Energy Harvesting and Scavenging

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I. SCANNING THE ISSUE

Energy-harvesting technologies are fundamental in enabling the realization of "zero-power" wireless sensors and implementing the Internet-of-Things (IoT) and machine-to-machine (M2M) communication. Their increasing utilization in low-power and power-efficient sensors and electronics could potentially find application in numerous critical areas ranging from health, agricultural, structural health monitoring to logistics, localization, and security. Energy-harvesting devices, including solar panels, piezoelectric devices, thermocouples, and RF energy scavengers, can dramatically extend the operating lifetime of nodes in wireless sensor networks (WSNs). Furthermore, this technology enables a completely battery-less operation and reduces the operation cost of WSNs, which is mainly due to battery replacement, thus making it very important for a sustainable "near-perpetual" WSN operability.

This special issue covers recent advances in energy-harvesting and energy-scavenging systems with a focus on numerous "renewable" transducer technologies as well as emerging applications.

Current methods for deploying large-scale sensor networks involve miles of cabling that provide source power and collect data, or battery-operated wireless sensors, which pose a serious environmental risk with the disposal of billions of batteries every year. While these methods are necessary in some situations where real-time data or harsh environments prohibit manual monitoring of critical environment parameters, the cost, installation difficulty, and maintenance rarely justify their use over manual inspections and monitoring. This is where the concept of energy harvesting comes in. Energy harvesting is the process by which energy is derived from external sources (e.g., solar power, thermal energy, wind energy, electromagnetic ambient energy, salinity gradients, kinetic energy, etc.), captured, and stored in order to power small, wireless autonomous devices, like those used, for instance, in wearable electronics and wireless sensor networks. Such technologies could play a critical role in the first real-world implementations of IoT, M2M communication systems, wearable biomonitoring systems and generally, the first autonomous wireless "smart skins."

"Smart skins" are cognitive, intelligent skins that sense, wirelessly communicate, and, in the future, will be able to modify environmental parameters using simple passive radio-frequency identification (RFID) technology. These skins can be applied everywhere, be it a shelf lining in a grocery store or the outside of a Boeing 787, while maintaining an unobtrusive and lightweight form factor similar to the application of a decal sticker. Smart skins are "zero-power" devices, meaning they scavenge their own energy using ambient electromagnetic, solar, thermal, mechanical,

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or RFID/radar-based interrogation techniques. In short, energy harvesting could enable such smart skins to be the ultimate sensing tool that could potentially allow for the mass implementation of perpetual wireless networks, even in extremely rugged environments.

This power autonomy through the harvesting of ambient "green" energy would allow real-time knowledge of various sensed parameters, such as the stress gradients due to trucks passing over bridges, or of the propagation rate of a gas leak or fire within a building. The applications of energy-harvesting systems could also revolutionize body-wearable skins for "near-perpetual" monitoring and reporting of critical biosignals, utilizing novel liquid antenna principles, while they could also enhance the applicability of *ad hoc* emergency-response and "ambient intelligence" wireless systems in any rugged environment.

On the one hand, the dramatically increasing need for wireless sensing applications is leading to an increased interest in harvesting technologies. On the other hand, while the fundamental operating principles of transducer technologies have been identified many years ago, recent advances in fabrication technologies such as MEMS/NEMS, inkjet printing, and 3-D printing, as well as nanotechnology including carbon nanotubes, nanoribbons, nanomotors, and graphene are leading to transducer miniaturization, complex/optimal 3-D implementation, and enhanced performance as well as to dramatically reduced power requirements for electronics and sensors enabling numerous novel applications.

Energy-harvesting and energy-scavenging systems are the epitome of multidisciplinary topologies encompassing virtually most of the topics in the electrical engineering discipline. They typically include energy-acquisition/scavenging components and transducers (e.g., antennas, piezoelectric and thermoelectric materials, solar cells), electronics (e.g., rectifiers and dc/dc converters), and energy storage devices (e.g., supercapacitors), all of which feature major challenges in terms of active and passive circuit topologies, power conversion/handling, and materials. In addition, due to the commonly low amounts of harvested energy, they require extremely low-power-consuming communication and control protocols. Last, but not least, the integration of such systems with sensing or identification systems necessitates novel interconnect and packaging approaches to minimize detrimental effects from neighboring objects or human bodies to mount on. It has to be stressed that energy-harvesting systems will play a critical role in the fastest growing state-of-the-art electrical applications, such as IoT, smart skins, smart cities, gas sensors/biosensors, wearable/implantable electronics, and perpetual wireless sensing networks, maintaining autonomy, rugged performance in an environmentally friendly manner.

This special issue covers recent advances in energy-harvesting and energy-scavenging systems with reviews of numerous "renewable" transducer technologies, including solar, electromagnetic, thermal, and kinetic energy transducers, and highlights research challenges as well as emerging applications from perpetual nodes for IoT and M2M applications to "zero-power" smart skins and biomedical implants. In addition, this widely multidisciplinary issue highlights new perspectives resulting from material and nanotechnology advances and from novel low-cost fabrication technologies, such as inkjet and 3-D printing advances, combining inputs from RF and power electronics, computer science, and networking toward complete harvesting system implementations. The issue starts with the review of various ambient energy-harvesting technologies, followed by the discussion of specific implementations and requirements of electromagnetic, solar, vibration, biofuel, and wind energy-harvesting systems. Energy storage devices are thoroughly covered, while the issue closes with numerous articles about the practical implementation of autonomous "energy-harvesting-enabled" systems in wearable, implantable, and "smart house" applications.

Kim *et al.* review, in detail in their paper, various ambient energy-harvesting technologies (solar, thermal, wireless, and piezoelectric) while investigating their applicability in the development of self-sustaining wireless platforms. Examples ranging from ambient ultrahigh-frequency (UHF) TV to fourth generation/fifth generation (4G/5G) cell and WiFi signals as well as an energy harvester for on-body applications at 460 MHz demonstrate the potential of ambient UHF/RF as an enabling technology for IoT and smart skin applications. The paper also presents the major challenges for the implementation of energy-harvesting modules utilizing additive manufacturing techniques, such as inkjet printing, as well as future directions in the area of environmentally friendly fully autonomous energy harvesting ("green") RF electronics and "smart-house" conformal sensors.

Hemour *et al.* review in their paper the roadmap evolution and the historical milestones/breakthroughs of electromagnetic energy conversion techniques over the years with an emphasis on low-density energy-harvesting technologies. A set of performance criteria and development considerations required to meet the specifications of ambient electromagnetic energy-harvesting systems is derived from the thorough analysis of potential ambient radiating sources. Various existing rectifying devices are reviewed in light of the defined performance criteria. The paper closes with a technological outlook of the expected harvesting performance of different device technologies, including state-of-the-art devices, such as spin diodes.

Costanzo *et al.* present in their paper a rigorous procedure for the circuit-level analysis and design of entire systems, developed to provide power wirelessly in a very efficient way. A unified theoretical approach is first introduced in order to describe accurately the wireless power transfer link when the transmitter and the receiver are either in near-field or far-field region reciprocally. This approach allows for the easy calculation of the system figure of merit, namely the power transfer efficiency. Several practical examples complement this discussion demonstrating the performance of numerous devices for both near-field and far-field usage.

Niotaki *et al.* review in their paper numerous existing efforts and solutions in the field of solar and electromagnetic (EM) energy harvesting and wireless power transmission. Specifically, the authors present examples of solar/EM harvesters utilizing "solar antenna" structures to achieve a compact implementation, dc combining circuits for the combination of the outputs of the solar and EM harvesters as well as efficient solar-to-EM converters. The paper closes with the discussion of numerous novel topologies aiming at the minimization of the sensitivity of the rectifier circuits to practical fluctuations of the ambient RF energy.

Energy harvesting has been recognized as one of the most critical technologies for the real-world implementation of Internet-of-Things (IoT) systems. The paper by Roselli *et al.* focuses on large-area "smart surfaces," RFID systems, and wearable RF electronics that could substantially benefit from multisource energy harvesting. After reviewing potential energy sources as well as addressing materials, antennas, RFID, and chipless implementation challenges, the authors present practical examples of "smart floors," "smart shoes," and body area networks with autonomous operability utilizing RF, piezoelectric, and solar energy harvesting.

Increasing the energy conversion efficiency from vibrating bodies and keeping it high at a relatively large vibration amplitude has been very challenging in the past, and no miniaturized energy harvester has provided more than tens of milliwatts for submillimeter vibration amplitudes. Zhang *et al.* present in their paper a new energy conversion approach to convert mechanical vibrations into electrical energy with output power levels in excess of a quarter watt. The technique utilizes an array of alternating north- and south-orientation magnets to enhance magnetic flux change by more than an order of magnitude. Various examples ranging from 0.09 to 26 cc generate significant amounts of energy for vibrations up to 290 Hz with amplitudes up to 660 μm.

A fundamental difficulty in the integration of harvesting systems of renewable energy sources (e.g., wind and solar power) has been their typical high variability. To mitigate this issue, numerous advances in smart grid technologies are required. Kong *et al.* focus on how to plan wind farms with high capacity and low variability locally and universally. Studying the characteristics of both wind resources and wind turbines, the authors discuss the tradeoffs between wind power's quantity and quality for large-scale wind farms and propose optimal turbine types as well as optimal combinations and geographic distribution of different types of turbines for best performance. Preliminary results verify that the proposed approach coupled with novel wind power estimation techniques significantly outperforms conventional single-turbine-type farms and balance efficiently the quantity-quality tradeoff.

Over the last few decades, the energy storage systems (ESSs) have come to play an important role in the electric grids as the number of the applications requiring a certain power or voltage level over a short period of time has increased dramatically. Air-quality concerns coupled with the increasing numbers of electric cars connecting to the grid as well as the first "smart" grid/renewable energy sources implementations further enhance the role of ESSs. Boicea presents in his paper the most important technological achievements in the area of ESSs since their inception in mid-1700s. Plus, he discusses and performs a market analysis of various ESSs that could potentially couple with renewable energy-harvesting systems drastically enhancing their efficiency and applicability.

Future implantable medical devices, such as cardiac defibrillators/pacemakers, deep brain neurostimulators, insulin pumps, cochlear implants, etc., powered by implanted biofuel cells extracting electrical energy directly from the human body are potentially possible. Wey *et al.* present an overview of enzymatic biofuel cell theory and a summary of experimental results up to date, while discussing key electronic interfacing issues that must be considered in practical "*in vivo*" application of biofuel cells as power sources. A 1-D biofuel cell electric circuit model is introduced that can accurately model *in vivo* operability in snails, clams, and lobsters under various operational conditions. The paper closes with practical considerations and challenges regarding *in vivo* design, interfacing, and architecture of enzymatic biofuel cells.

Telemedicine (telediagnostics, teletherapy, and telemonitoring) as well as other "intelligent" wearable and implantable electronics/sensing applications significantly enhance the quality of life as they are capable of continuous real-time monitoring of biosignals. Walk *et al.* present in their paper a system for wireless power supply and communication with medical implant applications guaranteeing their truly autonomous operability for practical high data rates and realistic attenuation losses due to the human body. Implementations in two frequency bands, one at 13.56 MHz and the other at the medical implant communication service (MICS) band (402–405 MHz) verify the feasibility of autonomous telemonitoring, implantable biosensors, and telemedical sensor implants (e.g., intelligent medicine dosage sensor) harvesting energy through wireless power transfer principles.

Smart-fabric interactive-textile systems offer numerous exciting possibilities, provided they feature sufficient robustness and autonomy in rugged applications. Textile multi-antenna systems, unobtrusively integrated with garments, would be key components for the setup of energy-efficient wireless body-centric communication systems. Lemey *et al.* demonstrate in their paper the compact integration of a power management system with multiple diverse scavenging transducers and a storage module on well-chosen textile antenna topologies. In addition, the authors present guidelines to allow for the efficient antenna performance and ensure that the simultaneous scavenging from different sources significantly increases the autonomy of wearable systems and the subsequent reduction of required batteries. ■

ABOUT THE GUEST EDITORS

Manos M. Tentzeris (Fellow, IEEE) received the Diploma degree in electrical and computer engineering from the National Technical University of Athens (*magna cum laude*), Athens, Greece and the M.S. and Ph.D. degrees in electrical engineering and computer science from the University of Michigan, Ann Arbor, MI, USA.

He is currently a Professor with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA. He has published more than 500 papers in refereed journals and conference proceedings, five books, and 19 book chapters. He has helped develop academic programs in highly integrated/multilayer packaging for RF and wireless applications using ceramic and organic flexible materials, paper-based RFIDs and sensors, biosensors, wearable electronics, inkjet-printed electronics, "green" electronics and power scavenging, nanotechnology applications in RF, microwave MEMS, and SOP-integrated (UWB, multiband, mmW, conformal) antennas. He heads the ATHENA research group (20 researchers). He is currently the Head of the GT-ECE Electromagnetics Technical Interest Group, and he has served as the Georgia Electronic Design Center Associate Director for RFID/Sensors research from 2006 to 2010 and as the Georgia Tech NSF-Packaging Research Center Associate Director for RF Research and the RF Alliance Leader from 2003 to 2006. He was a Visiting Professor with the Technical University of Munich, Munich, Germany, during summer 2002; a Visiting Professor with GTRI-Ireland, Athlone, Ireland, during summer 2009; and a Visiting Professor with LAAS-CNRS, Toulouse, France, during summer 2010.

Dr. Tentzeris was the recipient/corecipient of the 2014 Georgia Tech ECE Distinguished Faculty Achievement Award; the 2013 IET Microwaves, Antennas and Propagation Premium Award; the 2012 FiDiPro Award in Finland; the iCMG Architecture Award of Excellence; the 2010 IEEE Antennas and Propagation Society Piergiorgio L. E. Uslenghi Letters Prize Paper Award; the 2011 International Workshop on Structural Health Monitoring Best Student Paper Award; the 2010 Georgia Tech Senior Faculty Outstanding Undergraduate Research Mentor Award; the 2009 IEEE Transactions on Components and Packaging Technologies Best Paper Award; the 2009 E.T.S. Walton Award from the Irish Science Foundation; the 2007 IEEE APS Symposium Best Student Paper Award; the 2007 IEEE IMS Third Best Student Paper Award; the 2007 ISAP 2007 Poster Presentation Award; the 2006 IEEE MTT Outstanding Young Engineer Award; the 2006 Asian-Pacific Microwave Conference Award; the 2004 IEEE Transactions on Advanced Packaging Commendable Paper Award; the 2003 NASA Godfrey "Art" Anzic Collaborative Distinguished Publication Award; the 2003 IBC International Educator of the Year Award; the 2003 IEEE CPMT Outstanding Young Engineer Award; the 2002 International Conference on Microwave and Millimeter-Wave Technology Best Paper Award (Beijing, China); the 2002 Georgia Tech-ECE Outstanding Junior Faculty Award; the 2001 ACES Conference Best Paper Award; the 2000 NSF CAREER Award; and the 1997 Best Paper Award of the International Hybrid Microelectronics and Packaging Society. He was the TPC Chair for IEEE IMS 2008 Symposium and the Chair of the 2005 IEEE CEM-TD Workshop and he is the Vice-Chair of the RF Technical Committee (TC16) of the IEEE CPMT Society. He is the founder and chair of the RFID Technical Committee (TC24) of the IEEE MTT Society and the Secretary/Treasurer of the IEEE C-RFID. He is the Associate Editor of the IEEE Transactions on Microwave Theory and Techniques, the IEEE Transactions on Advanced Packaging, and the International Journal on Antennas and Propagation. He has given more than 100 invited talks to various universities and companies all over the world. He is a member of URSI-Commission D, a member of the MTT-15 committee, an Associate Member of EuMA, a Fellow of the Electromagnetic Academy, and a member of the Technical Chamber of Greece. He served as one of the IEEE MTT-S Distinguished Microwave Lecturers from 2010 to 2012.

Apostolos Georgiadis (Senior Member, IEEE) was born in Thessaloniki, Greece. He received the B.S. degree in physics and the M.S. degree in telecommunications from the Aristotle University of Thessaloniki, Thessaloniki, Greece, in 1993 and 1996, respectively, and the Ph.D. degree in electrical engineering from the University of Massachusetts at Amherst, Amherst, MA, USA, in 2002.

In 1995, he spent a semester with Radio Antenna Communications (RAC), Milan, Italy. In 2000, he spent three months with Telaxis Communications, South Deerfield, MA, USA. In 2002, he joined Global Communications Devices (GCD), North Andover, MA, USA, where he was a Systems Engineer involved with CMOS transceivers for wireless network applications. In June 2003, he was with Bermai Inc., Minnetonka, MN, USA, where he was an RF/Analog Systems Architect. In 2005, he joined the University of Cantabria, Santander, Cantabria, Spain, as a Researcher. He is currently a Senior Research Associate and Group Leader of the Microwave Systems and Nanotechnology Department, Technological Telecommunications Center of Catalonia (CTTC), Barcelona, Spain, in the Communication Technologies Division, where he is involved in active antennas and antenna arrays and more recently with RFID technology and energy harvesting.

Dr. Georgiadis was the recipient of a 1996 Fulbright Scholarship for graduate studies with the University of Massachusetts at Amherst; the 1997 and 1998 Outstanding Teaching Assistant Award presented by the University of Massachusetts at Amherst; the 1999 and 2000 Eugene M. Isenberg Award presented by the Isenberg School of Management, University of Massachusetts at Amherst; and the 2004 Juan de la Cierva Fellowship presented by the Spanish Ministry of Education and Science. He is involved in a number of technical program committees and serves as a reviewer for several journals including the IEEE Transactions on Antennas and Propagation and the IEEE Transactions on Microwave Theory and Techniques. He was the corecipient of the EUCAP 2010 Best Student Paper Award and the ACES 2010 2nd Best Student Paper Award. He was the Chairman of EU COST Action IC0803, RF/Microwave communication subsystems for emerging wireless technologies (RFCSET), and the Coordinator of Marie Curie Industry–Academia Pathways and Partnerships project Symbiotic Wireless Autonomous Powered (SWAP) system. He is a member of the IEEE MTT-S TC-24 RFID Technologies (Chair 2012–2014) and a member of IEEE MTT-S TC-26 Wireless Energy Transfer and Conversion. He serves on the Editorial Board of the *Radioengineering Journal* and as an Associate Editor of the IEEE Microwave and Wireless Components Letters and *IET Microwaves Antennas and Propagation Journal*. He is the Editor-in-Chief of *Wireless Power Transfer*.

Luca Roselli (Senior Member, IEEE) was born in Florence, Italy, in 1962. He received the ''Laurea'' degree in electronic engineering from the University of Florence, Florence, Italy, in 1988.

From 1988 to 1991, he worked at the University of Florence on SAW devices. In November 1991, he joined the University of Perugia, Perugia, Italy, where he is currently working as an Associate Professor and where he has been teaching several classes on electronic devices, microwave electronics, high-frequency (HF) electronic components, and applied electronics. Since 2000, he has been coordinating research activity at the High Frequency Electronics (HFE) Laboratory. In that year, he also founded the spin-off company WiS (Wireless Solutions) Srl, operating in the field of microwave electronic systems with which he cooperated as a consultant until it joined the new company ART Srl. in 2008. From 2008 to 2012, he was the Director of the Technical and Scientific Committee of ART Srl and a member of the Board of Directors. In 2005, he founded a second spin-off company: DiES (Digital Electronic Solutions) Srl. His research interests mainly focus on the design of high-frequency electronic circuits and systems, including the development of numerical methods for electronic circuit analysis with special attention to RFID–NFC systems, new materials (including organic and recyclable ones), and far-field wireless power transfer. In these fields, he published more than 220 contributions in international reviews and peer-reviewed conferences, the interest in which is testified by an HF index of 21 (source Google Scholar) and more than 1450 citations.

Mr. Roselli was the Chairman of the VII Computational Electromagnetic in Time Domain Workshop in 2007. In 2013, he was the Chairman of the First IEEE Wireless Power Transfer Conference (WPTC). Currently, he is member of the list of experts of Italian Ministry of Research and University (MIUR); member of several IEEE Technical Committees [MTT-24 RFID Technologies (past chair), MTT-25 RF nanotechnolgies, MTT-26 Wireless Power Transfer]; member of the Sub Committee 32 RFID Technologies of International Microwave Symposium (IMS) (past chair); member of the European Research Council (ERC) Panel PE7; member of the Advisory Committee of IEEE WPTC. He is involved in the boards of several international conference (RWCOM, RFID-TA, EuCAP, MAREW). He is a reviewer for many international conferences and journals (the PROCEEDINGS OF THE IEEE, the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, *ACES Journal*, *Radioengineering Journal*, Hindawi publishing corporation, *Elsevier Organic Electronics*, *ASP Nanoscience and Nanotechnology Letters*, Cambridge University Press, and *Wireless Power Transfer Journal*).