SCANNING THE ISSUE

Phased Array Technologies

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I. INTRODUCTION

Modern phased array technology brings together diverse disciplines throughout the electrical engineering community, covering not only radio-frequency (RF)/ microwave engineering, but also digital and mixed analog/digital VLSI design and fab, high-speed data networking, testing from direct current (dc) to microwave/ mm-wave, semiconductor device physics and materials, power distribution, computer science, thermal management expertise, and several more disciplines. New digital approaches in array architectures reflect a dramatic departure from the traditional RF/microwave approaches, and present new challenges where RF-speed data conversions and even Terabit per second data flows must be carefully managed and exploited. As the use of phased arrays grows throughout both the military and commercial worlds, new opportunities will arise that will draw from diverse engineering disciplines.

This Special Issue provides the reader a look into the future of phased arrays by broadly describing emerging core technologies as well as potential new applications covering a diverse range of disciplines.

II. BACKGROUND ON PHASED ARRAYS

The general principal of the phased array is to achieve focusing and steering of transmitted or received electromagnetic energy. This steering is achieved by introducing a specific time delay at each element of the array such that the contributions of the transmitted or received signal from each element are coherently summed at a desired angle to the array face. Early concepts of electronic array beam steering can be found in Belgian and British patents [1][1] dating from 1899 to 1903. The advantages of electronic steering, at least in principle, became apparent during the early days of radar as a means of avoiding the need to reposition enormous and heavy reflectors and feed assemblies for the tracking of aircraft [2]. Early arrays contained various configurations of movable horns, mechanically tuned radiating elements, waveguide arrangements, reflector dishes, and other implementations, all with the aim of achieving some form of electronic beam steering. In 1942 Bell Labs implemented an S-band (∼3 GHz) shipboard radar with an integrated fire control system. In this array, rod-like radiating elements contained mechanically driven phased shifters. Other early phased array designs can be found in [2].

During the 1950s, MIT Lincoln Labs advanced the state of the art in phased arrays in response to the growing Soviet military threats, including the Soviet detonation of an atomic bomb in 1949 and Sputnik, among other factors. This work continued into the 1960s and is reviewed in [3] and [4]. Large electronically steerable arrays, mainly for ballistic missile, space, and other U.S. perimeter long-range warning were deployed during the 1970s. Among these systems are the 34768-element Cobra Dane, a 29-m-diameter phased array built by Raytheon comprising 96 subarrays fed by L-band (∼1 GHz) traveling wave tubes. Another large-scale array is PAVE Phased Array Warning System (PAWS), which runs at

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[1] Reference [1] mentions: A. Blondel, Belgian Patent 163516 (1902) and British Patent 11427 (1903); S. G. Brown, British Patent 14449 (1899); R. M. Foster, "Directive diagrams of antenna arrays," *Bell Syst. Tech. J.*, vol. 5, pp. 292–307, Apr. 1926.

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ultrahigh-frequency (UHF) bands and contains solid state power amplifiers. Shipborne systems from the 1970s included Lockheed Martin's (then RCA) SPY-1 array, which served as the phased array antenna aperture for the Aegis Combat System. Early versions of the SPY-1 contained about 4000 transmit and receive elements operating at S-band. One such SPY-1 array has been repurposed as a multipurpose weather and air traffic surveillance radar testbed, as is described in the paper by Torres *et al.* In the case of airborne radar, early examples of phased arrays include the AN/APQ-164 arrays for the F-111; Russian counterparts included the Russian SBI-16 Zaslon, Phazotron Zhuk Ph and NIIP N-011M systems.

While the above systems are electronically scanned arrays (ESAs), their RF transmission power is supplied by a common source (or just a few sources) shared by the array elements; likewise, signal reception from the array is consolidated to one or a few receivers. Each element contains phase shifters and attenuators to achieve beam steering and tuning of the beam shape. Such systems are therefore referred to as passive electronically scanned arrays (PESAs).

Thanks to advancements in GaAs microwave circuits during the 1980s, including the fabrication of GaAs circuits at a monolithic scale, the possibility of active electronically scanned arrays (AESAs) emerged. In contrast to PESAs, each element within an AESA contains its own fully independent amplifier, switching, and phased shifting components, usually packaged in a transmit/receive module (T/R module); for more details, see the paper by Talisa *et al.* Early deployments of AESAs occurred during the late 1990s and can be found in both ground and airborne radars such as the Israel Aerospace Industries/Elta Phalcon L-band early airborne warning radar, the U.S. JSTARS platforms, and the X-band AN/APG-63 (V)2 for the F-15C. AESAs are now common in airborne platforms because of their reduced size owing, in part, to the elimination of traveling wave tubes (TWTs), plus lighter weight from continued miniaturization of the RF components. The largest AESA constructed to date by physical size is presumably the Sea Based X-Band radar (SBX). This radar contains more than 45 000 GaAs T/R modules and is placed in a radome atop a sea-based rig that can be positioned in the ocean. The SBX will be supplanted in size by Lockheed Martin's Space Fence. Space Fence, which will operate at S-Band, is among the first large-scale arrays to introduce a digital architecture. It will bring the disciplines of data networking and digital data processing to phased arrays, at a massive scale.

Nevertheless, an AESA can become a very expensive piece of hardware, given the multiplicity of elements and corresponding electronic T/R module hardware. Furthermore, providing the power to drive all of the components and thermal management imposes severe engineering challenges—especially with regards to overall system power efficiency. Megawatt-scale high-powered shipboard arrays contain elaborate plumbing to circulate sea water through the arrays to cool the electronic elements and structures. Power and cooling challenges can likewise be substantial for smaller airborne arrays containing hundreds to a couple of thousands radiating elements, whether on fighter jets or unmanned aerial vehicles (UAVs). Power source capabilities, along with array size, cooling, and weight constraints place enormous demands on the array design. Satellite-based arrays address these issues to the extreme. As we will see in the paper by Bailleul, developments in new electronics component technology are working to alleviate these challenges, all of which must be overcome for arrays to be realized. General array costs issues are also covered in the paper by Herd and Conway.

Compared to earlier mechanically fixed and rotating, as well as PESA designs, the chief advantages of AESA architectures include:

- extremely rapid beam sweeps, and without the constraints of mechanically positioned systems;
- beamforming agility with respect to the instant shaping of beams and sidelobes;
- the ability to manage multiple beams simultaneously (this is handled by superimposing multiple signals onto each element, or by assigning beams to specific array partitions);
- reliability (if just a few elements fail, the entire array's performance is minimally compromised; this is in contrast to fixed/rotating and PESA architectures, which are vulnerable to single points of failure at the amplifier, receiver, mechanical, and other stages).

AESA architectures vary to best serve a specific or mix of missions. For radar applications, the T/R module manages both RF reception and transmission, typically in a time-duplexed manner; i.e., the array operates in a transmit mode, followed by a receive mode through appropriate control of each T/R module. For other applications such as communications, send/receive signals are assigned to separate frequency bands. The phase shifting operations within analog beamforming arrays draw from a variety of technologies, including ferrite devices, switched true time delay lines, varactors, electromagnetic lenses, and other devices. In the case of receive arrays, the elemental signals with either phase or time delays are combined and sent to an analog-to-digital converter (ADC) for subsequent beam-level processing. Transmitting arrays distribute an exciter signal to the array elements; this exciter can be the output of a digital-to-analog converter (DAC) followed by an amplifier. The signal frequency processed by the ADCs and DACs can be at an intermediate frequency (IF) or baseband. Until recently, this hybrid analog–digital subarray approach had been considered necessary given the high costs, limited sampling rates, linearity, and large power requirements of ADCs. The situation is changing.

III. TRANSITION OF ARRAYS FROM ANALOG TO DIGITAL ARCHITECTURES

In "elemental digital" architectures, an ADC and a DAC are situated at every element and can be within the element's T/R module. The array architecture now becomes less of a massive RF system, but rather a massive digital data distribution network. Data networking standards familiar to IT specialists, such as GigEthernet, Infiniband, etc., which are alien to RF engineers, now become critical technologies for phased array systems. The analog front ends, with individual T/R modules per element as in the AESA analog architecture case, still exist. The T/R modules would still perform the usual amplification, filtering, and perhaps phase shifting operations; however, core beamforming, signal combining, and signal distribution can now be shifted to the digital domain. This calls for the use of field-programmable gate arrays (FPGAs) or custom applications-specific integrated circuits (ASICs) to perform the beamforming operations, including array-wide signal combining and routing (elaborated on further in the paper by Miller). The beamforming operations of phase shifting or true time delay can now be performed in the digital domain as numerical operations or brute-force signal delay chains. Current implementations of digital array architectures include the CEA (Australia) CEAFAR elemental digital array, which has been deployed on ships, the Lockheed Space Fence, shipboard arrays from Elta, and new communications arrays now under development for wireless communications (see the paper by Niknejad *et al.*, where digital array architectures play a critical role in massive MIMO array designs).

Refinements in component technology have consistently pushed the design and performance of phased arrays since their beginning. This especially became apparent with the advent of GaAs monolithic microwave integrated circuits (MMICs) during the 1980s, thanks in part to the Defense Advanced Research Projects Agency (DARPA) MIMIC program. MMICs led to highly integrated T/R module circuits of substantially reduced size, weight, and power consumption that enabled the practical implementation of AESAs. This trend continued with refinements in RF circuits to incorporate GaN devices, resulting in higher power T/R modules at manageable costs. The latest trend, however, is the migration of a large portion of the T/R modules to silicon. While GaAs and GaN devices may continue to serve as a preferable platform for achieving the requisite array power outputs (ranging from a few to hundreds of watts per element) and perhaps low noise amplification for received signals, radio-frequency integrated circuits (RFICs) built upon SiGe and complementary metal–oxide–semiconductor (CMOS)-only technologies will soon become the norm for many array applications. These technologies are beginning to find an important place in emerging multiple-input–multiple-output (MIMO) phased arrays for fifth-generation (5G) broadband communications systems (cf. Niknijad *et al.*'s paper on massive MIMO).

IV. OVERVIEW OF PAPERS

This Special Issue provides to the reader an overview of where phased array technology is headed in the years to come. With the above discussion in mind, the papers are broadly divided into those describing emerging core technologies for phased arrays, with the remainder describing how phased arrays will drive new applications covering a diversity of disciplines. We start with an examination of the fundamental challenges of digital beamforming, as described in the paper by Fulton *et al.* These challenges include assessing the architectural trades for managing the massive amounts of data that must be processed and distributed throughout the array. Other topics covered in this paper are digital array calibration to account for component drift, adaptive beamforming, and methods to reduce the amount of beamforming computation while minimally sacrificing performance. Equally important are an understanding of how nonlinearities and phase noise at the elemental level translate to overall linearity and noise levels for beams at the overall array level. Talisa *et al.* examine such issues, while also providing an overview of newly deployed digital arrays systems.

Wideband phased arrays need true time delay at the element level. Rotman and Tur discuss innovative methods for achieving true time delay at each element, as applied to analog and digital systems. The methods range from a traditional approach, the Rotman lens, to advanced photonic control systems. The use of true time delay enables control of the beam steering over extended frequency bandwidths. This contrasts to the legacy use of phase shifting (e.g., with ferrite and electronic elements), which only operate over narrow frequency ranges.

As mentioned earlier, digital array architectures make use of FPGAs and/or ASICs for carrying out fundamental beamforming operations, which include signal time delay (or phase shifting), routing, filtering, adding, amplification, and other functions. Miller shows how new generations of FPGAs exhibit substantially reduced power consumption at faster data throughputs through advanced Si node implementations and faster, more power-efficient data interfaces. These factors make FPGAs ever more suited for beamforming over a wide range of applications and array sizes. Nevertheless, optimal power efficiency and performance will still be obtained through ASICs in the array beamforming and data distribution roles, at least when the array element volumes can justify the substantial investment in development time and costs for such chips.

While phased arrays are often thought of as having a planar structure with regularly spaced array elements, this should not always be the case, especially when element counts must be reduced for cost, size, weight, and power consumption reasons, or in situations where element layout must conform to available space and other geometrical restrictions. Rocca *et al.* examine resulting "unconventional array" architectures. These authors describe systematic modeling methods that enable the layout of arrays of unusual shapes through element clustering, or various levels of sparsity in the element counts. Time-modulated arrays provide an additional "degree of freedom" to achieve desired array performance when element counts are to be reduced.

Another view toward unusual array design is described by Krishnaswamy and Zhang, who have modeled and constructed a prototype phased array system that makes use of "mixer first" technology followed by active filtering and interference cancellation techniques. The end result provides a capability that not only mitigates the impact of interfering signals that operate within the frequency range of the array, but that enable the tuning of the interference cancellation according to the direction of the interferer relative to the array face. This work is especially important because elemental digital arrays are more susceptible to the effects of interference compared to the earlier PESA counterparts. Unlike the traditional PESA arrays which perform off-axis cancellation of incoming signals prior to the ADC stages, digital array front ends are exposed to the interferers, regardless of their source direction or frequency. The described work helps to address this problem.

The last of the array technology papers, by Herd and Conway, provides a brief history of how U.S. Department of Defense programs have advanced array component technology to bring down the costs of arrays while addressing ever stringent performance requirements. Herd and Conway also discuss systematic and highly scalable approaches for simplifying array design for improved manufacturability.

New array technologies facilitate a growing applications base to which phased arrays are well suited for public safety and commerce. Stailey and Hondl discuss a promising initiative that attempts to consolidate U.S. nationwide air traffic control radar and weather radar (including the National Weather Service's NEXRAD weather radar network) with a common phased array platform. The resulting multipurpose phased array radar (MPAR) network will deliver unprecedented aircraft tracking and weather sensing capabilities, at reduced operating costs. Much of the promise of MPAR is grounded in the work of Torres *et al.*, who describe how the National Weather Radar Testbed, which is based on a decommissioned SPY-1 phased array radar, is bringing new perspectives to weather tracking and prediction.

This Special Issue likewise presents a comprehensive paper by Niknejad *et al.*, who describe advancements in microwave and millimeter-wave MIMO arrays. Massive MIMO arrays offer the promise of spectral efficiency for 5G wireless services. This will be achieved through massive MIMO's highly dynamic spatial sectoring, while leveraging the effects of multipath to enhance wireless data rates and user density.

Radio astronomy implements large-scale arrays of highly sensitive radio receivers. Warnick *et al.* discuss current and evolving radio astronomy array practices, including the use of phased array feeds to enhance array sensitivity (in part, through improved noise and temperature management), steering flexibility, and beam management. The paper provides a thorough overview on existing radio astronomy arrays, and where the discipline is headed (e.g., the "Square Kilometer Array"). Space-based arrays are described by Bailleul. The design and construction of such arrays are particularly challenging due to demanding size, weight, and power consumption conditions imposed on the array architecture, while attaining requisite geographical coverage ranging from narrow "pencil beams" to wide geographical swaths. The newly evolving digital phase array architectures show particular promise for space-based array applications, given the beam count flexibility and migration away from sophisticated RF hardware toward much simpler digital data handling.

New developments in array technology are beginning to have a positive impact on the use of arrays for both therapeutic as well as diagnostic medical procedures. Bucci *et al.* describe how careful element design and placement, along with robust analytical modeling, enables the delivery of precise doses of nonionizing radiation to precisely heat tumor sites, all with a minimum element count. These authors likewise describe how advanced near-field propagation models can provide clinically useful microwave imaging, again with a minimal number of transmit and sensing elements.

This Special Issue's presented range of applications for phased arrays is admittedly limited, for space and time do not permit a more comprehensive guide. Nevertheless, it is hoped that the reader will gain from a reading of these papers a better appreciation for what phased arrays can do and where they are headed. ■

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ABOUT THE GUEST EDITORS

Benjamin R. Epstein (Senior Member, IEEE) received the B.S. degree in electrical engineering from the University of Rochester, Rochester, NY, USA, in 1978, the Ph.D. degree from the School of Engineering and Applied Sciences, University of Pennsylvania, Philadelphia, PA, USA, in 1983, and an MBA from Stern School of Business, New York University, New York, NY, USA, in 1991.

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Ruth Rotman received the B.S.C. and M.S.C degrees from the Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, in 1983 and 1985, respectively, with theses on the subject of microwave detection of breast cancer, and the Ph.D. degree from the Department of Interdisciplinary Studies, Tel Aviv University, Tel Aviv Israel, in 2007, with her dissertation on the subject of photonic true time delay for phased arrays.

She worked at Elta Electronics Industries on phased arrays from 1985 to 2014. From 1985 to 2001, she worked in Elta's Antenna Department where she designed several of Israel's first phased array antennas and calibration systems. She later joined Elta's Advanced Research and Development Radar Imaging Department from 2001 to 2014, where she concentrated on the development of wideband phased arrays. She has a special interest in, and has published on, the subject of analog true time delay beamformers, ranging from the original Rotman lens to an advanced photonic beamformer. In recent years, she has been active on the subject of microwave antennas for medical imaging.

Dr. Rotman has been a Session Chairman at various IEEE conferences, including the IEEE AP and the IEEE International Conference on Microwaves, Communications, Antennas, and Electronic Systems (COMCAS). She was one of the original members of the TPC committee of IEEE COMCAS. She likewise has given many invited seminars at various institutions, including AFRL, ARL, Ohio State University, and University of Massachusetts. She has presented invited papers at IEEE conferences, including the International Conference on Electromagnetics in Advanced Applications (ICEAA) , the IEEE Conference on Microwaves, Communications, Antennas, and Electronic Systems (COMCAS), the IEEE Symposium on Antennas and Propagation (AP), and the European Conference on Antennas and Propagation (EUCAP). She has served as a reviewer for Wiley Books and for several of the IEEE publications, including the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, IEEE PHOTONIC LETTERS, and IEEE ANTENNAS AND WIRELESS LETTERS.