrays, the elements location can be arbitrary, possibly under some geometrical constraints (f. i., a minimal inter-feed distance, to avoid their overlapping).

Whatever the architectural choice, the synthesis of such arrays is by no means an easy task, since it is a strongly non-linear and non-convex problem. Therefore, local optimization procedures may be trapped into ‘local minima’, which may be far from the global optimum without a-priori knowledge of a sound starting point. On the other side, global algorithms are strongly limited by the problem size [6], due to the large number of unknowns typically involved in the case of satellite antennas. Therefore, smart approaches aimed at obtaining a (computationally) efficient and effective sub-optimal solution, near to the global optimum, are needed. In this context, following the pioneering procedures proposed in the early sixties [7]-[12], several approaches have been proposed in the recent years[2]-[5], [13]-[25].

In this work, we present an overview of the results achieved by a team from four CNIT research units (Università Federico II, Università di Cassino, Università Parthenope and Università Mediterranea di Reggio Calabria) in the frame of two Invitations To Tender (ITTs) of the European Space Agency (ESA) to which the team participated as subcontractor for Space Engineering SpA. Both ITTs were focused on the design of isophoric sparse arrays for geostationary (GEO) satellite communications [26], [27]. More specifically, according to the ESA requirements in [26], [27], we considered three different application scenarios:

- sub-regional Earth coverage by means of narrow and steerable beams;
- full Earth coverage by means of narrow and steerable beams;
- full Earth coverage by means of steerable beams switchable between two widths.

As a preliminary step, by referring to the first application scenario, we have compared the three above-mentioned architectural choices, in terms of achievable performances and minimization of the number of control points. To this end, a new and effective synthesis approach has been devised, in order to avoid computational complexity as well as providing a

Inverse problems in antenna radiation and diagnostics

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Abstract: *The inverse source problem consists in the reconstruction of a source current from radiated field data and can be found in many antenna synthesis and diagnostics problems. A stable solution algorithm makes use of the spectral decomposition of the relevant linear radiation operator (i.e. the Singular Value Decomposition), which depends on both the source and the observation domain geometries. Analytical results are discussed with applications to conformal arrays synthesis and diagnostics and the optimal discretization of the near field for antenna testing purposes.*

1. Introduction

Solving an inverse source problem, and more in general an inverse problem, consists in finding causes from the knowledge of their effects. As opposed to the so-called forward problems, inverse source problems entail, in some sense, to reverse the "causality law" (for this reason they are also addressed in literature as causation problems) [1]. This generally makes inverse problems ill-posed [2], which, in short, means that they are much more difficult to solve than their forward counterpart [3]. Causation problems are obviously innate in human thought and actually we solve them many times in everyday life. Indeed, literature is rich of contributions reporting about inverse problems, although, in general, not under the precise mathematical setting under which we now conceive them [4]: think, for examples, to the Plato's cave myth, where chained people must infer reality from shadows on the wall they can watch [5], or to the Le Verrier's discovery of Neptune, which is a famous example of an inverse problem that demanded an identification of the cause. Indeed, the "mathematical formulation" of inverse source problems is relatively recent. Maybe, the first attempt in that direction is the study of Abel's (which only dates back to 1826) concerning the mechanical problem of finding the curve of an unknown path [6]. Since then, inverse source problems (and more in general inverse problems) have been (scientifically) studied in order to investigate a vast range of problems, practically in all fields of engineering sciences [7]. Actually, inverse source problems have triggered a great deal of research effort that produced a large number of methods and tools [8] with new ideas still continuing to be fed in the field [9].

The corresponding literature is huge and it would be impossible to give a comprehensive account of it. Accordingly, here, we just spotlight a narrow beam on some aspects of inverse source problems by focusing only on a few topics we have been concerned with in our research activities. More specifically, the physical framework is "non-stationary" electromagnetic inverse source problems whose mathematical foundations are provided by the wave equation. Accordingly, the problem consists in reconstructing an electric current (or/and an equivalent magnetic current) from electric (and/or magnetic) field measurements [10], [11].

As well known, reconstructing the current from field measurements is a typical problem in electromagnetics arising in several important applications. For example, in the synthesis problem, one is interested in determining the source distribution that allows to obtain the assigned radiated field (more often the radiation pattern) [12]. In antenna diagnostics, field

Blending Electromagnetic and Information Theory in Antenna Synthesis: Theory, Applications and Perspectives

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Abstract: *The aim of this contribution is to summarize some results regarding how much information can be reliably transmitted over a wireless channel, and how to use this theory in the framework of antenna synthesis. Using the theory developed by Kolmogorov it is possible to quantify the amount of information that can be transmitted by a wireless communication system taking into account the physical limitations governed by the laws of electromagnetism. Starting from the results related to the amount of information carried by an electromagnetic field, an example of antenna synthesis strategy that simultaneously takes into account the requirements of information and antenna theory is shown.*

1.Introduction

In the last decades there has been a dramatic improvement in the bit rate of wireless communication system. Loosely speaking, the attention in past generations of personal communication systems was focused on signal processing. However, the fast-growing demand of videos and other bandwidth-intensive services on cellular phones requires new technological advances at the physical layer level. Antennas offer large possibilities of improvements, as also testified by the interest toward active antennas and Multiple Input Multiple Output (MIMO) arrays in 5G communication systems. In particular, in modern communication systems the use of the space resource, besides the classic time resource, is a key factor to increase the bit rate. The approach followed in 5G is still classic, and antennas and signal processing are treated as separate entities. However, from the wireless communication system perspective the final goal of an antenna is to transmit information selectively in the space. This observation suggests to characterize antennas also by their ability to transmit information. To reach this goal it is necessary to study the relationship between information theory and electromagnetic theory and how electromagnetic theory limits the amount of information reliably transmissible by a wireless system.

In order to clarify the role of the electromagnetic field, let us introduce a trivial example. The most successful ancient communication system was based on reliable riders on horseback. The task of the horseman was to keep the mailed documents safe while riding the horse. The job of the horse was to bring the horseman and the documents intact to the final destination as fast as possible. The question is: how many documents can this communication system carry at a time? The horseman is capable of carrying a large number of documents, but only if the horse can bear their weight. When the horseman's bag is too heavy, the horse stops running.

Large Sparse Array Synthesis for 5th Generation (5G) Communication Systems

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Abstract

In this contribution we are going to discuss the importance of array synthesis for 5G applications. In particular, we will show that in massive MIMO applications, when dealing with mm-wave frequencies, that provide an almost Line-of-Sight propagation condition, the use of equispaced arrays is far to be optimal. We then discuss a method for the efficient synthesis of very large sparse arrays, showing that the use of the obtained non equispaced array is beneficial for massive MIMO applications.

I. Introduction

The progress in communications systems in the latest years has been, undoubtedly, spectacular. With reference to mobile communications, we went from the first (1G) networks with few contemporary users, that were capable of transmissions with very limited bandwidth, to the latest (5G) networks where hundreds of contemporary users can have a communication bandwidth with a quality comparable to that of a good ADSL connection.

This evolution has not stopped. In order to reach the challenging performance promised by the 5th generation communication systems, in terms of number of contemporary served users, bandwidth, and latency [1], future antenna systems are going to exploit the use of huge antenna arrays [2]. The use of very large antenna arrays for civil applications is going to be enabled by the use of mm-wave frequencies, where arrays of hundreds of wavelengths could indeed have a manageable size.

Even if a huge research effort has been focused on 5G communication systems up to now, a minimum part of this effort has been specifically devoted to the optimization of the array geometry in 5G environments, and most contributions are still based on simple array models having half-wavelength equispaced geometries [3]–[14]. In most of the papers published up to date, the physics of propagation is not considered at all, and the importance given to the antenna array is really limited.

Actually, array geometry is an important degree of freedom in the design of 5G communication systems, that can help to improve the overall capacity of the network. Non equispaced geometries have already been shown to be beneficial in MIMO applications [15], and recent studies show that equispaced positioning of the elements is not optimal for Line-of-Sight (LoS) massive MIMO systems [16], so the use of sparse, non-equispaced geometries could be of great help in these kinds of applications.

It is well known, in the antenna community, that sparse arrays have a number of significant advantages with respect to equispaced ones; in particular we can avoid the appearance of grating

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Optimal Trade-Off Synthesis for Future Generation Phased Arrays @ ELEDIA Research Center

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Abstract: *Antenna arrays are a key technology enabling a huge number of applications in our everyday lives. They are used in communications, radar, navigation, remote sensing, radio-astronomy, and in many other systems. Pushed by the continuous growth of wireless services, antenna arrays have significantly evolved since their introduction. In recent years, modern applications (e.g., 5G, satcoms, autonomous driving) are imposing more and more challenging constraints and requirements on antenna arrays. These include the need for multiple functionalities, large bandwidth, and high reconfigurability. These additional functions add significantly to the cost, the complexity, and the weight of the array, but they cannot be jointly accomplished without a careful consideration of the overall array architecture. Recent advances in the development of high-power amplifiers, analog-to-digital converters, and artificial materials have enabled new array architectures. Indeed, advanced array architectures, including sparsity through thinning or adding some functionalities at the subarray level, can help to incorporate these extra capabilities, albeit with trade-off in terms of gain or aperture efficiency and potentially increased sidelobes as compared to conventional array solutions. This technical report will focus on state-of-the-art and most recent methodologies for the design and synthesis of advanced unconventional arrays, by discussing capabilities, limitations, and perspectives.*

1. Introduction

Phased array antennas are key components in the development of communication and radar technologies [1]. Thanks to their high flexibility and reconfiguration capabilities, such antennas are suitable devices for 5G and their next generation systems. However, the cost represents a heavy obstacle to their wide diffusion in the commercial wireless industry, especially when dealing with large fully-populated arrays where each element is equipped with an expensive

Recent Advances in Leaky-Wave Antennas: From Far-field to Near-field Applications

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Abstract: *Leaky-wave theory has fruitfully been exploited since many decades to design a class of frequency-scanning microwave antennas and arrays. In the last years, the role of leaky waves in the efficient description of radiation phenomena has proven to be an advantageous means to realize further innovative antenna functionalities. These functionalities involve features useful for various recent appealing applications (5-G communications, wireless power transfer, etc.), such as far-field pattern and polarization reconfigurability, wideband broadside radiation, as well as near-field limited-diffractive beam focusing. The research advances in these contexts are reported here, with specific attention to planar leaky-wave radiators operating in microwave, millimeter-wave, and terahertz ranges.*

1. Introduction

Leaky-wave antennas (LWAs) are traveling-wave antennas, capable of producing a directive beam of radiation that can possibly be steered by varying the frequency. Owing to their ease of fabrication, simple feeding scheme, cost-effectiveness, low-profile, and straightforward design, LWAs became attractive in the early ‘60s for microwave applications, especially in remote sensing and telecommunications [1–6]. More recently, LWAs and more in general leaky waves have found application at higher frequencies, and various realizations are being currently proposed at millimeter-wave frequencies up to the visible range [7], including the more exotic terahertz (THz) range [8].

However, these relatively new applications required LWAs to exhibit unconventional radiating features, thus stimulating novel and fascinating research pathways in the field of leaky-wave theory. Interestingly, just to give but a relevant example, it has recently been shown that leaky waves can fruitfully be exploited not only to optimize the *far-field* properties of LWAs, but also to tailor their *near-field* distribution to obtain focused radiation [9, 10].

Therefore, after a brief introduction aimed at reviewing the general properties of LWAs (Section 2), we will separately discuss the recent advances in the context of far-field (Section 3) and near-field (Section 4) applications. Specifically, in Section 3 we will discuss the efforts made in improving the performance of Fabry–Perot cavity (FPC) LWAs (Subsection 3.1) and of periodic LWAs (Subsection 3.2), with emphasis on the possibility of achieving wideband and highly-directive broadside radiation, as well as beam-scanning capabilities at fixed frequency. In Section 4, we will discuss the generation of focused radiation in the near-field regime in

Metamaterials for Radiating Structures with Enhanced Functionalities

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Abstract: *In the related scientific literature, a metamaterial is typically considered as an arrangement of artificial structural elements, whose dimensions, separation, and constituent materials are properly designed to achieve advantageous and unusual electromagnetic properties. The advent of this intriguing and prolific research field can be dated back to 1999-2000, when negative refractive index materials, only theoretically envisioned in 1968 by Victor Veselago, were realized and experimentally characterized. This was followed by twenty years of intense and still growing investigations on their fundamental properties, design concepts and techniques, numerical and analytical modeling, and possible realistic applications. Originally proposed at microwaves, metamaterials are now a paradigm that can be applied in different areas of physics, such as terahertz and optical frequencies, as well as in acoustics, mechanics, hydrodynamics and thermodynamics. Nevertheless, one of the more active and prolific application field of metamaterials is still at microwave frequencies, where metamaterial concepts have been used to overcome the inherent limitations of conventional microwave components or to propose innovative systems based on new wave phenomena. Fundamental element of almost every microwave system is the radiating element that, thus, has been subject of intensive research by the metamaterial community at microwaves. This Chapter gives a brief introduction and classification of metamaterial-based and metamaterial-inspired antennas. In particular, the potentials, as well as, the challenges in metamaterial antenna engineering will be reviewed and discussed. Particular emphasis will be given to some examples of metamaterial concepts successfully employed to meet industrial needs in the design of radar and telecommunication systems. Moreover, our latest insights and achievements on this topic will be provided.*

1. Introduction

Wireless systems are ubiquitous in modern life, being integrated on most of our devices such as smartphones, smartwatches, handheld tablets, and GNSS systems. Their proliferation has requested great research and industrial efforts on both the user terminals and network infrastructures, with the main objective of supporting, in a single and compact device, several communication standards with different communication paradigms, operative frequencies, bandwidths, etc. Within any wireless system, a crucial role is played by the radiating element that, for satisfying increasingly stringent requirements, is typically designed to be compact,

Metasurface Antennas

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Abstract: *The purpose of this work is to present some of the most recent antenna prototypes relevant to a new class of compact and light weight antennas based on modulated metasurfaces (MTSs). Metasurfaces technology recently opened for the possibility of implementing a variety of new and uncommon devices; for this reason the latter assumed a growing importance as a research topic in microwave domain and antenna community, mostly thanks to their capability of implementing flat antennas. The key feature of modulated metasurface antennas indeed consists in conveniently exploiting the interference phenomenon between a guided surface wave (SW) wavefront and an artificially tailored surface impedance, which is periodically modulated and generally assumes a tensorial form. By interference, the impressed field is thus transformed into a series of generalized curvilinear wavefront Floquet modes, one of them entering in the visible range. The equivalent boundary conditions provided by the MTS can easily be customized in terms of the modulation phase and amplitude in order to reproduce a desired aperture field profile. Due to the large variety of aperture fields that can be synthesized, this kind of modulated apertures are eligible to comply with even peculiar and demanding constraints. The MTS impedance surface is commonly implemented, at microwaves regime, by using patches of different dimensions that can have various shapes; nevertheless some solutions have been proposed to extend the MTS applicability range at Terahertz regime. In this chapter we introduce a novel design approach for determining the requested aperture field. Next, it is treated the MTS synthesis by sub-wavelength printed patches and aperture analysis; finally different examples of designs and antenna implementations are shown, featuring, high gain, shaped patterns, multiple beams, broadband and dual frequency operations.*

1. Introduction

Metasurfaces (MTSs) are thin engineered layers that comprise a homogeneous background constituted by a grounded or non-grounded dielectric periodically loaded by small inclusions whose geometrical features are properly varied in space for modulating the macroscopic host medium properties in the desired manner [1]. Several different kinds of devices have been recently proposed in literature, which implement surfaces showing peculiar properties in reflection or transmission of space waves [2], [3] or able to alter the dispersion of surface waves [4]-[12]. At the microwaves range MTSs top film is represented by sub-wavelength printed metallic elements [13]-[24] disposed on a regular grid, usually a Cartesian or hexagonal lattice, or in the Terahertz domain elements can be constituted by protruding metallic pins on a ground plane [25]-[27].

Conformal Phased Array Diagnostic by Fast Matrix Method

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Abstract

Near-field data are used as diagnostics tool to reconstruct the aperture field distribution of conformal array antennas and identify defective element. The matrix method is used for the diagnosis of faulty elements in large conformal arrays antennas. The problem of inversion and regularization of resulting matrix is addressed. A new sampling method is proposed and successfully compared, in terms of computation time, with other existing approaches.

1 Introduction

The identification of faulty elements in large antenna arrays, that can cause performance degradation in terms of gain and sidelobe levels, is a problem of practical and theoretical relevance.

The most commonly adopted method to reveal faulty in an antenna array is the Back Propagation Method (BPM) [1]. This method, because based on the Fourier Transform relationship between the fields on the array aperture and the measurement plane, works only with planar array and consequently planar measurement plane. The sampling step adopted is obtained by the Nyquist theory and in many practical cases is equal to half-wavelength. Accordingly, the number of measurement points and consequently the time required for data acquisition becomes large.

Recently conformal arrays have been developed to obtain the possibility to conform to the shape of the antenna to an airplane, high-speed train, or other vehicle. Furthermore selecting shape cylindrical, conical, spherical or other exotic forms is possible to obtain a beam agility in direction and shape not reachable with planar arrays.

Near-field measurements can be used as diagnostic tools to reconstruct aperture field distribution of conformal array antennas and to locate their possible defective elements.

The matrix method for array diagnosis, first introduced in [2, 3, 4], is based on the reconstruction of the excitation from measured near-field data

Phaseless Antenna Diagnostics via Compressive Sensing

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Abstract: *A review of some research activities on array antennas diagnostics the CNIT unit of the University of Reggio Calabria is presented. In particular, the Authors developed a novel approach on this subject which has the interesting characteristics of being based on amplitude-only measurements of the radiated field while exploiting the Compressive Sensing theory. As a result, the array diagnosis can be successfully performed through a small (and provably non-redundant) number of phaseless measurements in both cases of linear and planar arrays, also in case where mutual coupling effects are present.*

1. Introduction

New applications push towards multi-band and possible reconfigurable antennas. In turn, such a circumstance implies the need for new fast and possibly inexpensive ways to characterize the antennas at hand at the different modalities.
In this context, the exploitation of the Compressive Sensing (CS) paradigm has been proposed as a fast and effective way to provide a fast on-off diagnosis of the elements of an array [1,2,3]. The basic idea underlying the proposed approach is that one can define a virtual array whose excitations are essentially the difference amongst the reference (ideal) array, and the actual (faulty) one. As a result, the excitations of the virtual array can be considered to be sparse, so that CS theory and tools can be profitably exploited.
On the other side, the quest for higher and higher frequencies for 5G, radio astronomy, and many other cases implies possible difficulties in the amplitude and phase measurements of antennas, and 'off' elements are not the unique case of faults in arrays and more general in antennas. In such a scenario, we have proposed in [4] a new technique for the (array) antennas diagnostics which just need phaseless measurements. The basic concept underlying the approach is that, in case of a few faults, square amplitude measurements of the field radiated from the faulty array still depend in an essentially linear fashion from the excitations of the virtual array, so that the CS theory and tools (amounting to solve a Convex Programming problem) can be exploited again.
Later, we have generalized the results of [4], which just can be used in case one can define an array factor, to the case where mutual coupling plays a role, as well as to (large) planar arrays [5]. In particular, we argue that new effective representations of aperture field (paralleling the Active Element Pattern, but with reference to the equivalent source rather than to the far field) can be profitably used, which suggests that the technique can be extended to the case of sources other than arrays.
In the following, the devised diagnosis procedure is resumed in Section 2, while Section 3 report some test cases. Conclusions follow.

Recent developments in the Near-Field to Far-Field transformation techniques @ UNISA

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Abstract: *The research activity carried out at the University of Salerno on the near-field to far-field (NF-FF) transformation techniques using the classical scans and on the innovative ones, wherein the NF data are acquired along spirals wrapping the traditional scanning surfaces, is reviewed in this chapter. Such an activity has remarkably improved the NF measurement systems. These improvements are based on the application of the nonredundant sampling representations of the antenna radiated electromagnetic fields to the voltage acquired by the scanning probe. The so developed nonredundant NF-FF transformations employ an optimal sampling interpolation (OSI) expansion to accurately reconstruct the massive NF data required by the corresponding classical transformation from the collected nonredundant samples, thus allowing to get a remarkable measurement time-saving. A further saving of such a time is achieved by the developed NF-FF transformations with spiral scannings, where the NF samples are acquired on fly by continuous and synchronized movements of the probe and of the antenna, thus making faster their acquisition. An OSI expansion is employed also in this case to recover the NF data needed by the NF-FF transformation using the corresponding classical scan from the nonredundant samples gathered along the spiral.*

1. Introduction

Chapter aim is to review the research activity, performed at the UNiversity of SAlerno (UNISA) in the last thirty years, on the optimization of the near-field to far-field (NF-FF) transformation techniques employing the conventional scans and on the development of those using innovative spiral scans. Such an activity, which has produced very significant improvements in the performances of the NF measurement systems, has been carried out for a long time in strict cooperation with Professors Ovidio Mario Bucci of University of Naples "Federico II" and Catello Savarese of University of Naples "Parthenope" and is continued with this last until his dead on December 2007.

As well-known, the NF-FF transformation techniques [1-7] have been widely employed in the last fifty years to accurately determine, from NF measurements performed in a controlled environment, as a shielded anechoic chamber, the far field radiated by antennas, whose sizes with respect to the wavelength do not allow the fulfillment of the FF distance requirements in an anechoic chamber. These techniques usually consider the electromagnetic (EM) field radiated by the antenna under test (AUT) as summation of modes, which are elementary solutions of the vector wave equation in a free sources region. Plane, cylindrical, or spherical waves are generally employed. The kind of modal expansion adopted to represent the field determines the type of the NF scanning surface, which accordingly will be a plane, a cylinder, or a sphere. From two sets of amplitude and phase measurements of the voltage detected by the measuring probe in two its different orientations on a proper grid of the scanning surface, it is possible to determine, by exploiting the orthogonality properties of the modes on these surfaces and properly taking into account the probe effects, the modal expansion coefficients. These last, once substituted in the expansion valid in the FF region, allow to accurately reconstruct the AUT radiated far field [4, 5].

By properly applying the nonredundant (NR) sampling representations of the EM fields, radiated

Computational-enhanced antenna and platform measurements/characterization

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Abstract: *This contribution deals with practically provable ways to enable performance evaluations with infrastructures and/or times and costs that would not be possible otherwise. This involves large and complex antennas, or mounted on large platforms, as well as more conventional or simpler cases but where testing time is crucial. Typical examples are antennas for satellite applications, automotive radars, and 5G. The technologies involved in this report are based on adding information on the device under test via simulation of parts of the structure, and/or use of existing measurements of parts thereof. The methodology can be used also with non-canonical grids, and when only a limited number of measured points is available.*

1. Introduction

Characterization of antennas via experimental procedures, or *measurement* at large, is a technological issue of recognized importance. The task has witnessed a steady increase in demands, due increasing complexity of antennas, the frequent need to assess radiation performances of antenna mounted on platforms, the need to carry out a reliable test in reduced times, or, finally, at a reduced overall cost.
Also, when the antenna is housed on a complex platform (e.g. a satellite), one sometimes cannot conduct a measurement with the necessary number of samples for reasons of accessibility, or because of geometrical size of the necessary sampling infrastructure.

In most situations of practical interest, while one is interested in far-field (FF) radiation, measurement in the near field (NF) of the antenna is a necessity, with a subsequent, numerical near-field to far-field (NF-FF) transformation.

In this scenario, considerable attention has been given to techniques for reducing the number of sampling points to a minimum (although practical existing measurement systems may have special constraints in terms of overall sampling paths).
Almost invariably one uses the available information on the spatial occupation of the antennas under test (AUT), starting from the seminal work on degrees of freedom (DOF) of the field 1.
Theoretical work to optimize the number of necessary sample points can provide significant reductions on the number of necessary samples with respect to standard state-of-the-art available commercial systems 23. However, the underlying theory 1 amounts to setting a lower bound to the number of necessary samples; this result is very well known in measurement communities, and is analogous to the Nyquist-Shannon sampling limit; for this reason it will be referred as to the "Nyquist" sampling limit in the rest of this work. Hence, all optimization endeavors in this class aim at finding the tightest-fitting Nyquist limit for specific antennas