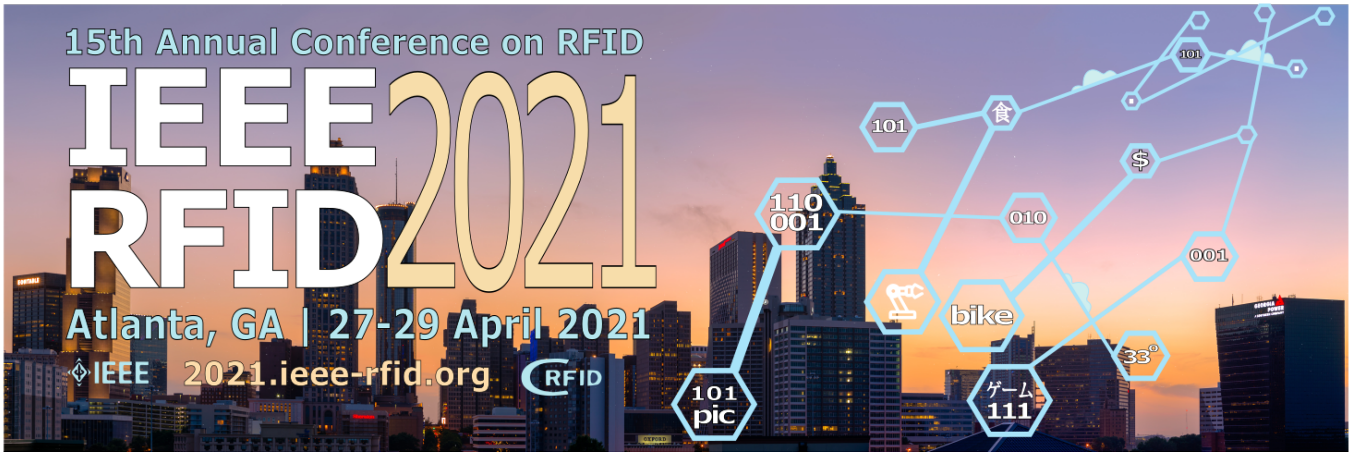

IEEE RFID 2021

ENERGY HARVESTING WORKSHOP

28-29 April 2021

Organizers: Cheng Qi, Stewart Thomas, Alanson Sample, Gregory D. Durgin

Final Program

Table of Contents

Table of Contents 2

Letter from the Organizers 3

Presentations 4

Keynote: The Potential of Programmable and Configurable Techniques Towards Low-Voltage RFIDs 4

WEH Tutorial: So What Is the Ultimate Limit of RF Energy Harvesting? 4

WEH Tutorial: Energy Harvesting,an Introductory Circuits Perspective 4

WEH: Energy Scavenging of Passive Tags with Unspecified Locations 5

WEH: Room-Scale Wireless Power Delivery via Quasi-Static Cavity Resonance 5

WEH: Powering Digital Devices: Just add RF! 5

WEH: RF Energy Harvesting Friendly Self-Clocked D-LDO For SoC IoT 6

Design and Experimentation of a Novel Five Coil Asymmetric Magnetic Resonance Wireless Power Transfer System 7

Channel Inversion Method for Optimum Power Delivery in RF Harvesting Backscatter Systems 7

Synthesis of Compact, Low-loss Beam-forming Networks for RF Energy Harvesting 7

Letter from the Organizers

Welcome to the IEEE RFID 2021 Workshop on Energy Harvesting! This workshop – hopefully a regular occurrence at CRFID conferences – explores the vast, multi-disciplinary topic of energy-harvesting and low-powered electronics. Arguably, the first such workshop was the IEEE RFID 2015 Workshop on Wireless Power, began by Dr. Daniel Arnitz.

In forming the workshop, we cast a broader net to consider cutting-edge works in the following fields of interest:

- RF and hybrid energy harvesting techniques
- Wireless power transfer and charging
- Low-powered electronic techniques
- Applications and systems related to energy-harvesting

Our sincerest appreciation to the Technical Program Committee for *IEEE RFID 2021* for accommodating the unique demands of this workshop.

Hoping to see everyone in person next year for IEEE RFID 2022 in Las Vegas, Nevada!

Sincerely,

The Organizers

Cheng Qi[3], Stewart Thomas[1], Alanson Sample[2], Gregory D. Durgin[3]

[1]Bucknell University; [2]University of Michigan; [3]Georgia Tech




Presentations

Keynote: The Potential of Programmable and Configurable Techniques Towards Low-Voltage RFIDs
Jennifer Hasler (Georgia Institute of Technology, USA)

RFID systems often have low-power, low-energy, and low supply voltage constraints while simultaneously requiring ever increasing computation in that constrained environment. The past two decades have seen considerable amount of energy-efficient computing techniques based on analog techniques validating Carver Mead's 1990 hypothosis that analog computing should be 1000x or more efficient than corresponding digital computation. One approach that enables programmable and configurable approaches are the large-scale Field Programmable Analog Arrays (FPAA), an approach that includes a family of devices, and resulting design tools that are innovating a path for automated analog design. This talk will review these various approaches, discuss how to adapt these techniques to RFID applications, as well as give a picture of where these techniques could positively impact RFID applications. The talk will discuss how FPAA devices could be adapted to operate in very low voltage applications (e.g. 250-500mV) typical of RFIC voltage supplies.

WEH Tutorial: So What Is the Ultimate Limit of RF Energy Harvesting?
Gregory Durgin (Georgia Tech, USA)

This short tutorial reviews the state-of-the-art of RF energy harvesting, outlines the fundamental limitations from first principles, and explains where future gains will come from. Techniques for achieving -30 dBm sensitivity for RF-driven digital circuits will be discussed, including novel materials and devices and unusual forms of RF excitation.

WEH Tutorial: Energy Harvesting,an Introductory Circuits Perspective
Brian Degnan (White River Technologies, Italy)

An introductory tutorial on UHF RFID energy-harvesting that covers charge pump design with insights into practical CMOS implementations.

WEH: Energy Scavenging of Passive Tags with Unspecified Locations

Edwin Kan (Cornell University, USA)

In the full implementation of Internet of Things (IoT), we may have more than 30 sensors and ID tags in a common room, and more than 300 sensors/tags in a hospital room. In consideration of not only battery recharging but also recycling, the last layer of IoT needs to be passive to support this aggressive number scaling of pervasive tag deployment. This trend will be even more aggravated in the future Internet of Everything (IoET). Hence, energy scavenging of passive tags to support digital ID modulation and sensor readout is critical to realize the eventual IoT and IoET vision. Under the assumption of unspecified tag location within a zone of at least 5m, we will briefly discuss the advantages and limitations of the approaches by RF, thermoelectric, ultrasound/vibration, and solar cells. Following similar arguments, the operational range of modern RFID star network is often limited by the tag sensitivity, where the tag needs to harvest sufficient ambient energy to build the digital communication link. For the RF energy harvesting by charge pumping, we will then investigate the limitation set by the impinging energy and device nonlinearity which render the design tradeoffs between the energy efficiency and peak voltage. Last but not least, we will show how manufacturing variation of the diodes and passive devices can severely influence the harvesting performance and then present possible mitigation methods.

WEH: Room-Scale Wireless Power Delivery via Quasi-Static Cavity Resonance

Alanson Sample (University of Michigan, USA)

Wireless power offers the promise of seamlessly charging our electronic devices as easily as data is transmitted through the air. However, existing solutions are limited to near contact distances or low delivered power levels and thus, do not provide the geometric freedom and ease of use the term "wireless" suggests. This talk presents an overview of work on the use of resonant cavity modes to control magnetic field distribution in order to provide uniform wireless charging in large chambers and rooms. We introduced Quasi-Static Cavity Resonance (QSCR) as a means of enabling large purpose-built structures to generate near-field standing waves that safely deliver kilowatts of power to mobile receivers contained nearly anywhere within. Experimental demonstrations show that our 256 square foot, QSCR enabled room offers a unique charging experience where user's devices can be powered simply by entering the room.

WEH: Powering Digital Devices: Just add RF!

Stewart Thomas (Bucknell University, USA); Brian Degnan (White River Technologies, Italy)

In this talk, we discuss the latest developments in using existing digital devices as power harvesting components. While most RFID devices rely on carefully tuned harvesting components, the underlying technology is already present in the everyday digital devices we use. We show that with the addition of a simple wire antenna to microcontroller, we can turn a device into a fully-functioning wireless sensor. We will discuss how to build an "ex-nihilo" harvester, the characteristics of the ESD protection systems and how we utilize these circuits for power harvesting. We will also present a battery-free Bluetooth sensor that is able to run entirely from harvested RF energy, created from an unmodified Bluetooth sensor.

WEH: RF Energy Harvesting Friendly Self-Clocked D-LDO For SoC IoT

Christos Konstantopoulos (University Of Innsbruck, Austria); Thomas Ussmueller (Universität Innsbruck, Austria)

Digital Low Drop-Out regulators, in contrast to analog counterparts, provide an architecture of sub-1 V regulation with low power consumption, high power efficiency, and system integration. Towards an optimized integration in the ultra-low-power System-On-Chip Internet of Things architecture that is operated through a Radio Frequency energy harvesting scheme, the D-LDO regulator should constitute the main regulator that operates the master-clock and rest loads of the SoC. In this context, we present a D-LDO with linear search coarse regulation and asynchronous fine regulation which incorporates an in-regulator clock generation unit that provides an autonomous, self-start-up, and power-efficient D-LDO design. In contrast to contemporary D-LDO designs that employ ring-oscillator architecture which start-up time is dependent on the frequency, this work presents a fast start-up burst oscillator based on a high-gain stage with wake-up time independent of coarse regulation frequency. The design is implemented in a 55-nm Global Foundries CMOS process. With the purpose to validate the self-start-up capability of the presented D-LDO in the presence of ultra-low input power, an on-chip test-bench with an RF rectifier is implemented as well which provides the RF to DC operation and feeds the D-LDO. Power efficiency and load regulation curves of the D-LDO are presented as extracted from the RF to regulated DC operation. The D-LDO regulator presents 83.6 % power efficiency during the RF to DC operation with 3.65 uA load current and voltage regulator referred input power of -27 dBm. It succeeds 486 nA maximum quiescent current with CL 75 pF, maximum current efficiency of 99.2 %, and 1.16x power efficiency improvement compared to analog voltage regulator counterpart oriented to SoC IoT loads. Complementary, the transient performance of the D-LDO is evaluated under transient droop test and the achieved Figure-Of-Merit is compared with state-of-the-art implementations.

Design and Experimentation of a Novel Five Coil Asymmetric Magnetic Resonance Wireless Power Transfer System

Rafael R Figueroa III, Allen G Morinec, Jr, Ethan J Jones, Sebastian Tapias and Lancina Djibo (Georgia Institute of Technology, USA); Gregory Durgin (Georgia Tech, USA)

This paper introduces a wireless power transfer system using a 5-coil asymmetric topology to mitigate range limitations when powering devices requiring small coils. The efficiency of a traditionally coupled wireless power transfer system falls sharply at distances beyond the diameter of the coils used. In order to power devices requiring small packaging at a distance, this limitation must be eliminated. Magnetically coupled coils have demonstrated the ability to extend power transfer distances beyond that of traditional coupling techniques; however, power transfer is still limited by coil size. We utilized the power transfer capabilities demonstrated by a 4-coil magnetic resonant transfer system and introduced a fifth coil to extend the transfer range. Coil asymmetry was then introduced to overcome coils radius limitations. This power transfer technique was demonstrated by charging a cell phone at a distance of 61 cm. The 5-coil transfer system operates at 40% efficiency from amplifier output to rectifier input. We develop an end-to-end power transfer system including a power amplifying source, 5-coil transfer system, and load including rectification to feed the cell phone. Circuit models and equations are introduced for all three stages with an emphasis on the asymmetric 5-coil system. Key parameters characterizing the 5-coil wireless transmission segment are also derived. Individual and system-wide efficiency limitations are discussed, and areas of future work are presented.

Channel Inversion Method for Optimum Power Delivery in RF Harvesting Backscatter Systems

Rui Chen and Shuai Yang (University of Cambridge, United Kingdom (Great Britain)); Richard Penty (Cambridge University, United Kingdom (Great Britain)); Michael J Crisp (University of Cambridge, United Kingdom (Great Britain))

This work presents a method for enhanced wireless power transfer using an algorithm to calculate the optimum phases of multiple transmitting antennas in a passive UHF RFID system. The algorithm performs the calculation based on measured backscatter phase value of individual antenna port and the phase rotation caused by each port's receiving channel. Through experimental validations, it is shown that the proposed algorithm can achieve up to 18 dB improvement in the tag RSSI using three transmitting antennas. The proposed algorithm could be used in the next generation sensor tags to optimise power delivery efficiency.

Synthesis of Compact, Low-loss Beam-forming Networks for RF Energy Harvesting

Blake Marshall and Gregory Durgin (Georgia Tech, USA)

The new algorithm described in this work produces an optimized RF beam-forming network. Based on a sequential optimization technique that has been particularly adapted to microwave circuitry, the technique is well-suited for design of energy-harvesting networks with arrays because it can emphasize compact size and low-loss. This methodology defines a planar area (with a ground plane), ports, and a goal scattering matrix then iterates through various design structures to find an optimal solution. Numerous circuit design applications beyond energy-harvesting would also benefit.