Introduction to the Issue on Time/Frequency Modulated Array Signal Processing

PHASED-ARRAY is known for its capability to electronically steer a beam towards a desired direction. However, this beam steering does not account for the target range. There is an increasing need to control the range-dependent transmit energy distribution in applications involving interference suppression, directional communications, and range ambiguity. Towards this end, several advanced array design approaches have been introduced, which include time modulated array (TMA), frequency diverse array (FDA), and frequency diversity or time division based multiple-input multiple-output (MIMO) systems. By connecting and disconnecting the elements from the feed network, TMA can form a beampattern with low sidelobes. FDA uses small frequency increments across the array elements so as to produce a range-dependent pattern, whereas MIMO provides increased degrees-of-freedom (DOFs) beyond the number of physical antennas. We adopt the term *time/frequency modulated arrays* to represent all the above approaches and describe their corresponding configurations.

Time/frequency modulated array techniques have recently emerged to address pressing and important problems in radar, satellite navigation, radio astronomy, wireless communications, microwave imaging, and biomedical engineering. These techniques have been developed to benefit range-dependent transmit beamforming, range-angle target localization, cognitive interference/clutter suppression, physical-layer security communications, spectrum sharing and co-existence, dual system functionality, etc. Nevertheless, there remain many technical challenges that require devising novel signal analysis and array processing methods. These include new design of array parameters and transmit waveforms for optimum system performance. It is noted that array optimality is entwined with its configuration, and, as such, prior conditions on array geometry and sensor spacing must be avoided when applicable. Further, time/frequency modulated arrays should handle multiple targets characterized by range, time, angle, and frequency dependent responses. In essence, there is a strong demand for developing innovative, effective and efficient signal processing algorithms within the time/frequency modulated array framework for improved system functionality.

This special issue (SI) covers a variety of signal processing approaches, all based on time/frequency modulated arrays. It aims to compile relevant research contributions from various disciplines, including statistical signal processing for radar and communications, antenna array design and synthesis, and applied mathematics. The papers included in this SI address various applications based on different signal modalities. We were delighted to receive a total of 58 submissions, out of which 16 papers were finally selected. Unfortunately, many good papers could not be considered due to space limitation.

This issue begins with an overview article by Wang *et al.*, which provides foundations of time/frequency modulated arrays including TMA and FDA from a signal processing perspective. Potential applications in secure communications and cognitive radar are also discussed, along with the issues pertaining to joint optimization of waveform design and transmit beamforming.

In this SI, TMA signal processing are represented by three papers. Maneiro-Catoira *et al.* propose a wireless communication system that employs digital linear modulated signals, and consists of a TMA for nonlinear beamforming followed by a maximum ratio combiner. It is demonstrated that this approach provides a good balance between hardware complexity and system performance in terms of signal-to-noise ratio and symbol error rate. The same authors have a second article on an enhanced TMA framework where the array excitations are time modulated with periodic sum-of-weighted-cosine pulses to provide flexibility in controlling the harmonic radiation patterns. Barott and Fucharoen examine the sidelobe blanking (SLB) implementation using TMA and digital beamformer, referred to as TMA-SLB, for both spectrometry and radar applications. The TMA-SLB is applied to data recorded by the Allen Telescope Array, and shown to effectively blank sidelobe interferences via a computationally simple technique.

Regarding FDA, the SI includes five papers. Yao *et al.* propose the use of FDA to synthesize time-invariant spatial beampattern which can focus energy in the short-range. Two time-modulation optimized frequency offset schemes are presented to handle single- and multiple-target scenarios. Liu *et al.* devise a new variant of FDA, referred to as random FDA. The main idea is to randomly assign the carrier frequency of each array element so that uncoupled range and direction estimation can be achieved. Furthermore, Cramér-Rao lower bound (CRLB) for location estimation and mutual coherence for target indication, are derived. Next, Xu *et al.* present an adaptive range-angle-Doppler processing approach for colocated MIMO airborne radar system employing FDA. They exploit both increased number of DOFs and dimensionality reduction in range, angle and Doppler domains, such that clutters from different range regions can be effectively suppressed. In order to attain a high number of DOFs, Qin *et al.* incorporate both coprime arrays and coprime frequency offsets in the FDA design. By exploiting sparsity of point targets in both range and angular domains, the localization problem is formulated using a two-dimensional sparse reconstruction model

Digital Object Identifier 10.1109/JSTSP.2017.2652098

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which is solved within the Bayesian compressive sensing framework. Wang *et al.* propose the use of FDA for high-resolution wide-swath synthetic aperture radar (SAR) imaging. The main concept is to exploit the extra controllable DOFs in range so that the FDA can distinguish the range ambiguous echoes in the spatial frequency domain.

Apart from TMA and FDA, five articles relating to time and/or frequency modulation based MIMO systems are also included in the SI. Targeting the Internet-of-Things applications, Gokceoglu *et al.* consider the problem of multiuser-multiantenna waveform design and optimization for massive MIMO downlink with low-cost oversampled 1-bit receivers. McCormick *et al.* design an iterative scheme that jointly optimizes the beampattern and spectral content of a wideband MIMO radar based on physically realizable frequency-modulated waveforms emitted from a uniform linear array. Space-frequency nulling is also implemented in the iterative process via a reiterative uniform-weight optimization method. Gao *et al.* propose a method of generating piecewise nonlinear frequency modulated waveforms for MIMO radar where waveform diversity is exploited by dividing each sub-pulse into three segments with different bandwidths and durations. The first and the third segments are linear frequency modulation signals, whereas the second segment is a nonlinear frequency modulation signal. Next, Liu *et al.* present a space-time coding scheme based on time and frequency comb-like chirp waveform diversity design for MIMO SAR imaging with suppression of interchannel ambiguous energy and interferences. The idea is to put two successive signal periods into one transmit duration, while the even and odd components of the transmitted waveforms are modulated into distinct Doppler frequencies in the azimuth direction and separated via bandpass filtering in the range-Doppler domain. Furthermore, La Manna and Fuhrmann provide the analytical CRLBs for target localization employing the planar hybrid MIMO phased-array radar (HMPAR). By fixing the total number of transmit/receive elements, comparative studies between the CRLBs of different HMPAR configurations and that of MIMO are performed. The SI ends with two more relevant articles. The first one is authored by Cheng *et al.* who use stochastic frequency modulated array for radar coincidence imaging, which is a super-resolution staring imaging technique based on the idea of wavefront modulation and temporal-spatial stochastic radiation field. Lastly, Ding and Fusco propose a synthesis-free directional modulation transmitter by modifying the classical retrodirective array architecture. Their method performs well when there are multiple legitimate receivers positioned along different directions or in the presence of multipath propagation.

Our guest editorial team would like to thank all authors who submitted their manuscripts to this SI and the reviewers for their careful assessments and timely responses. Finally, we hope that this SI is informative and spurs future developments and advancements of time/frequency modulated arrays within the signal processing community and beyond.

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