Reconfigurable Systems: Advanced Applications and Technologies

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I. INTRODUCTORY REMARKS

This issue of the Proceedings of the IEEE is the second focusing on reconfigurable systems. In the first special issue (vol. 103, no. 3, Mar. 2015), we addressed the foundational concepts. Reconfigurability is about "change," specifically soft-defined change, whereby through the manipulation of bit sequences we can customize the properties of components, and in some cases define systems themselves. One can design systems for reconfigurability (the art of engineering degrees of freedom into embedded systems), so that users expecting this reconfigurability can exploit it. We concentrated on important reconfigurable platforms [field-programmable gate arrays (FPGAs)], development tools, and applications (reconfigurable computing and software radios). As we discussed, reconfigurability can be both dynamic and adaptive, but one should not confuse the two concepts. Reconfigurability refers to specific features that can be changed (to include dynamic and partial reconfigurability), whereas adaptiveness addresses the behavioral constructs that inform how reconfigurable features might best be exploited in live use conditions. They can have synergistic effects, as in a system that might be able to morph in response to changing conditions (such as battery saving, reduced bandwidth, noisy communications channels) by altering a few of its own "knobs" or, more radically, by reshaping and replacing complex circuits in real time. Reconfigurability does not lead to "self-awareness" for example, but if we ever devise a self-aware system, it could take advantage of intrinsic reconfigurability to tune and optimize its own performance.

This special issue expands the previous focus on reconfigurable systems by considering basic mechanisms, emerging technologies, and the extension of reconfigurability to other phenomenologies, domains, and applications.

In this special issue, we amplify the basic concepts discussed in the first issue by considering more advanced applications, the extension of reconfigurability to other phenomenologies/domains, and the impacts of selected emerging technologies. In Fig. 1, we annotate the Venn diagram from the first issue to indicate some of the additional ground we will explore using numerals to indicate which of the special issues ("1" or "2") provide emphasis to particular topics.

In this special issue, we will examine more of the basic mechanisms that lead to the possibility of engineering reconfigurability in systems, such as memristors, metamaterials, and tunable radio-frequency and photonic mechanisms. We consider

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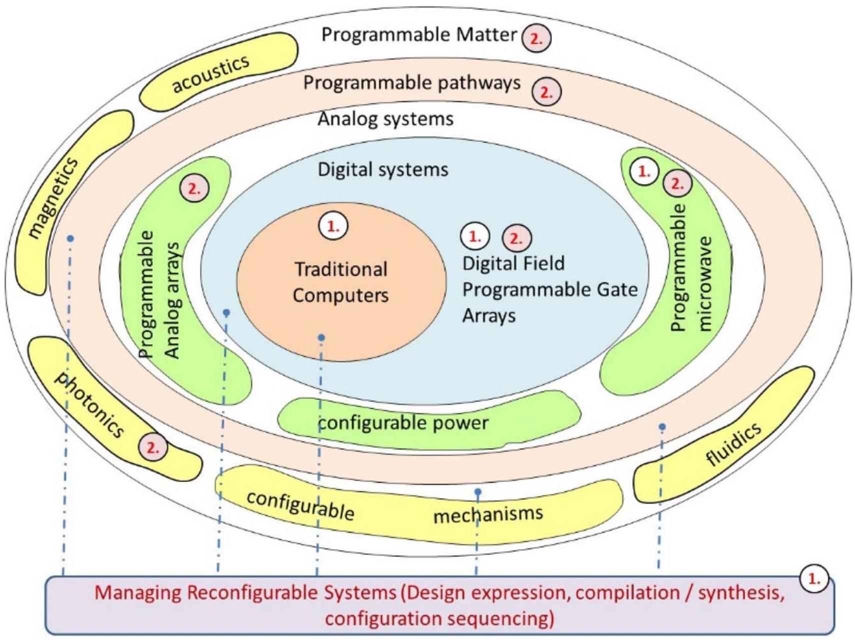


Fig. 1. ***Reconfigurable systems Venn diagram, annotated to indicate the special issue focusing on particular topics (e.g., "1" refers to the March 2015 special issue, and "2" refers to the present issue).***

configurable analog fabrics and optical hardware acceleration. We explore additionally concepts in reconfigurable pathways, reflected through papers on software-defined networking (wired and wireless) and concepts in field programmable wiring. We also consider extensions in performance, such as faster FPGA devices (based on SiGe substrates), and packaging, through papers on 3-D FPGAs and stretchable radio-frequency devices. We finally examine what is possibly the final frontier of reconfigurability in an essay on programmable matter.

II. RECONFIGURABILITY MECHANISMS

The first three papers of the special issue discuss fundamental mechanisms, which give rise to primitive building blocks around which reconfigurable devices and systems can be formed. The ability to apply the ideas of FPGAs in other domains requires elucidation of new mechanisms that represent the foundations for scalable fabrics for these domains. In the first of these papers, Edwards *et al.* examine the state of the art in memristive technologies. Their paper "Reconfigurable memristive device technologies" reviews ionic conduction, phase change, organic/organo-metallic technologies, recent advances in oxide-based memristor technologies, as well as the promise of 3-D integration. In the next paper, "Reconfigurable electromagnetics through metamaterials—A review," Oliveri *et al.* address recent advances on using metamaterials as an enabling technology for the design and the realization of reconfigurable devices at microwave and terahertz/optical frequencies. Li *et al.* introduce a mechanism for reconfigurable polarization in their paper titled "Novel polarization-reconfigurable converter based on multilayer frequency-selective surfaces."

III. RECONFIGURABLE DEVICES AND FABRICS

In the evolution of reconfigurable systems, primitive mechanisms lead to higher level constructs, such as circuitry building blocks and concepts to connect the blocks together, and the next two papers focus on higher level constructs useful in constructing configurable processing and circuitry. In "Tailoring wideband signals with a photonic hardware accelerator," Jalali and Mahjoubfar propose a new class of hardware accelerators to alleviate bottlenecks in acquisition, analytics, and storage of information carried by wideband streaming signals. These building block approaches are based on configurable photonic mechanisms, which may provide game changing benefits to certain classes of "big data" problems. In "Analog and mixed signal fabrics," Kemerling *et al.* provide discussion of configurable analog fabrics as alternatives to traditional full-custom analog/mixed-signal application-specific integrated circuits (ASICs). The approaches described draw from their experiences in creating modular and customizable mask-programmable analog architectures. While, strictly speaking, such fabrics are not reconfigurable, many of the concepts are directly applicable to fully reconfigurable mixed-signal systems.

IV. PROGRAMMABLE PATHWAYS

It is fitting in our discussions of reconfigurable systems that we examine the growing field of software-defined networks (SDNs). In different papers, we examine wired and wireless networks. In "Reconfigurable network systems and software-defined networking," Zilberman *et al.* review the current state of the art in reconfigurable network systems, covering hardware reconfiguration and its interplay with SDN. They also discuss programming languages and future trends, such as photonically enabled SDN. In a complementary paper, El-Mougy *et al.* examine the ubiquitous wireless network as a reconfigurable medium. "Reconfigurable wireless networks" presents a comprehensive overview of reconfigurable wireless networks and an in-depth analysis of reconfiguration at all layers of the protocol stack. Such networks characteristically possess the ability to reconfigure and adapt their hardware and software components and architectures, thus enabling flexible delivery of broad services, as well as sustaining robust operation under highly dynamic conditions. We can consider SDNs as a special case of reconfigurable transport, predominately of information content between nodes of a distributed system, with the fluidity necessary to accommodate changes in policies, technologies, and bandwidth/quality of service.

We also are concerned, in future reconfigurable systems, with the ability to transport electromagnetic signals, light, heat, fluids, and potentially other types of matter and energy. In "Field-programmable wiring systems," Murray *et al.* deal with concepts of adaptive wiring manifolds, in which persistent but alterable wires can be formed "on demand" to connect many points within an embedded system. These concepts are similar to those used in the wiring networks within every modern FPGA, but are extended to accommodate more electromagnetic domains, to include microwave and power. This approach amounts to a powerful software-definable wiring system, which may one day replace the traditional wiring harness. Such a software-defined wiring system, through its dynamicism, can lead to the ability to self-heal and to perform sophisticated diagnostics by generating software probe wires on-demand that are "dissolvable" when no longer needed. These are current impossibilities in a traditional fixed wiring system design.

V. RECONFIGURABILITY ENABLERS

Advances in reconfigurability will drive concomitant advances in microelectronics and electronics packaging technologies. Several papers in this special issue explore some of these possibilities. For example, in "High-speed reconfigurable circuits for multirate systems in SiGe HBT technology," LeRoy *et al.* describe FPGA fabrics based on high speed (> 50 GHz) reconfigurable integrated circuits and how they may drive reconfigurable system applications, such as software-defined radio, radar, and imaging. They propose SiGe BiCMOS as an example technology to enable this possibility. As we expect, 2.5-D and 3-D integrated circuits will play an important part in our collective struggle to extend Moore's law into the future, and we feature a glimpse of how they can apply to reconfigurable systems in a paper by Zhang *et al.* titled "Monolithic 3-D FPGAs." We also feature a paper describing an intriguing electronics packaging approach. In "Microfluidic stretchable radio-frequency devices," Wu *et al.* describe a new kind of radio-frequency electronic device made of a liquid alloy in a soft elastomer carrier. As we achieve even greater levels of integration in future reconfigurable systems on-chip, we are afforded greater opportunities to consider the relationship of structure and function. Once we have, through the advent of reconfigurable systems, managed to make circuitry that can "do almost anything," the next imperative may be to "make it all go away." Such are the challenges of Moore's law and advanced packaging, to drive incredible capabilities into vanishingly small volumes so that electronics themselves may become vital but ignorable. Glueless circuitry can be brought to intimate proximity of sensors, actuators, and embedded within structures, in which adaptive physical conformality (the ability to opportunistically bend and shape electronics to suit and applications) will likely become more important.

VI. THE FINAL FRONTIER OF RECONFIGURABILITY

What will the FPGA be in 50 or 100 years? In "The morphogenetic path to programmable matter," MacLennan argues that the endpoint toward which reconfigurable systems should develop is programmable matter. In this programmable matter, we can redefine functional and structural relationships between artificial "atom-like" infinitesimal cellular building blocks, subject to the caprice of users and designers. This sentiment has sometimes been captured and science-fiction. It would, however, not be the first time that science-fiction has been a leading indicator of an eventual reality.

VII. FINAL THOUGHTS

In these special issues on reconfigurable systems, we have tried to motivate consideration of reconfigurability as a discipline of engineering and as a field of pursuit. It is more than the FPGA that we see today. In considering the broad field of possibilities, we attempt to raise questions about the nature of our future. What types of systems may we build, and what demands may we place on them? What are the limits of virtualization? We already run virtual machines over real "bare metal" computers, define networks in software, express complex hardware designs virtually in real silicon, and today shape at least portions of radio systems using intellectual property instead of soldered components. We hear more about clouds for computing, and are becoming acclimated to many on-demand technologies. We do not envision these trends reversing. As such, for as long as we can see in the future, possibly long after Moore's law really ends, we imagine the drive to even more reconfigurability. Maybe even programmable matter.

We hope that these special issues in reconfigurable systems will stimulate a broader range of thinking about how we can engineer adaptive features in present and emerging designs and how we might exploit them in a coordinated sense to fulfill the expectations that everything in the future will be accessible and shapeable on-demand, not just for the purposes and whims of leisure, but to improve the world around us, whether saving lives in the ER, to improve or eliminate complex acquisition cycles, or to improve efficiencies and eliminate waste in countless ways.

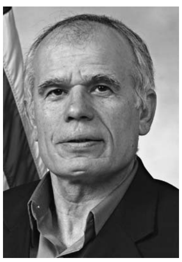
In this project, we received many excellent submissions, more than we were able to share with the readership. We want to thank all of the diligent author teams who contributed to these special issues, including those whose works we could not feature. ■

ABOUT THE GUEST EDITORS

James Lyke (Senior Member, IEEE) received the B.S. degree in electrical engineering from the University of Tennessee, Knoxville, TN, USA, in 1984, the M.S. degree in electrical engineering from the Air Force Institute of Technology, Wright-Patterson Air Force Base, OH, USA, in 1989, and the Ph.D. degree in electrical engineering from the University of New Mexico, Albuquerque, NM, USA, in 2004.

He was in active duty military service with the U.S. Air Force from 1984 through 1995. Since 1990, he has supported the Air Force Research Laboratory (AFRL), Space Vehicles Directorate (AFRL/RV), Kirtland Air Force Base, NM, including its precursor organizations (Weapons Laboratory, 1990–1991, and Phillips Laboratory, 1991–1998), in a number of capacities. He is currently technical advisor to the AFRL Space Electronics Branch (Space Vehicles Directorate) and an AFRL Fellow (since 2008). He has led over 100 in-house and contract research efforts involving 2-D and 3-D advanced packaging, radiation-hardened microelectronics, and scalable, reconfigurable computational and systems architectures, with recent emphasis on modularity and the rapid formation of complex systems. He has authored over 100 publications (journal and conference papers, book chapters, and technical reports), four receiving best paper awards, and he has been awarded 11 U.S. patents.

Dr. Lyke is an Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA) and serves on the AIAA Computer Systems Technical Committee. He was selected as recipient of the Federal Laboratory Consortium Award for Excellence in Technology Transfer in 1992 and for the U.S. Air Force Science and Engineering Award in Exploratory and Advanced Technology Development in 1997 and 2000.



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Dr. Christodoulou is a member of Commission B of URSI, and a Distinguished Professor at UNM. He was appointed as an IEEE Antennas and Propagation Society (AP-S) Distinguished Lecturer (2007–2010) and served as an Associate Editor for the IEEE Transactions on Antennas and Propagation for six years. He was a guest editor for the Special Issue on "Applications of Neural Networks in Electromagnetics" in the *Applied Computational Electromagnetics Society (ACES) Journal*, the coeditor of the IEEE Transactions on Antennas and Propagation Special Issue on "Synthesis and Optimization Techniques in Electromagnetics and Antenna System Design" (March 2007), and the guest editor for the IEEE Transactions on Antennas and Propagation Special Issue on "Antenna Systems and Propagation for Cognitive Radio" in 2014. He has also given keynote and invited talks in several places in Asia, Europe, Latin America, and the United States. He is the recipient of the 2010 IEEE John Krauss Antenna Award for his work on reconfigurable fractal antennas using MEMS switches, the Lawton-Ellis Award, and the Gardner Zemke Professorship at the University of New Mexico.

Alonzo Vera (Senior Member, IEEE) is currently a member of the technical staff at the Configurable Space Microsystems Innovations Applications Center (COSMIAC), University of New Mexico, Albuquerque, NM, USA, where he and his group work on the design of small spacecraft for a broad range of missions. At COSMIAC, he has focused on embedded system design for aerospace applications, dynamic partial reconfiguration applications using FPGAs, radiation effects mitigation techniques for FPGA-based systems and custom ASICs as well as radiation effects testing. He has numerous publications and has also been an invited lecturer on digital design and digital signal processing using FPGAs in numerous countries. His current areas of interest are reconfigurable computing, embedded system design for aerospace applications, and digital signal processing.

Arthur H. Edwards (Member, IEEE) received all of his degrees from Lehigh University, Bethlehem, PA, USA, including the Ph.D. degree in physics, with an emphasis on solid state theory, in 1981.

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