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Wednesday, April 23

Wednesday, April 23 9:00 - 10:40

B1: Next Generation RFID

Room: Salon III
Chair: Luca Catarinucci (University of Salento, Italy)

9:00 *A Self-Matched Passive Single Varactor loaded Transmission Line for Efficient Harmonic Generation in Backscatter IoT Devices...1*

Ali Nezaratizadeh (Northeastern University, USA & University of Florida, USA); Xiuhan Chen, Haoling Li and Najme Ebrahimi (Northeastern University, USA)

This paper presents a passive harmonic generator circuit designed for backscatter IoT devices, utilizing a single varactor-loaded transmission line. The proposed design is implemented on an FR4-based PCB with only one varactor, simplifying the circuit and reducing costs. Simulation results demonstrate a significant improvement in output power at the second harmonic, achieving a maximum of -8.5 dBm, outperforming existing designs. The compact, energy-efficient, and low-cost nature of the proposed circuit makes it an ideal solution for batteryless IoT applications, contributing to the advancement of sustainable and maintenance-free IoT networks.

9:20 *A two-channel frequency selective 2.4 GHz backscatter modulator for Wi-Fi and Bluetooth backscatter using Bulk Acoustic Wave (BAW) filters...7*

Kevin J Ho and Matthew Reynolds (University of Washington, USA)

We present a two-channel frequency selective 2.4 GHz backscatter modulator for Wi-Fi (IEEE 802.11) and Bluetooth backscatter communication. Prior backscatter modulators create unwanted spectral pollution by backscattering every signal incident over the entire antenna bandwidth. In contrast, the proposed frequency selective modulator employs narrow-band bulk acoustic wave (BAW) filters having a 20 MHz bandwidth to enable backscatter modulation in either Wi-Fi channel 1 (2401-2423 MHz) or Wi-Fi channel 11 (2451-2473 MHz). The measured differential reflection coefficient $|\Delta\Gamma|$ exceeds 0.568 across Wi-Fi channel 1 and 0.601 across Wi-Fi channel 11. The opposite-channel rejection exceeds 47.02 dB from Wi-Fi channel 1 to Wi-Fi channel 11 and 48.99 dB from Wi-Fi channel 11 to Wi-Fi channel 1. Both simulated and measured performance are presented and compared. When generating BPSK modulation at 11 Mbps (as used by IEEE 802.11b), the modulator has an average power consumption of 20.9 μW and a measured energy figure of merit of only 1.9 pJ/bit; meanwhile, when generating FSK modulation at 1 Mbps (as used by Bluetooth Low Energy), the modulator has an average power consumption of 1.9 μW and a measured energy figure of merit of 1.9 pJ/bit. By addressing the key unsolved problem of backscatter-induced spectral pollution, this work paves the way for backscatter devices to become "first-class citizens" of the wireless spectrum.

9:40 *Improving Communication Performance of Passive Backscattering Tags Using Collaborative Backscatter 13*

Abeer Ahmad (Stony Brook University, USA); Manavjeet Singh (State University of New York at Stony Brook, USA); Yang Xie (Stony Brook University, USA); Xiao Sha (Stonybrook University, USA); Milutin Stanacevic (SUNY Stony Brook, USA); Samir R. Das and Petar M. Djurić (Stony Brook University, USA)

We propose collaborative backscatter techniques for tag-to-tag communication between battery-less RF tags. The low incident backscatter power and the limited processing ability in the passive receive circuits limit the performance of such links. By recruiting 'helper' tags to boost backscatter signals, such links can be substantially strengthened. Two techniques are developed and evaluated on a prototype tag network, demonstrating close- to-optimal performance with low computational overhead.

10:00 ***Reflection of Modulated Radio: System-level Design, Analysis, and Performance Evaluation for Ambient Scatter Communication Systems...N/A***

Michael Varner (Georgia Institute of Technology, USA); Serhat Tadik (Georgia Tech, USA); Cheng Qi (Cognosos, Inc., USA); Rajib Bhattacharjea (Georgia Tech Research Institute, USA); Christopher Saetia (Georgia Institute of Technology, USA); Kaitlyn Graves and Gregory Durgin (Georgia Tech, USA)

Ambient scatter communication systems have long been a novelty form of radio communications, with most reported ranges limited to several meters or less and very low data rates. This work presents, implements, and analyzes the ReMoRa (Reflection of Modulated Radio) architecture for extending ambient scatter communication systems to long ranges and/or high data rates. ReMoRa comprises of a unique way to encode, down-convert, and detect signals scattered from mote to reader using ambient RF carriers that already contain information. Our ReMoRa implementation on a GNU radio demonstrates read ranges of up to 20 meters between a low-powered sensor mote and an ambient reader that uses an existing FM radio signal at 91.1 MHz in Atlanta, GA with a data rate of 300.7 kbits/s. We show how these links can easily be extended to hundreds of meters or more for future sensing and communication links.

10:20 ***Exploiting Tunneling Reflection Amplifiers for Amplitude and Phase-Shift Keying Backscatter Communications...N/A***

Christopher Saetia (Georgia Institute of Technology, USA); Gregory Durgin (Georgia Tech, USA)

This paper proposes and explores the idea of using low-power reflection amplifiers, made with tunnel diodes, to perform amplitude and phase-shift-keying (APSK) modulation for backscatter communications. Past work used tunneling reflection amplifiers for backscatter range extension and binary-phase shift keying (BPSK) with two different voltage biasing states to generate one bit per symbol. It is advantageous to exploit the different reflection states from different applied biasing voltages to perform multi-bit backscatter communications. This work sweeps these amplifiers' biasing voltages within a 225mV range (below a maximum 300mV of applied voltage) to modulate the amplifiers' reflection coefficients and generate APSK symbols for low-power backscatter communication applications. The implementation of APSK allows for the transmission of more than 1 bit per symbol. Unlike previous passive multi-symbol modulation schemes, the use of tunnel diode reflection amplifiers allows for creation of multiple symbols with just one device that can generate different load impedance states and reflection coefficients/gains above 0dB to allow for a greater range of magnitude to place APSK symbols and extend read-ranges between tag/modulator and reader/receiver. These tunnel diode reflection amplifiers allow for scaling of modulation order and versatility of implementing different modulation schemes that are amplitude and phase-based.

Wednesday, April 23 1:30 - 3:30

B3: Localization and Sensing

Room: Salon III
Chair: Michael J Crisp (University of Cambridge, United Kingdom (Great Britain))

1:30 ***A Bioresorbable Backscatter Sensor...19***

Yuheng He, Chinaza Ogbonna, Sree Adinarayana Dasari, Luke A Beardslee and Nima Ghalichechian (Georgia Institute of Technology, USA)

We present the design, simulation, fabrication, and measurement results of a biodegradable sensor for post operative monitoring. A backscattering measurement technique is demonstrated to detect frequency shifts resulting from the change in the thickness of a sensing film. Our sensor is composed of a modified split-ring resonator loaded with interdigitated capacitors. The sensor operates at around 3.2 GHz in free space and around 2 GHz in liquid solution. We demonstrated that our backscattering measurement data, quantified as resonance frequency in a laboratory

environment, matches well with the simulation results.

1:50 *RFID Localization with Multistatic Interrogation and Deep Neural Networks...24*

Georgios Papadopoulos and Dimitrios Angelou (Technical University of Crete, Greece); Aggelos Bletsas (Rutgers University & WINLAB, USA)

Deep neural networks (DNN) have become a widely used tool for improving efficiency in various problems; however, the time-consuming training process and the need for large amounts of labeled data often limit their practicality. This work presents a deep feed-forward neural network, designed for real-time tag localization, which addresses these challenges by leveraging easily-generated simulation data for training. The network uses phase-based feature inputs and performance is evaluated using simulation data, as well as real-world measurements from a custom multistatic RFID interrogation testbed. In the first part, state-of-the-art techniques are contrasted to neural networks, in a simulated environment, and a pronounced advantage for the latter is demonstrated, for random tag positions. Then, a substantially improved setup is presented, which, by utilizing only one extra antenna, yields a remarkable 76% reduction in mean absolute error (MAE), in the order of 2.48 cm, while median absolute error is below 1 cm. It is shown that this outcome is not caused by phase ambiguity, but instead due to the increased distance between antenna pairs. In the second part, experimental data are used to evaluate the efficiency of the DNNs in two real-world immobile scenarios, using a custom multistatic experimental setup with software-defined radios (SDR). Even though the DNNs are trained exclusively on simulated data, they are found to perform in a comparable fashion to the conventional methods, with MAE ranging from 19 to 27 cm, for the first and second scenario, respectively; similarly, the median absolute error is found within 1 cm between the two scenarios, at approximately 8.5 cm. These results suggest that DNNs offer a tremendous potential for further localization improvements, especially if more real-world measurements, possibly through future automated (e.g., robotic) processes, are blended in the training process.

2:10 *Localization and Sensing Leveraging Inter-tag Channel Estimation...N/A*

Shuai Yang and Ryan Jones (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 paper introduces novel sensing applications leveraging tag-to-tag communication. Building on a prior method for inter-tag channel estimation, we explore various sensing modalities enabled by this technique and compare to conventional reader to tag measurements. We demonstrate that tag displacement information, including both 1D and 2D localization, can be accurately estimated. Specifically, our approach achieves better than 2.5 cm error in over 90% of the test locations with only a single reader antenna. Furthermore, we investigate the inter-tag channel dependence on angular misalignment of the tags, and show that rotation measurements can be made by exploiting inter-tag channel amplitude, while the inter-tag channel phase is independent of rotation. Finally we demonstrate liquid level sensing of a container in the inter-tag channel, showing that the fill level of a bottle can be estimated, independent of its position.

2:30 *SenSync: Real-Time and Accurate Passive Sensing...30*

Ishan Bansal (University of California San Diego, USA); Nagarjun Bhat and Agrim Gupta (University of California, San Diego, USA); Harine Govindarajan (University of California San Diego, USA); Dinesh Bharadia (University of California, San Diego, USA)

SenSync tackles key challenges in RFID-based differential sensing systems, including temporal misalignment, phase ambiguity, and environmental sensitivity. Traditional techniques are limited by sequential data processing, which introduces time shifts, and arbitrary phase jumps injected by commercial RFID readers, which obscure accurate differential measurements. These issues, compounded by multipath effects and dynamic environments, hinder the deployment of robust RFID sensing systems at scale. To address these challenges, we propose innovative algorithms and signal processing techniques to align and interpret time-shifted data from multiple ICs. Our approach mitigates the effects of temporal misalignment and phase ambiguity, ensuring reliable differential sensing in real-world applications. By improving data alignment and robustness, we accelerate the sensory resolution by 5x. Furthermore, we developed a user interface capable of automatically detecting sensors within the system's field of operation and displaying their readings in real-time, demonstrating the practical applicability and versatility of our proposed solution.

2:50 ***Simultaneous Temperature and Capacitance Sensing with Self Decoupling for Analog Pulse-Width-Modulation Backscatter...36***

Taotao Wu, Yuxiao Zhao, Xiaochuan Peng and Jing Feng (Fudan University, China); Hao Min (State Key Lab of ASIC & System, Fudan University, China)

Battery-less RFID sensor tags in the Internet of Things (IoT) call for low-cost and power-efficiency multiparameter sensor design. Traditional multiparameter sensors rely on time-multiplexed parameter selection to avoid output coupling, which requires extra control logic and increases cost and design complexity. This paper presents a temperature and capacitance (T/C) sensor achieving self decoupling through the proposed self-switching double sampling (SDS) interface. With double sampling, a temperature-sensitive current alternately charges a reference capacitor and a sensing capacitor, simultaneously translating T/C information into a pulse-width-modulated (PWM) waveform. Measuring the low pulse width and the pulse width ratio can decouple temperature and capacitance information, respectively, eliminating the demand for parameter selection. Meanwhile, SDS reuses the PWM waveform as the double-sampling control signal without external control logic. The PWM signal can be sent back by analog PWM backscatter without the need for digitization. The SDS sensor designs a dual-slope relaxation oscillator (RxO) with area efficiency, ultralow power and inherent self-switching topology as the T/C-to-PWM converter. A prototype sensor has been designed and simulated in 55-nm CMOS technology, occupying 0.037 mm2 and consuming 59.6 nW at room temperature with a 0.8-V supply voltage. The T/C sensor achieves a temperature inaccuracy of -0.58/+0.38 ℃ in -20~120 ℃ and a capacitance inaccuracy of -24.9/+20 fF in 0~30 pF.

3:10 ***Real-time, Multistatic RFID Localization with Commodity, Unsynchronized Radios...42***

Dimitrios Angelou (Technical University of Crete, Greece); Aggelos Bletsas (Rutgers University & WINLAB, USA)

Passive RFID tag localization has been mostly focused on monostatic and/or synchronized setups. This work moves a few steps further and performs real-time localization with distributed, i.e., multistatic radios, which are also unsynchronized at the carrier level. It succeeds by exploiting the elliptical direction of arrival (EllDoA) algorithm with a "playback" carrier frequency offset (CFO) mitigation method, showing localization feasibility at a small error cost, even with very cheap software defined radios. The inherent carrier phase offset (CPO) of such distributed setups is addressed and it is shown that the calibration step needs to be performed only once, and not for further reruns of the experiment; thus, the proposed method is suitable for many real-world and real-time applications, which has not be shown before, to the best of our knowledge.

Thursday, April 24

Thursday, April 24 3:20 - 5:00

C4: Applications, Protocols and Security

Room: Salon III
Chair: Ali Abedi (University of Maine, USA)

3:20 ***Building Digital Product Passports: EPCIS 2.0 Meets Knowledge Graphs...48***

Yalew K Tolcha, Gunwoo Park and Daeyoung Kim (KAIST, Korea (South))

The EU Digital Product Passport (DPP) regulation mandates robust product traceability to support sustainability reporting and regulatory compliance. However, the inherent complexity of global supply chains, marked by frequent changes in product ownership, transformations, and aggregations, poses significant challenges. While GS1 EPCIS 2.0 offers a standardized framework for capturing and sharing product visibility data, querying traceability information becomes inefficient and cumbersome, particularly in scenarios involving multilevel transformations and aggregations. This paper proposes an integrated architecture that combines EPCIS 2.0 with a knowledge graph to address these challenges. By linking traceability events using GS1 keys, the system constructs a graph-based model that enables the retrieval of complete product histories with a single query, regardless of the complexity of the supply chain. The platform ingests visibility events in real time from distributed sources, enhancing scalability, interoperability, and traceability accuracy.

3:40 ***MCSMARA: A MAC Protocol for RFID Systems...54***

Bernard Amoah and Xiangyu Wang (Auburn University, USA); Jian Zhang (Kennesaw State University, USA);
Shiwen Mao, Senthilkumar Periaswamy and Justin Patton (Auburn University, USA)

Dense RFID environments pose critical challenges such as Reader-to-Reader Interference (RRI), Reader-to-Tag Collisions (RTC), and inefficient resource utilization, which degrade system performance and scalability. Traditional Media Access Control (MAC) protocols, including CSMA and TDMA, struggle to address these issues effectively, particularly in dynamic and large-scale deployments. This paper introduces MCSMARA (Markov Decision Process (MDP)-based Carrier Sense Multiple Access with Reader Arbitration), a novel MAC protocol designed to optimize reader coordination in dense RFID networks. By leveraging an MDP framework, MCSMARA models reader state transitions and employs a utility-based arbitration mechanism to dynamically allocate frequencies and time slots. The protocol incorporates adaptive backoff and decentralized neighborhood discovery for efficient resource management without centralized control. Simulation results demonstrate that MCSMARA reduces collisions by up to 30%, improves throughput by 25%, and ensures superior scalability, supporting a large amount of readers with minimal computational overhead. These findings establish MCSMARA as a transformative solution for RFID networks in logistics, retail, and industrial IoT, with potential for extension to mobile and heterogeneous environments.

4:00 ***Enhancing RFID tag count speeds using information encoded in collided slots...60***

Sobhi Alfayoumi (Universitat Oberta de Catalunya (UOC), Spain); Heyi Li (MIT, USA); Marta Gatnau Sarret (Universitat Oberta de Catalunya (UOC), Spain); Rahul Bhattacharyya (Massachusetts Institute of Technology, USA); Joan Melià-Seguí (Universitat Oberta de Catalunya (FUOC), Spain); Sanjay Sarma (MIT Auto-ID Center, USA)

Fast and efficient RFID tag counting is an essential requirement for a lot of modern applications, particularly in high-density environments. This paper proposes an innovative algorithm designed to accelerate counting while maintaining compatibility with the EPCglobal Class 1 Generation 2 (C1G2) protocol. Relying on a single RN16 answer from each tag to validate its presence, the method speeds up counting by eliminating a full reader-tag communication, reducing processing time. The proposed method was validated using a software-defined radio (SDR) platform. Compared to the standardized protocol, our experiments demonstrated that up to four tags can be counted in the time required to identify a single tag, achieving approximately 77% time savings across various data rates. This paper shows that the algorithm provides a feasible and scalable solution for RFID tag counting, incorporating collision information into its design to greatly improve counting speed, even in crowded environments.

4:20 ***Representation learning using RAIN RFID tag backscatter features for material classification in circular economy applications...66***

Rahul Bhattacharyya and Fatima Villa-Gonzalez (Massachusetts Institute of Technology, USA); Pavel Nikitin (Impinj, USA & University of Washington, USA)

We present how RAIN RFID power-on-tag-reverse (POTR) features can be used to reliably differentiate between materials having different relative dielectric permittivity (\epsilon*{r}) and effective loss tan(\delta). Our approach shows how this is achieved using 15 diverse RAIN RFID tags, having an embedded T-match antenna design, deployed on 7 different material types. We present a data visualization and K-means clustering algorithm that can reliably differentiate between material types with 94% accuracy. We show how our approach is particularly useful at differentiating between materials having very similar (\epsilon*{r}) but different tan(\delta). We also demonstrate the technique appears to be robust to reflections, wet inlay adhesives and material thickness via a limited study conducted in a non-idealized warehouse environment. Future research directions are also discussed.