WORKSHOPS

Sunday, 4 June 2017

All Workshops and Short Courses are located at the Hawai'i Convention Center. Specific room assignments will be provided onsite.

WSA 08:00–17:00

100-1000 GHz: Crossroads for New Design Paradigms Connecting Devices, Circuits, Systems and Applications
Sponsor: IMS; RFIC

Organizer: Kaushik Sengupta, *Princeton University*; Goutam Chattopadhyay, *NASA Jet Propulsion Laboratory, Caltech*

Abstract: The decade of frequency spectrum spanning 100 GHz to 1000 GHz has promised a plethora of novel applications ranging from communication to sensing, spectroscopy and high-resolution imaging. The spectrum has been successful in attracting rapt attention (and controversies in perhaps equal measure) from scientists and engineers who have been dedicated to finding the killer application with the right technology for many years. However, it is only in the last decade, that we have seen unprecedented improvement in the technology space that has allowed early demonstrations of fully integrated complex systems at these frequencies including chip-scale and wafer-scale phased arrays, multi-GB/s communication systems, imaging and spectroscopy, to name a few. Not surprisingly, at the intersection between microwave and infra-red frequencies, the underlying technology space also spans from solid-state devices (III-V, silicon, hybrid etc) to photonics-based approaches. Now that we are closer than ever before to a potentially diverse set of technology that can successfully address the spectrum, it is time to look into the future to gauge the prospects that lie ahead and ask fundamental questions: What are the unique opportunities in this frequency range and what is the right technology? Is this evolving spectral space comparable to what mm-Wave (below 100 GHz) was a decade ago? Are there unique design methodologies and paradigms cutting across the various layers of abstraction that can break the classical trade-offs in efficiency and scalability. In this workshop, we bring experts working across the technology space to understand the challenges and discuss these fundamental opportunities that can open up the spectrum for transformative technology in the coming decade.

1. Advanced InP HEMT Technology for Terahertz Amplifier Circuits
   Richard Lai, *Northrop Grumman*
2. Characterization and Scaling of Silicon Devices and Benchmark Circuits for mm-Wave and THz Applications
   Sorin Voinigescu, *University of Toronto*
3. Wafer-Scale CMOS for THz Sources and Phased-Array Transmitters
   Gabriel Rebeiz, *University of California, San Diego*
4. Circuit-Electromagnetics-Systems Co-Design for High-Performance Terahertz Chip-Scale Systems
   Kaushik Sengupta, *Princeton University*
5. Interconnecting Technologies for Terahertz Components and Instruments
   Goutam Chattopadhyay, *Jet Propulsion Lab, Caltech*
6. Photonics-Enabled Terahertz Technologies and Their Applications
   Tadao Nagatsuma, *Osaka University*
7. Polymer Waveguides as an Alternative to Optical and Copper High-Speed Communication
   Patrick Reynaert, *Katholieke Universiteit Leuven*
8. Beyond Active Terahertz Imaging in Silicon Technology
   Richard Hadi, *University of California, Los Angeles*

WSB 08:00–17:00

5G Communications Innovations: Connectivity for the Next Decade
Sponsor: IMS; RFIC

Organizer: Edward Niehenke, *Niehenke Consulting*; Nuno Borges Carvalho, *Universidade de Aveiro*; Alberto Valdes-Garcia, *IBM T. J. Watson Research Center, Yorktown Heights, NY*; Laurent Dussopt, *CEA-TECH, Lyon Area*; Roberto Gomez-Garcia, *Polytechnic School – University of Alcala*

Abstract: 5G communication is a unifying connectivity fabric for the next decade empowering new user experiences, connecting new industries and devices, enabling new services and delivering new levels of efficiency. This workshop will focus on technologies leading the 5G connectivity. An overview of the 5G communication system will be presented showing usage scenarios, enhanced broadband mobile, mission critical services, massive internet of things, standards and spectrum. Propagation, system design and performance of 5G millimeter wave mobile communications will be presented. 5G C-Ran technologies approaches will be presented with the path to all digital radios. A fusion of millimeter-wave access and mobile edge computing (MiEdge) is introduced to alleviate the problem of backhaul links facilitating millimeter-wave technologies in 5G systems. Architectures and circuits for 5G Base Station Transmitters will be shown with new analysis techniques to meet 5G requirements. Designs of critical mm-wave circuits for 5G base stations are presented including an integrated 30 GHz SiGe BiCMOS transmitter. Power Amplifier (PA) Innovations for 5G System will be presented with innovative state-of-the-art designs that integrate the power amplifier with digital pre-distortion. CMOS mm-wave PAs for 5G communication will be shown including on-chip power combining and wideband AM-PM cancellation of 64 QAM and 256 QAM modulations. Several PA examples in 40 nm and 28 nm CMOS, operating at 28 GHz, 60 GHz and 85 GHz will be used throughout the presentation. Millimeter-Wave Phased-Arrays for 5G Systems will be presented showing latest development in 5G communication systems at UCSD including 28 GHz and at 60 GHz phased-arrays and related communication links using silicon RFICs and innovative packaging. Architectures and circuits for millimeter-wave Massive MIMO will be presented with recent developments on a few candidate CMOS-based circuit and system technologies for 5G millimeter-wave applications. A new filter development employing hybrid-lumped-element-acoustic wave filter will be presented that allows large bandwidth, multi-band operation, and transfer-function adaptiveness.

1. Communications Innovations: Connectivity for the Next Decade and Beyond to 2030
   Upkar Dhaliwal, *Future Wireless Technologies*
2. Millimeter Wave Mobile Communications: Propagation, System Design and Performance
   Ashwin Sampath, *Qualcomm, Inc.*
3. ~~CLOUD RAN Approaches and the Path to All Digital Radios~~
   ~~Arnaldo Oliveira, *Telecommunications Institute – Aveiro*~~
4. MiEdge: Fusion of mmWave Access and Mobile Edge Computing for 5G
   Keii Sakaguchi, *HHI Fraunhofer Institute*
5. Architectures and Circuits for 5G Base Station Transmitters
   Christian Fager, *Chalmers University*
6. Power Amplifier Innovations for 5G System
   Sergio Pires, *Ampleon*
7. CMOS mm-Wave PAs for 5G Communication
   Marco Vigilante, *ESAT MICAS*
8. Millimeter-Wave Phased-Arrays for 5G Systems
   Gabriel M Rebeiz, *University of California, San Diego*
9. Antennas for Integration in Miniaturized Wireless Communication
   Mario Pauli, *Karlsruhe Institute of Technology*; Thomas Zwick, *Karlsruhe Institute of Technology*
10. Architectures and Circuits for mmWave Full-Duplex and Massive MIMO
    Harish Krishnaswamy, *Columbia University*
11. Filter Developments for Next-Generation Wireless Communications Systems
    Roberto Gómez-García, *University of Alcalá*; Dimitra Psychogiou, *University of Colorado Boulder*; Dimitrios Peroulis, *Purdue University*
12. RF Front-End Innovations for 5G Systems
    Makoto Kawashima, *Murata Mfg. Co.*

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WSC 08:00–17:00

5G mm-Wave IC Front-End Co-Design with Antenna, Packaging, and Testing for Future SOC Solutions

Sponsor: RFIC; IMS

Organizer: Yanjie Jay Wang, *Intel Corporation - Intel Labs*; Didier Belot, *CEA-LETI*; Hua Wang, *Georgia Institute of Technology*

Abstract: The 5th generation wireless systems (5G) is proposed as the next major revolution of mobile wireless technologies. Mm-Wave carriers and MIMO systems are expected to be extensively employed in 5G systems to achieve significantly enhanced data rate, spectral/spatial diversity/efficiency, and minimized system latency. High-performance mm-wave front-end integrated circuit design has always been a major technical challenge, and the inflexible 50 ohm interface with antenna and packaging adds to such existing circuit challenges. In this full-day workshop, the speakers will demonstrate/discuss their recent innovations in the mm-Wave antenna and low-cost packaging designs as well as their co-designs with mm-Wave front-end circuits. Moreover, the sophisticate mm-wave testing for future System-on-Chip solutions is also discussed, as the cost of such industrial applications will be shared between the die, the package and the testing.

1. Millimeter-Wave Phased-Arrays for 5G Systems
   Gabriel Rebeiz, *University of California, San Diego*
2. mm-Wave SiGe Power Amplifiers for 5G
   Domine Leenaerts, *NXP*
3. Ultra-Broadband mm-Wave ICs for Next (5th) Generation Wireless
   Jacques Chris Rudell, *University of Washington*
4. Multi-Feed Antenna and On-Antenna Power Combining for High-Power High-Efficiency Mm-Wave Transmitter
   Hua Wang, *Georgia Institute of Technology*
5. Silicon-Based ICs and Organic Packaging/Antenna Solutions for 5G mmWave Communications
   Alberto Valdes-Garcia, *IBM*
6. mmW Antenna Integrated Front-End IC-Module Co-Design and Testing for 5G Applications
   Debabani Choudhury, *Intel Corporation - Intel Labs*
7. Non-Invasive mmW Built-in Test Techniques
   Jose Luis Gonzalez, *Leti, Technology Research Institute*
8. mmW Industrial Test Trends
   Dorine Gurney, *Tektronix*
9. Rethinking mm-Wave Multi-Antenna Transceiver Design to Accommodate Both Beamforming and Diversity
   Payam Heydari, *University of California, Irvine*

WSD 08:00–17:00

Advanced Concepts and Architectures for Future RF and mmW Transceivers in Nanoscale CMOS

Sponsor: RFIC

Organizer: Francois Rivet, *Universite de Bordeaux*; Gernot Hueber, *NXP Semiconductors*

Abstract: With the advent of nano-scale CMOS technology, exciting new developments have recently taken place in the field of RF and mm-wave transmitters, receivers and frequency synthesizers. The low-voltage, fast speed, fine feature-size and low cost of the new technology have forever changed the way we design circuits, architectures and systems. Not only the RF/mm-wave circuits have taken different shapes from what has been taught in textbooks but also their integration with digital processors have enabled new possibilities for digital assistance The motivation of this workshop is to capture what is the state at the edge of technology, what is the demand of the industry in the context of high volume products, as well, what are circuit and architectural concepts that are demanded or enforced by the technology. Hence, the idea is to capture and summarize the trends and directions RF design is heading to, which makes it highly valuable from early researchers to long time experienced experts as well as technology scouts.

1. Design by Mathematics: A Novel Approach for the Design of RFICs in Nanoscale CMOS
   Francois Rivet, *University of Bordeaux*
2. Designing Energy Efficient Radios for Emerging Low Power Standards
   Ramesh Harjani, *University of Minnesota*
3. Principles of Noise-Cancelling Receivers With Wide Dynamic Range
   Asad Abidi, *UC Los Angeles*
4. A Wideband Single-PLL Multi-Channel and Multi-Band Car Radio Receiver With High-Resolution DS ADCs
   Lucien Breems, *NXP Semiconductors*
5. Mmwave Transceivers in Nanoscale CMOS
   Khaled Khalaf, *imec*
6. 5G Race for 1-10Gb/s - Cellular and/or mmWave, Friends and/or Foes?
   Aleksandar Tasic, *Qualcomm*
7. Gigabit/s Over-the-Air Throughput in Nanoscale CMOS
   Renaldi Winoto, *Marvell*
8. Multi-Standard RF and mmW Transmitters Based on Semi-Digital FIR-DAC
   Antoine Frappé, *IEMN – ISEN*

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WSE 08:00–17:00

CMOSpace: Challenges and Accomplishments of Designing Advanced CMOS SoC for Space Communication and Instrumentation

Sponsor: IMS; RFIC

Organizer: Tim LaRocca, *Northrop Grumman*; Bryan Wu, *Northrop Grumman*

Abstract: As the cost per launch decreases with the advent of re-usable rockets such as the SpaceX Falcon9 and the size of satellites reducing to 1U Cube-Sat dimensions, the demand for miniaturized yet reliable RF and mixed-signal electronics is on the rise. Current military architectures will likely include disaggregated systems of smaller platforms working collaboratively to execute missions at lower cost and with increased responsiveness. Commercial enterprises such as OneWeb are looking to cover the globe with broadband access through thousands of LEO satellites. And NASA continues to push state-of-the-art in deep space sensing constrained by very low power satellite systems. With low-power and high integration capability, CMOS technology provides a platform for creating a System-on-Chip (SoC) with digital, mixed-signal and RF/mmWave circuitry for SWaP reduction. This workshop will discuss issues and challenges relevant to the design and reliability of CMOS technology requirements for space based electronics. The workshop will start with a review of a CubeSat electronic requirements, progress through radiation and semiconductor effects and delve into system demonstrations of space electronics for digital and RF/mmWave. This is a great start for engineers to be acquainted with the adventure of space.

1. Requirements and Capabilities of the Standardized CubeSat Platform for Supporting CMOS SoC Development
   Adam Gunderson, *Northrop Grumman*
2. Utilizing Advanced Semiconductor Device Technologies in the Natural Space Environment
   Jonny Pellish, *NASA Goddard Space Flight Center*
3. CMOS-Compatible SOI MESFETs for Extreme Environment Electronics
   Trevor Thornton, *Arizona State University*
4. Designing With CMOS for Space Applications
   Anthony Amort, *Boeing*
5. CMOS Systems-on-Chip for NASA Millimeter-Wave & THz Space Instruments
   Adrian Tang, *JPL NASA*
6. RHBD for Space – Addressing the Spectrum of Applications
   Andrew Kelly, *BAE*
7. Advanced Millimeter-wave Package for Space and Beyond
   Jean-Marc Rollin, *Nuvotronics*

WSF 08:00–17:00

Efficiency Enhancement Techniques for Linear and High Bandwidth Power Amplifiers

Sponsor: RFIC

Organizer: Ali Afsahi, *Broadcom Ltd.*; Patrick Reynaert, *KU Leuven*

Abstract: Increasing demand for higher data rate has forced the communication standers to use higher bandwidth and more complex modulation schemes which require a very linear power amplifier. Operating at back off power to meet linearity degrades efficiency significantly. This workshop covers various efficiency enhancement and linearization techniques for linear and high bandwidth power amplifiers.

1. Physical Foundations and Practical Implementations of Efficient RF Power Amplifiers
   Earl McCune, *RF Communications Consulting*
2. Si Envelope Tracking Power Amplifiers for High Peak-to-Average Power (PAPR) Signals
   Donald Kimball, *Maxentric*
3. Switched-Capacitor Power Amplifiers for Efficient Digital RF Transmission
   Jeffrey Walling, *University of Utah*
4. Digital Outphasing Techniques for Wideband WLAN Radios
   Paolo Madoglio, *Intel Corp.*
5. Doherty Architecture for Mixed-Signal Power Amplifiers and mm-Wave Power Amplifiers
   Hua Wang, *Georgia Tech*
6. A Self Destructive Phenomenon Affecting High Efficient and High Bandwidth PA's Performance , the Memory Effect
   Farbod Aram, *ProjectFT*
7. Digital Signal Processing Techniques for Efficient Power Amplifiers
   Paul Draxler, *Qualcomm Corp.*

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WSG 08:00–17:00

Energy-Efficient RF Transceiver IC and System Design for Healthcare Applications

Sponsor: RFIC

Organizer: Yao-Hong Liu, *IMEC*; Gernot Hueber, *NXP*

Abstract: The RF transceiver is typically one of the most power consuming building blocks in wireless sensor devices for different wearable/implantable healthcare monitoring, e.g., heart-rate monitor, capsule endoscope, etc. On the other hand, the efficiency of the RF transceiver has been dramatically reduced in the past few years, thanks to both CMOS technology scaling and the development of the new low-power/low-voltage digital-intensive design approaches, which enables many new wireless healthcare applications. In this workshop, we will discuss several latest wireless technologies for these applications, including Bluetooth Low Energy, Medical Implantable Communication Services (MICS), Body channel communication, and wideband wireless interface for neural recording/stimulation. The experts from both industrial and academic will introduce the topics from market, potential market, to regulations. In addition, this workshop will especially focus on the discussion of various design challenges, system requirements and potential solutions in developing energy-efficient transceiver ICs for the healthcare applications.

1. ULP Wireless Technologies in the Healthcare Domain
   Christian Bachmann, *IMEC*
2. A Body Channel Communication (BCC) Transceiver Design for Wireless Body Area Network (WBAN)
   Hyunwoo Cho, *KAIST*
3. Radar-Based Health Monitoring: System Requirement, Recent Advances, and Design Challenges
   Marco Mercuri, *IMEC*
4. Bluetooth Low Energy Communication for Implantable Medical Devices
   Perry Li, *St. Jude Medical*
5. ~~Wireless Medical Device Communication – Performance Considerations, System Design and Recent Innovations~~
   ~~Peter Bradley, *Microsemi*~~
6. Ultra-Low Power Radio and Antenna Design for Cubic-mm Sensor Nodes
   David Wentzloff, *University of Michigan*
7. An Ultra-Low-Power IEEE802.15.6/Proprietary Mode Radio SoC for Medical Applications
   Kazuaki Oishi, *Fujitsu Lab*
8. Wireless Bioelectronics
   Ada Poon, *Stanford University*

WSH 08:00–17:00

Frequency Synthesis and Clock Distribution for Massive MIMO and Phased-Arrays in 5G Communication Systems and Beyond

Sponsor: RFIC

Organizer: Jeyanandh Paramesh, *Carnegie Mellon University*; Xiang Gao, *Marvell*; Jaber Khoja, *IDT*

Abstract: Next generation communication systems (5G and beyond) seek to bridge the gap between the projected demand and supply of mobile data traffic through a combination of new system techniques and access to new spectrum below 6 GHz and especially in several millimeter-wave bands from 15 GHz to 86 GHz. In these systems, the design of frequency synthesizers that can access several such bands with low phase noise, spur levels and frequency granularity remains a critical block. Furthermore, "Massive MIMO" – which consists of a large number of antennas at the access point – is a promising technology to meet the high data rate and quality of service requirements of 5G wireless systems. Achieving stringent phase-noise specifications and scalable LO distribution to maintain phase coherence across the different units in the MIMO array is a critical challenge. This workshop will present the latest trends in the design of such synthesizers.

1. Phase Noise Limits of On-Chip mm-Wave Oscillators
   Hossein Hashemi, *University of Southern California*; Alireza Imani, *University of Southern California*
2. A 2-26 GHz Highly Flexible Synthesizer in 32nm SOI CMOS
   Bodhi Sadhu, *IBM*
3. On CMOS Clock Generation With Low Phase Error
   Eric Klumperink, *University of Twente*
4. Design Consideration of Integrated Frequency Synthesizers in CMOS SOCs
   Sheng Ye, *Maxlinear*
5. Frequency Synthesis and Clock Distribution Techniques for Phased-Array Technology and Massive MIMO
   Arun Natarajan, *Oregon State University*
6. CMOS mm-Wave Phased-Array Frequency Synthesis
   Howard Luong, *Hong Kong University of Science and Technology*
7. ~~All-Digital PLL Based Frequency Synthesis~~
   ~~Ashoke Ravi, *Intel*~~
8. Digital Loop Filter Architectures for Millimeter Wave Frequency Synthesizers Based on All Digital PLL Single Bit Binary Phase Detection
   Pasquale Lamanna, *Huawei*
9. Component Design for Millimeter-Wave All-Digital Phase-Locked Loops
   Jeyanandh Paramesh, *Carnegie Mellon University*

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WSI 08:00–12:00

Frontiers of Superconducting and Cryogenic Microwave Electronics
Sponsor: IMS; RFIC

Organizer: Michael C. Hamilton, *Auburn University*; Daniel E. Oates, *MIT Lincoln Laboratory*

Abstract: Recent years have seen renewed interest and increase in efforts directed towards development of technology for high-frequency (microwave and beyond) and high-speed superconducting and cryogenic electronics systems. The discovery of superconductivity is recognized as an IEEE Milestone in Electrical and Computer Engineering and has made possible many important applications across a wide range of disciplines. Cryogenic electronics holds the promise of high performance and super-low energy per operation for computing applications that can take us beyond the end of the semiconducting technology roadmap. Driven by goals of ultra-high speed computing and signal processing, super-sharp and low-loss filters, higher performance MRI/NMR systems and integration with computing or imaging systems that must be cryogenically cooled due to noise constraints, there is a growing interest in active and passive microwave components designed for operation at low temperatures. Historically, despite the potential of higher performance from cryogenic components and systems, conventional technologies have provided sufficient performance. There are, however, reasons to believe that this situation may change in the near future. As one example, consider the case of superconducting quantum computing, where communication between qubits occurs through signals in the microwave regime and where the noise constraints are of utmost importance. Proper communication, control and integration of systems such as this will require superconducting and cryogenic microwave technology advancements that are now in development. This workshop aims to provide a sufficiently detailed description and platform for discussion of the current status and future of superconducting and semiconducting electronics for cryogenic systems. Talks in this workshop will cover: RF MEMS + superconducting filters, HTS filters, superconducting filters for resonance imaging systems, advances in superconducting microwave technology in Japan and China, superconducting microwave interconnect technology, recent superconducting device technology developments for mixed-signal circuits, recent cryogenic semiconducting device technology developments and cryogenic electronics for quantum computing systems.

1. Prospect of Cryogenic Digital Technology
   Akira Fujimaki, *Nagoya University*
2. Superconducting Microwave Mixed-Signal Circuits
   Deepnarayan Gupta, *HYPRES, Inc.*
3. Developments in China for the Design and Application of High Temperature Superconducting (HTS) Filters
   Liang Sun, *Chinese Academy of Sciences*
4. MEMS-Based Superconductor Tunable Filters
   Raafat R. Mansour, *University of Waterloo*
5. Microwave Surface Resistance of Ion-Implanted YBCO Thin Films in High Magnetic Field and Development of NMR Pickup Coils Using YBCO Thin Films
   Shigetoshi Ohshima, *Yamagata University*
6. On-Chip Microwave Generation with a Josephson Junction Laser
   Maja Cassidy, *The University of Sydney*
   ~~Cryogenic Hardware at the Quantum - Classical Interface~~
   ~~David Reilly, *The University of Sydney*~~
7. Flexible Superconducting Microwave Transmission Line Interconnects
   Michael C Hamilton, *Auburn University*

WSJ 13:00–17:00

High Performance Power Efficient Clock Generation for Internet of Things Applications
Sponsor: RFIC

Organizer: Hiva Hedayati, *Applied Micro*; Salvatore Levantino, *Politecnico di Milano*

Abstract: Internet of Things (IoT) applications are becoming a reality that will sense and actuate the world around us. IoT presents semiconductor industries with a market opportunity that may exceed that of all previous processing classes. In many cases battery-operated satellite nodes face a performance and power paradox challenge that is driving the need for a new type of low-power clock generation. The workshop will introduce various timing technologies to enable the lowest power consumption with acceptable accuracy and smaller size. Fully integrated phase-lock loop (PLL) solutions are considered more attractive compared to expensive bulky crystal oscillators. The workshop will also focus on MEMS timing solutions or other leading technologies to enable far more compact high performance designs.

1. Energy-Efficient Radio Links for IoT Applications
   Jagdish Pandey, *Qualcomm*
2. Scalable Synchronization for Duty-Cycled Radio Networks
   Rajeev Dokania, *Intel*; Alyssa Apsel, *Cornell*; Xiao Y. Wang, *MIT Lincoln Laboratory*
3. Efficient Clock Multiplication
   Ahmed Elkholy, *Univeristy of Illinois at Urbana-Champaign*
4. Ultra-Low-Power RC Oscillators
   Patrick Mercier, *University of California, San Diego*
5. Fast Startup Techniques
   Christian Enz, *EPFL*

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WSK 08:00–12:00

Highly Digital CMOS Transmitters With Embedded Power Amplifiers
Sponsor: RFIC

Organizer: Jeffrey Walling, *University of Utah*; Hua Wang, *Georgia Tech*

Abstract: In recent years, RF front-end transmitters with direct digital interfaces have become common for low-to-moderate power wireless systems (e.g. Bluetooth, Wi-Fi, etc.). These transmitters include up-conversion, filtering and output power amplifier stages. They are capable of generating ~1 W of output power with very good total system efficiency. Furthermore, they provide flexibility for software defined systems that allow quick re-configuration via software programming. Additionally, they are compact, often requiring areas less than 1mm2. In this workshop we will examine three main types of digital transmitters: outphasing based pulse-width modulation, switched-capacitor power amplifiers and current-mode digital power amplifiers. Additionally, there are many different architectures that utilize each of the above topologies, including class-G, polar, outphasing and multiphase. The presenters will provide examples of these architectures and provide insight into their designs and the scenarios in which their use is optimal.

1. A Switched Capacitor Power Amplification Technique for Energy- and Area-Efficient Wireless Transmitters
   Sangmin Yoo, *Michigan State University*
2. RF Transmitter Based on Cartesian RFDAC
   Bumman Kim, *Postech University;* Hadong Jin, *Postech University*
3. SCPAs and the (R)evolution from Polar to Multiphase Transmitters
   Jeffrey Walling, *University of Utah*; Wen Yuan, *University of Utah*; Zhidong Bai, *University of Utah*; Ali Azam, *University of Utah*
4. Hybrid Broadband PA Architecture Leveraging RF Power DACs
   Hua Wang, *Georgia Tech*; Song Hu, *Georgia Tech University*; Jongseok Park, *Georgia Tech*
5. Impedance Modulation in Digitally Modulated Polar Power Amplifiers for Wireless Applications
   Debopriyo Chowdhury, *Broadcom Corp.*
6. Digitally-Modulated CMOS Polar Transmitters for Highly-Efficient mm-Wave Wireless Communication
   Khaled Khalaf, *IMEC*
7. Pulse-Width Modulation Based Transmitter Architectures for Wireless Applications
   Ranjit Gharpurey, *University of Texas*; Kunhee Cho, *University of Texas*; Hyejeong Song, *University of Texas*

WSL 08:00–12:00

Microwave Thru Sub-THz Imaging and Sensor Array Technology for Security, Industrial, Commercial and Medical Applications
Sponsor: RFIC

Organizer: Ed Balboni, *Analog Devices*; Brian Floyd, *NCSU*

Abstract: Advances in silicon technology now provides the ability to economically build large arrays operating in the microwave to THz frequencies supporting bandwidths in the 10 GHz-100 GHz range. This workshop will include presentations on state of the art sensor arrays. Included will be systems targeted toward security, industrial, commercial and medical applications.

1. THz Medical Imaging With RF technology
   Zackary Taylor, *UCLA*
2. Rotational Spectroscopy With Low Cost CMOS mmW Sensors
   Navneet Sharma, *UT Dallas*; Ken O, *UT Dallas*
3. Wideband Transmitters and Receivers for High Resolution Imaging
   Gabriel Rebeiz, *UCSD*
4. Carrier Distribution and Synchronization for Radar and Imaging Arrays
   Adrian Tang, *JPL*
5. Advances on Spectro and Terahertz Imaging: from Sources to Applications
   Patrick Mounaix, *IMS Bordeaux University*; Francois Rivet, *IMS Bordeaux University*

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WSM 08:00–17:00

Millimeter Wave for 5G: Which Systems With Which Frequency Band - 5G RF Transceiver Design and System Aspects

Sponsor: RFIC

Organizer: Andre Hanke, *Intel Deutschland GmbH*; Pierre Busson, *ST Microelectronics*

Abstract: In the last two decades data-rates in wireless communication systems have been increasing exponentially. This trend is continuing with the fifth generation of wireless systems (5G) that will require peak rates in excess of Gb/s for many users, several hundred thousands of simultaneous connections for massive sensor deployments, and substantially improved spectral efficiency. This workshop is focused on current state-of-the-art of 5G band and future directions of the key circuit techniques and system architectures for base station or between the Handset, or other portable devices, and the cell, or mini-cell, micro-cell, pico-cell base stations. All aspects covering normalization Systems, Architecture, and low power design solutions for beam orientation will be discussed.

1. Why Should 5G Go for mmWave (e.g. 28GHz) ?
   Uwe Rüddenklau, *Infineon Technologie AG*
2. ~~5G Operator Vision by Samsung UK~~
   ~~Maziar Nekovee, *Samsung Group*~~
3. 5G System and Design by Intel
   Jonathan Jensen, *Intel Corporation*
4. Requirements on Power Amplifiers and PLLs for 5G at mmW Frequencies
   Lars Sundström, *Ericsson*
5. Industrial Packaging & Antenna for Consumer Grade mm-Wave Products
   Frederic Gianesello, *STMicroelectronics*
6. Phased Arrays for 5G Systems at 28 GHz and 60 GHz
   Gabriel Rebeiz, *UCSD*
7. Millimeter-Wave Transceiver System Design for 5G Mobile Network
   Kenichi Okada, *Tokyo Institute of Technology*
8. Millimeter-Wave Systems for 5G
   Brian Floyd, *North Carolina State University*

WSN 08:00–17:00

Passive Integrated Circuits

Sponsor: IMS; RFIC

Organizer: Xun Luo, *UESTC Integrated Circuits Center, University of Electronic Science and Technology of China*; Roberto Gomez-Garcia, *University of Alcalá, Alcalá de Henares, Madrid*; Guoan Wang, *Department of Electrical Engineering, University of South Carolina*

Abstract: With the ever-increasing advances on the field of modern wireless communications technologies-e.g., 5G and internet-of-things (IoT)-, the design of compact and multi-functional transceivers to meet the stringent requirements demanded by such systems remains as a great challenge. In this context, high-performance integrated passive devices (IPDs) are considered key building circuits for their development. These components are based on novel miniaturized structures and specific technologies that can be utilized for the implementation of RF, microwave, millimeter-wave, and THz communication systems. This unique workshop focuses, for the first time, on the area of IPDs and their applications in the context of wireless-communications and sensing scenarios by reporting recent research findings in this exciting field. This includes current progresses about fully-electrically tunable RF passives based on the nano-patterned ferroelectric and ferromagnetic thin films technology, as well as new high-Q micro-electromechanical-system (MEMS) for spectrally-agile filter implementations with wideband operation, switches, and phase shifters. Miniaturized passive circuits that are integrated with BST technology for the development of reconfigurable IPDs are presented. Furthermore, novel on-chip passive circuits for performance improvement of active circuits using advanced CMOS and SiGe processes are reviewed. Their practical application goes from RF-to-THz bands. Metamaterial-inspired and plasmonic devices are also introduced for compact CMOS passive integration. In addition, multi-function filtering components and integrated antenna sub-system, along with hybrid acoustic-wave-lumped-element-microwave-resonator technologies for the realization of advanced compact microwave filtering devices, are described. Finally, the last advances in the area of RF and microwave passive microsystems for gas/chemical, biological, and nanomaterial-characterization sensing applications are also expounded.

1. Integration of Nano-Patterned Ferroelectric and Ferromagnetic Thin Films for Fully Electrically Tunable RF Passives
   Guoan Wang, *University of South Carolina*
2. On-Chip Integrated Passive Circuits for RF, Microwave, mm-Wave, and THz Application
   Xun Luo, *University of Electronic Science and Technology of China*
3. Towards CMOS THz Electronics: Metamaterial and Plasmonic Devices
   Hao Yu, *Nanyang Technological University*
4. How Can RF MEMS be as Successful as Other MEMS?
   James C. M. Hwang, *Lehigh University*
5. High-Power Handling Hot-Switching RF-MEMS Switches
   Xiaoguang Liu, *University of California, Davis*
6. High-Q Miniature Integrated Passive Devices
   Raafat R. Mansour, *University of Waterloo*
7. Hybrid Acoustic-Wave-Microwave-Resonator Technologies for High-Performance Microwave Filters
   Dimitra Psychogiou, *University of Colorado Boulder*; Roberto Gomez-Garcia, *University of Alcalá*; Dimitrios Peroulis, *Purdue University*
8. Dielectric Spectroscopy and RF and Microwave Passive Microsystems for Biological Application and Discrimination of Cells
   Arnaud Pothier, *University of Limoges*
9. Microwave Resonators for Sensing Applications
   Mojgan Daneshmand, *University of Alberta*

WORKSHOPS

Sunday, 4 June 2017

All Workshops and Short Courses are located at the Hawai'i Convention Center. Specific room assignments will be provided onsite.

WSO 13:00–17:00

Polar, ET, Outphasing, Doherty, Predistortion ... : Which One Survives at mm-Wave Frequencies?

Sponsor: RFIC

Organizer: Patrick Reynaert, *KU Leuven*; Ali Afsahi, *Broadcom*

Abstract: Various PA linearization and efficiency enhancement techniques exist. Their applicability in a certain situation depends on various factors such as operating frequency, power level, thermal constraints, operating voltage, dynamics of the signals, bandwidth, ... Today, there is a clear shift towards higher frequencies and the importance of communication systems operating above 20 GHz is rising. At these frequencies, the goal is to exploit the high available bandwidths to achieve very high data rates. Within this context, this workshop will have a closer look into mm-wave systems and Silicon technologies, and then explore which PA techniques are most suited for wideband mm-wave systems. It will give the audience an excellent overview of the pros and cons of each technique.

1. Comparison of PA Efficiency Enhancement Techniques at RF and mm-Wave Frequencies
   Dixian Zhao, *South-East University*
2. MMW RF Pre-Distortion Linearization for Multi-GHz Broadband PA Applications
   Tian-Wei Huang, *National Taiwan University*
3. CMOS Doherty PAs at mm-Wave Frequencies
   Patrick Reynaert, *University of Leuven*
4. mm-Wave Switching Power Amplifiers
   Kunal Datta, *University of Southern California*

WSP 13:00–17:00

Recent Advances in Microwave Noise: From Device Modeling to Network Design and Characterization

Sponsor: IMS; RFIC

Organizer: Luciano Boglione, *Naval Research Laboratory*

Abstract: This workshop introduces and thoroughly reviews recent advances made in the broad field of microwave noise, from device modeling to measurement techniques. In the first talk, for the purpose of comparison of different technologies such as HFETs, CMOS, HBTs their noise models are reviewed with emphasis on their common noise properties. Certain limits on the allowable values of transistor noise parameters are established and possible limits of low noise performance upon further scaling of gate or emitter size discussed. Widely published concepts in the treatment of noise in transistors and amplifiers, amongst those "gate induced noise" in FETs, wideband low noise amplifier design, CMOS "noise cancelling" amplifiers, are critically examined. The second talk reviews standard techniques to determine the noise performance of 2 port microwave networks, including a recent procedure extending the noise parameters characterization to N port linear networks. The implications to the measurement of differential amplifiers will be addressed. Then, the talk will focus on a novel, tuner-less procedure particularly suited for the determination of on-wafer microwave transistor noise parameters because solely based on transistor size. The third talk discusses the paradoxes of mixer noise characterization, shows how well established noise characterization methods can be applied to mixers, and presents established and advanced methods for optimizing mixer noise figure in both passive and active mixer circuits. Finally, the last talk addresses the question of how to simulate noise in nonlinear circuits. After an introduction on how nonlinear effects such as upconversion of 1/f noise are simulated in time and frequency domains, special emphasis is placed on modeling GaAs and InP HBTs and GaN HEMTs. The talk will also discuss how nonlinear excitations may impact the properties of flicker and white noise sources from the physical standpoint, and how to reflect this behavior in a large-signal transistor model.

1. On the General Noise Properties of Low Noise Microwave Transistors and Amplifiers
   Marian Pospieszalski, *National Radio Astronomy Observatory*
2. Measuring Microwave Noise: From Standard to Advanced Techniques
   Luciano Boglione, *Naval Research Laboratory*
3. Noise in Mixers
   Steve Maas, *Nonlinear Technologies, Inc.*
4. Simulating Noise in Nonlinear Circuits
   Matthias Rudolph, *Brandenburg University of Technology*; Fabrizio Bonani, *Politecnico di Torino*

WORKSHOPS

Sunday, 4 June 2017

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WSQ 08:00–17:00

RFIC Design Challenges for the IoT at Scale

Sponsor: RFIC

Organizer: Nathan Roberts, *PsiKick*; Haolu Xie, *ZTE USA*

Abstract: In 2008 the number of "things" connected to the internet surpassed the number of people living on earth and by 2020 the number of "things" is predicted to reach beyond 50 billion on the way to trillions. The potential for the Internet of Things (IoT) and its ubiquitous computing reality is staggering, but limited in present day by many technical challenges. This workshop will look at two contradictory technical challenges to the IoT vision: wireless communication at scale and low power energy efficient circuit design. The workshop will begin with an overview of present day and upcoming wireless standards used for IoT and will discuss challenges as well as introduce novel approaches for supporting large scale sensor networks. The second part of the workshop will discuss the RFIC system and circuit design landscape for the IoT highlighting the intersection of challenges presented by the previous discussions and the need for low power and energy efficient systems. The workshop will help participants understand the complexity of the challenges presented by the IoT as well as an appreciation for the novelty that will arise from it.

1. An Overview of Wireless Standards for the IoT
   Christian Bachmann, *IMEC*
2. Cross-layer Optimized, Ultra-Low Power Wireless Communication Solutions for Energy-Constrained Internet-of-Things
   Hun-Seok Kim, *University of Michigan*
3. NB-IoT for a Better Connected World
   Sam Zhang, *ZTE*
4. Energy-Efficient Phase-Domain Receiver Design for IoT
   Yao-Hong Liu, *IMEC*
5. Design of Ultra-Low-Power Spectrally-Efficient Radios
   Patrick Mercier, *University of California, San Diego*
6. RFICs for Energy Autonomous Sensor Nodes
   Nathan Roberts, *PsiKick*
7. Battery-Free Computing and Communication
   Shyam Gollakota, *University of Washington*

WSR 08:00–17:00

RFIC Design for Automotive Radar

Sponsor: RFIC

Organizer: Franz Dielacher, *Infineon Technologies AG*; Gernot Hueber, *NXP Semiconductors;* Marc Tiebout, *Infineon Technologies*

Abstract: Recent advances in microwave and millimeter-wave silicon technology have drawn strong interest in the RF community for applications like safety, radar, and communications systems. The goal of this workshop is to provide an in-depth coverage of state of the art and future development trends specifically for FMCW and pulse radars, MIMO and novel CMOS-based architectures and solutions. This includes silicon solutions from 24 GHz to 240 GHz with an emphasis on automotive radar in the 77 to 79 GHz frequency range as highest volume example of commercial millimeter-wave application. Distinguished speakers from industry and academia will highlight system requirements, technology advances, challenges and solutions for implementations on system and silicon level.

1. System Architecture Concepts of ADAS Systems for Autonomous Vehicles
   Holger Meinel, *Consultant (Daimler)*
2. RFIC Concepts for Future Integrated Automotive Radar Sensors
   Rainer Stuhlberger, *DICE / Infineon Technologies*
3. Phased-Arrays for High-Resolution Automotive Radar Systems
   Gabriel Rebeiz, *University of California, San Diego*
4. CMOS Circuit and System Techniques for mmWave MIMO Radar
   Harish Krishnaswamy, *Columbia University*
5. Circuits and Systems of Millimeter-Wave Automotive Radars
   Jri Lee, *National Taiwan University*
6. Transceivers for Automotive Radar Applications
   Angelo Scuderi, *STMicroelectronics*
7. GHz Radar SoC Integration in 28 nm CMOS
   Andre Bourdoux, *imec*
8. 28 nm CMOS mmWave Building Blocks for Wideband Automotive Radar Applications
   Nader Rohani, *NXP Semiconductors*; Sergio Pacheco, *NXP Semiconductors*

WORKSHOPS

Sunday, 4 June 2017

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WSS 08:00–17:00

RFIC Design in CMOS FinFET and FD-SOI

Sponsor: RFIC

Organizer: Magnus Wiklund; *Qualcomm Atheros*; Gernot Hueber; *NXP Semiconductors*

Abstract: Both, CMOS FinFET and FD-SOI are the enabling technology that allows nanoscale CMOS beyond 20nm. This technological revolution does not only allow highest integration density for high volume products at low cost. Due to the fundamental change how a transistor is built, there is impact on its characteristics as e.g., Ft, Vt, VDD. Considering this change, traditional and well-known circuits and architectures need to adapted or even be invented for FinFET. This workshop shall give an overview of novel architectures and designs in the context of RF that benefit from latest CMOS FinFET and FD-SOI technology. In several presentations trends, design challenges, and how these are overcome supported by application/circuit examples shall be shown.

1. CMOS FD-SOI Technology and Benefits for RF
   David Harame, *Global Foundries*; Thomas McKay, *Global Foundries*
2. GPS SoC's in FD-SOI
   Ken Yamamoto, *Sony Semiconductor Solutions*
3. ~~Analog RF mmW Design with FD-SOI~~
   ~~Andreia Cathelin, *ST Microelectronics*~~
4. Ultra-Low-Voltage Wideband Transmitter and LNA in FD-SOI
   Cecilia Gimeno, *University Catholique Louvain*; Denis Flandre, *University Catholique Louvain*
5. RF Synthesizers for Wide Area IoT SoC's in FD-SOI
   Thomas McKay, *Global Foundries*; Chi Zhang, *Global Foundries*
6. RF and mm-Wave Design in FD-SOI CMOS Technologies
   Sorin P. Voinigescu, *University of Toronto*
7. RF Data Converters in 16 nm FinFET for Wireless and Wired Infrastructure Applications.
   Brendan Farley, *Xilinx*
8. Design Challenges of RF/Analog Circuits Operating in a Hostile Digital Environment (Case Study of a Low Jitter PLL in 10 nm FinFET)
   Philip Kwan, *Oracle*
9. Noise Cancelling LNAs in FinFET Technology
   Stephen Weinreich, *Stanford University/Global Foundries*
10. RF Circuits in 14 nm FinFET
    Edwin Thaller, *Intel*

WST 13:00–17:00

RF-Inspired Silicon Photonic

Sponsor: RFIC

Organizer: Hossein Hashemi, *University of Southern California*

Abstract: Advancements in silicon semiconductor processing enables silicon photonics integrated circuits (PIC) for applications including communication, imaging, sensing, and display. The level of integration and complexity in PICs has lacked those of RF and microwave integrated circuits (IC). This workshop brings leading researchers to cover the latest developments in the design and implementation of complex PICs that are inspired by the systematic design and verification of RFICs.

1. Silicon-Photonics for Energy-Efficient Data Communication
   Azita Emami, *California Institute of Technology*
2. Linear Microwave Photonic Techniques for Silicon Photonic Integrated Circuits
   James Buckwalter, *University of California, Santa Barbara*
3. Electronically Assisted Optical Synthesis, Stabilization, and Phase Noise Reduction
   Firooz Aflatouni, *University of Pennsylvania*
4. Examples of Hybrid Electronics and Photonics ICs: Optical Phased Arrays, Equalization, and RF Power Generation
   Ali Hajimiri, *California Institute of Technology*
5. Monolithic Optical Phased Arrays
   Hossein Hashemi, *University of Southern California*

WORKSHOPS

Sunday, 4 June 2017

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WSU 08:00–12:00

The Many Flavors of CMOS/Bipolar RF Harmonic Oscillators

Sponsor: RFIC

Organizer: Pietro Andreani, *Lund University*; Mohyee Mikhemar, *Broadcom*

Abstract: Recent developments in the art of integrated CMOS/bipolar oscillator design have witnessed the introduction of new topologies – class-C, class-F, class-F2, clip and restore, and other still unnamed – that complement well-known and much appreciated architectures such as the beloved class-B (in its many variations) and Colpitts. This workshop offers an overview of all these oscillators, bringing some clarity on the pros and cons of each.

1. Common-Mode Resonance in LC Oscillators
   David Murphy, *Broadcom*
2. Class-F and Switching Current-Source CMOS Oscillators
   Masoud Babaie, *TU Delft*
3. The Good, the Bad and the Ugly of Bipolar Voltage-Controlled Oscillators
   Andrea Bevilacqua, *University of Padova*
4. Fundamental Limitations in RF and mm-Wave Harmonic Oscillators
   Danilo Manstretta, *University of Pavia*
5. The Insider Guide to Designing mm-Wave Silicon VCOs
   Waleed Khalil, *The Ohio State University*

WSV 08:00–17:00

Uncertainty in RF/Microwave Measurement and Modeling

Sponsor: IMS; ARFTG

Organizer: Keefe Bohannan; *Keysight Technologies, EEsof EDA*; Peter Aaen; *University of Surrey*

Abstract: This workshop is focused on new techniques to help engineers understand and overcome uncertainty for the measurement and modeling of their RF and microwave designs. Sources of uncertainty exist in both linear and nonlinear problems, for both the measurement and modeling domains. As such, enhanced approaches for identifying and overcoming these inaccuracies are constantly sought. Specific areas of focus will range across uncertainty in measurement, modeling, and the correlation between the two. The processes that can make measurements appear uncertain, along with the two main methodologies that are currently being used for evaluating the size of a measurement's uncertainty, will be examined in detail. A new real-time uncertainty approach for modern Microwave systems will be shared. Further, a new nonlinear verification device will be presented, with an exploration of the device performance and an improved Figure-of-Merit. Regarding the modeling and simulation domains, eye-opening insights for Electromagnetic simulation errors will be reviewed, as will the compounding of modeling uncertainties and errors that can form in simulations when complex RF Modules are designed. In deeper computational discussions, the measurement and modeling of stationary and cyclostationary stochastic Electromagnetic Fields will be reviewed, and an introduction to fundamental aspects of the mathematical theory of uncertainty quantification in computational physics will be delivered, from an engineering perspective. The two families of uncertainty quantification techniques, namely non-intrusive and intrusive, will be also discussed. Finally, methods for improving model-to-hardware correlation will be examined in a message that unifies the workshop's topics. A panel session during the final hour will allow attendees the opportunity to further engage. Once complete, the audience will certainly depart with a better understanding of uncertainty, how it impacts the performance of their RF & Microwave designs, and how to employ the latest techniques to mitigate it. This workshop spans MTT-1, MTT-8, MTT-11, MTT-15

1. Are Measurements Really Uncertain? If So, Why? And, by How Much?
   Nick Ridler, *National Physical Laboratory*
2. How to Break EM Software
   James C. Rautio, *Sonnet Software*
3. Real-Time Uncertainty on Microwave Data: Why We Need it and How We Can Achieve it
   Andrea Ferrero, *Keysight Technologies*
4. Design and Evaluation of a Nonlinear Verification Device for Nonlinear Vector Network Analyzers
   Troels S. Nielsen, *Keysight Technologies*
5. Measurement and Modeling of Stationary and Cyclostationary Stochastic Electromagnetic Fields
   Johannes A Russer, *Technical University of Munich*
6. Computational Methods for Uncertainty Quantification
   Costas Sarris, *University of Toronto*
7. Minding the Gap: Electromagnetic Simulation vs Measurement
   Peter Aaen, *University of Surrey*
8. Risk Mitigation in the Modeling of Complex RF & Microwave Modules
   Keefe Bohannan; *Keysight Technologies*

SHORT COURSES

Sunday, 4 June 2017

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SSA 08:00–17:00

Introduction to Solid-State Power Amplifier Design and Considerations for Space-Borne Applications

Sponsor: IMS

Organizer: Natanael Ayllon, *European Space Agency*; Iain Davies, *European Space Agency*; Vaclav Valenta, *European Space Agency*

Abstract: The aim of this short course is to provide a general overview of solid-state power amplifiers (SSPA), their architecture, and use in the space applications. The course will delineate the main differences in designing SSPAs for ground and for space segment applications in terms of achievable RF performances, overall cost and lead times. The course will also describe the environment in which the equipment operates and give an overview of the necessary provisions made during the design of this equipment to ensure the high level of reliability needed in space. The impact of market trends will be described, driving the need for research and development at an architectural and technological level in increased efficiency and output power whilst at the same time reducing volume, mass and cost, as the next generation of megaconstellation demand.

SSB 08:00–12:00

Principles of Solid-State Microwave and RF Control for Circuit Reconfigurability

Sponsor: IMS

Organizer: Robert Caverly, *Villanova University*; Art Morris, *WiSpry*

Abstract: This short course will cover the basics of Microwave and RF Control using PIN diodes, FETs and MEMS devices. The goal of the course is to provide engineers enough of an overview of the topic to be able to design, simulate and implement simple control and other reconfigurable circuits using commercial off the shelf components to fulfill their design requirements. An introduction to CAD models for the devices will be covered as part of the design flow goal. This workshop is intended to be a crash course for microwave engineers in the field of RF/microwave control/reconfigurability device technologies. The course covers the basic principles illustrated with examples from advanced practice in applications such as reconfigurable switches, attenuators and filters/tuning networks in such applications pertaining to communications and magnetic resonance imaging.

SSC 08:00–17:00

From Bits to Waves: Building a Modern Digital Radio in 1 Day

Sponsor: IMS; RFIC

Organizer: David Ricketts, *North Carolina State University*

Abstract: In this fun and interactive short course, participants will learn the basic theory of modern digital radios as well as the RF circuits and systems used to build them. After an introductory session on digital radios, participants will select an RF building block to design and build. There will be short mini-classes (run in parallel) on each component: double balanced mixer, microstrip filters, low noise amplifiers, power amplifiers, baluns, patch antenna, etc. The radios will operate in the ISM 920 MHz band. After the mini-classes, each participant will design their RF component using NI AWR software, including full layout and EM simulation. In the afternoon, the designs will be transferred to PCB via a simple "PCB in a bag" method and each circuit built and tested using a simple VNA. The workshop will conclude with a full radio test of at transmitter and receiver. Participants need only a basic background in RF circuits, such as S-parameters and basic transmission line theory. Example designs will be available to ensure that everyone, form the most advanced RF designer, to the student can build a successful RF component. You only need to bring your laptop - all materials and equipment will be provided. Due to the nature of this practical short course, your attendance during the entire day is required. Course notes can be found at www.rickettslab.org/bits2waves