Guest Editorial: Special Cluster on Compressive Sensing as Applied to Electromagnetics

COMPRESSIVE SENSING (CS) has spurred the introduction, development, and application of a huge number of new methodologies in information theory, signal processing, computer science, and electrical engineering [1]–[3]. Its success is motivated by the CS promise to overcome Shannon–Nyquist famous theorem and to enable recovery of signals/phenomena from far fewer measurements than traditional techniques. This possibility has gathered considerable interest in applied areas traditionally constrained by Nyquist's sampling rate, including imaging [4][5], audio/video capture [6], and communications [7]. In this framework, Electromagnetics represents a relatively new area of application, although some problems, comprising antenna array synthesis and diagnosis, inverse scattering, and radar imaging, have already been addressed through CS techniques [3]. The letters in this special cluster explore solutions to a variety of these problems.

A. Compressive Sensing Paradigm and Methodologies

The CS paradigm is rooted on the concept that several physical signals/phenomena are *sparse* if properly represented, that is they can be discretized by few nonzero coefficients in suitable expansion bases [1]. Accordingly, CS recovery approaches essentially search for solutions of linear systems of equations enforcing that the unknown vector contains as few nonzero entries as possible. Under this assumption, and if suitable conditions on the linear system at hand are met [1], sparse signals can be *exactly* retrieved from a very small set of measurements [8]–[11]. Besides this evident advantage over Shannon-Nyquist theorem-based methodologies, the success of these formulations is related to the their intrinsic flexibility [1], their numerical efficiency [11], and the availability of software libraries implementing state-of-the-art CS algorithms [12].

Within this paradigm, two main problems are usually addressed, namely *(i)* the *CS sampling problem* and *(ii)* the *CS recovery problem.*

The *Sampling Problem* is concerned with the design of the signal acquisition procedure (i.e., the *type* and the number of measurements) so that the arising linear system of equations is well-posed [3]. This is actually made possible thanks to the following theorem

Theorem 1[8]. A necessary and sufficient condition for the well-posedness of the CS problem when the signal is S-sparse is that the linear system of equations complies with the *Restricted Isometry Property* of order *2S*.

Since checking the above *condition* is numerically unfeasible even for small problems [8], systems of equations that *a-priori* fit it are often considered in CS signal processing problems [13]. Unfortunately, these solutions cannot be adopted in Electromagnetics, as in this case the properties of the equation systems are mainly dictated by the physics of the problem at hand (e.g., array synthesis or imaging). Consequently, the solution of the *Sampling Problem* has been only seldom considered in electromagnetics [3].

The *Recovery Problem* aims at finding an S-sparse vector fitting the set of measurements equations, and it has a unique solution if *Theorem 1* is satisfied [3]. To address such a problem, several deterministic and Bayesian methods have been proposed in the literature [11]. From a deterministic point of view, the solution of the *CS Recovery Problem* is usually carried out as the constrained minimization of a ℓ_0-norm functional, which turns out a NP-hard problem [8][14]. To address it effectively, *greedy pursuit* methods [15], [16] aimed at finding the sparsest vector of unknowns through an iterative search have been proposed. Alternatively, *convex relaxation* techniques based on the *Basis Pursuit*[17] have been widely adopted by substituting the ℓ_0-norm functional with an ℓ_1-norm one ("relaxation") to yield simple and effective recovery methods [11]. Nevertheless, the basic assumptions (i.e., Theorem 1) that enable the effective application of many deterministic CS recovery algorithms cannot be *a-priori* guaranteed in several practical scenarios [3]–[20]. Consequently, alternative algorithms based on *Bayesian CS* formulations have been studied that, on the one hand, do not rely on the Theorem 1 to yield accurate and stable results, and, on the other, naturally provide the degree of confidence of the retrieved solution [9]–[22].

B. Application of CS to Electromagnetics

The first electromagnetic applications of *CS* methods have been developed for the solution of *sparse recovery* problems that naturally fit the standard CS requirements (i.e., linearity and sparseness [1]–[23]). Afterwards, the field of application of CS has been significantly broadened by observing that many electromagnetic problems can be suitably formulated to comply with the above assumptions [3]. As a consequence, CS has been more recently extended to antenna array diagnosis and synthesis [18]–[25], direction-of-arrival estimation [26][27], inverse scattering [28]–[30], and radar imaging [23].

Starting from the linearity of the relationship between the field radiated by an array and its excitation coefficient, two standard array problems have been formulated within the CS framework [3], viz. the diagnosis/correction of isolated element failures and the synthesis of sparse arrangements.

More specifically, both deterministic [19] and Bayesian CS methodologies [31] have been applied to the detection of array failures/damages, and the resulting methods have been shown to overcome standard methods based on truncated singular value decompositions [3]. Moreover, the synthesis of maximally-sparse arrays has been firstly solved for symmetric linear

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[18], [32] and planar [32] arrangements with real excitations, and later extended to asymmetric linear [33], planar [34], and conformal arrangements [35]. Mask-constrained [24][25] and isophoric ring array [36] syntheses have been considered as well.

CS-based inverse scattering has been investigated in the literature, as well [20], [28], [29], [30], [37], [38], [39], [40], [41][42], and several formulations have been proposed starting from the "fully-nonlinear" inverse scattering equations. For instance, CS strategies have been applied to qualitatively image sparse dielectric scatterers in 2-D scenarios assuming transverse-magnetic [29] or transverse-electric data [43], and to localize sparse metallic scatterers [44]. The application of CS strategies to imaging problems linearized through the Born approximation has been also demonstrated by using Laplace priors [10] or hierarchical priors [37][45], while total variation methods have been used to handle piecewise-constant contrast profiles [46]. Furthermore, CS retrieval strategies have been adopted in phaseless data processing in [20].

Another area of active research in Electromagnetics has been *in-situ* CS[47], whereby the intervening medium itself is judiciously exploited to provide CS capabilities, as exemplified by time-reversal techniques [47]–[54]. Finally, in regards to radar imaging, the solution of synthetic aperture radar (SAR) problems through CS strategies has gathered much attention since, on the one hand, most targets in reflectivity maps can be easily modeled as sparse distribution, and, on the other hand, the relation between the received signal and the unknown reflectivity field can be approximated as linear [3][55]. Typical applications have been mainly concerned with spotlight SAR [55], [56], [57] where both total variation [55] and Bayesian [56] formulations have been employed. CS approaches have been considered in tomographic SAR as well for minimizing the number of signal measurements while keeping the desired accuracy in radar reconstruction [58]–[60]. ISAR problems have been widely discussed within the CS paradigm [61][62] because of their intrinsically sparse nature related to the representation of the targets as few strong scatterers in a large radar image [62]. Data acquisition and imaging methods based on CS have been also applied to obviate hardware limitations related to the high data acquisition speed in stepped-frequency continuous-wave ground penetrating radars [63]–[66].

C. Open Challenges and Future Trends

Despite the tremendous advances in the application of CS to electromagnetic problems, several challenges still need to be addressed in order to bridge the gap between the current status of the research and the potential applications of these techniques. Indeed, it can perhaps be said that CS as applied to Electromagnetics is still in its infancy, and several advances are expected from ongoing and future research activities in this area.

One of the most challenging research topics in this field is currently represented by the solution of the *Electromagnetic SamplingProblems*, that is the minimization of measurements required in inverse scattering and antenna characterization [3]. As a matter of fact, no general-purpose solution has been yet proposed in order to guarantee that an arbitrary measurement setup result in a linear systems of equations which comply with Theorem 1 [3]. The development of the proper theory to handle such a problem, as well as of the associated algorithms and tools, would represents a fundamental step to minimize hardware and processing costs in electromagnetic measurement systems.

From the applied viewpoint, the capability to effectively compute the expansion basis that guarantee maximal sparseness in a given scenario still represents an important issue [3]. Indeed, the definition of this "dictionary," which essentially represents the *a-priori* information available within the solution process, is known to greatly affect the accuracy of CS recovery techniques [3]. Current methodologies in electromagnetics often assume pixel-based or wavelet-based discretizations, and therefore they are limited to scenario where these assumptions are adequate to guarantee the sparsity of the vector of the unknown coefficients [3]. However, future efforts towards the developments of methods to compute the "optimal basis" for any given CS problem are envisaged.

Finally, a well-known limitation of many current CS retrieval methods as applied to electromagnetics is that they address linear (or linearized) problems [3]. Unfortunately, many design and retrieval problems in Electromagnetics are inherently nonlinear. As a consequence, the extension of CS theory, formulations, and solution tools to fully nonlinear problems could boost the application of CS techniques in Electromagnetics.

D. Scanning the Issue

The Special Cluster of the IEEE Antennas and Wireless Propagation Letters comprises 7 papers representing the state-of-the-art research being developed in Compressive Sensing as applied to Electromagnetics. The Cluster includes some of the most interesting recent achievements from both the methodological and the applied viewpoints in this field, and it reviews the potentialities and current trends. The letters address several different problems including array correction in the presence of failures, microwave prospecting of 2-D and 3-D targets, and innovative radar imaging techniques.

A pattern correction problem is addressed in the paper by Migliore *et al.* by means of a nonintrusive fault detection procedure. More in detail, to achieve fast and high accuracy fault detection, a proper choice of the near field sampling points is combined with a deterministic CS retrieval strategy, whose application is enabled thanks to the sparse nature of the element failures.

As regards the application of CS in inverse scattering problem, the retrieval of three-dimensional cracks in anisotropic layered media is the topic addressed by the letter by Oliveri *et al.* while the combination of compressive sensing and virtual experiments to enable the imaging of nonweak targets is discussed in the letter by Isernia *et al.* Moreover, the letter by Liang *et al.* exploits principal component analysis to generate *ad-hoc* bases for improving the performance of compressive sensing imaging methods.

Finally, innovative radar imaging techniques based on CS are discussed in the letters by Wu *et al.* Halman *et al.* and Zhang and Hoorfar, which address high-resolution polarimetric through-the-wall imaging problems by means of a cluster multitask Bayesian Compressive Sensing approach, multifrequency inverse radar inversion problems through the combination of physical and polynomial basis functions to enhance the convergence of greedy CS methods, and a generalized Green's function based approach for the SAR and MIMO radar imaging of targets behind single or multilayered building walls with *CS*, respectively.

To conclude, we would like to thank the Editor-in-Chief Prof. Yang Hao for the opportunity to serve as Guest Editors of this Special Cluster, as well as for his continuous guidance and help. We would also like to thank all of the authors for their patience with us, and all the reviewers for their commitment and support. We hope that you will find this Special Cluster interesting, and that it will succeed in fostering the spread of *CS* methods and ideas in the electromagnetic community. The letters in the Cluster serve to indicate that *Compressive Sensing* is an extremely active cross-disciplinary research area where many advancements are still to be foreseen.

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