From the Guest Editors' Desk

Advancing Ultrahigh-Frequency RFID Through Digital Signal Processing

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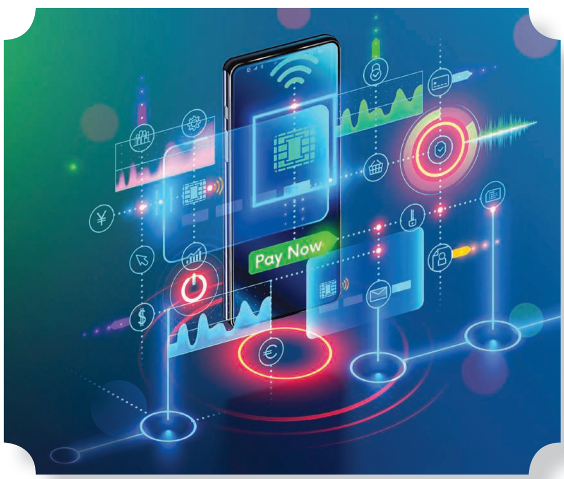

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Digital signal processing (DSP) is a key technology for a vast number of different applications, including RF functions. This issue of *IEEE Microwave Magazine* focuses on using DSP techniques for RF identification (RFID) systems. As the name implies, RFID is a technology for wireless object recognition. Typical RFID systems consist of at least one reading device and multiple mobile nodes, often referred to as *tags*. The most common related standards apply to low-frequency (LF), high-frequency (HF), and ultrahigh-frequency (UHF) RFID.

LF RFID works in the band between 125 and 135 kHz and is mainly used for animal tracking. HF RFID is the most common standard and is used for many applications. HF RFID tags are widely employed for access control in electronic passports and for secure payment solutions. Most modern smartphones also utilize near-field communication, which is based on HF RFID technology. Both LF and HF RFID operate in the electromagnetic near field. The reading device and tags are coupled inductively and form a loosely coupled transformer. With the help of this link, the reader and the tags can communicate with one another by means of load modulation. In addition, power for the tag operation can be transmitted from the reader. Since the energy is wirelessly conducted in the near field, the achievable communication distance for LF and HF RFID is shorter than 1 m.

In contrast to the first two standards, UHF RFID works in the electromagnetic far field. It operates at much higher frequencies, either from 865 to 868 MHz or from 902 to 928 MHz. Instead of load modulation, the communication from the tag to the reader employs backscatter modulation. This principle dates to the 1940s, when Harry Stockman published an article about communication by means of reflected power [1]. In general, wireless data transmission requires altering the amplitude, phase, and frequency of an electromagnetic wave. Classic wireless systems directly create this type of signal. For backscatter communication, however, the reader transmits a continuous wave signal to the tag. A part of this signal is reflected back to the reader and modulated by changing the tag's reflection coefficient

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according to the data stream. The big advantage of backscatter communication is that it does not need any complicated transmission circuitry. Where typical RF systems require a mixer, a phase-locked loop, a power amplifier, and various other components in the transmit path, a backscatter system in its simplest form can be realized with a switch. That way, RF systems can be orders of magnitude more power efficient.

This issue is a joint effort by two technical committees: IEEE Microwave Theory and Techniques Society (MTT-S) MTT-15 (the RF/Mixed-Signal Integrated Circuits and Signal Processing Committee) and MTT-26 (the RFID, Wireless Sensor, and Internet of Things Committee). In 2019, the committees organized a workshop during the IEEE MTT-S International Microwave Symposium in Boston, "Digital Signal Processing for Radio Frequency Identification." The talks presented during that event form the foundation of this issue. The goal is to disseminate recent results that were made possible by the involved scientists' interdisciplinary research.

The four articles in this issue cover UHF RFID technology advancements achieved via DSP techniques. They target different RFID system layers, starting, in the first two articles, with analog front-end aspects [all-digital data conversion and software-defined radio (SDR) hardware platforms], followed by SDR-based RFID protocols and algorithm testbeds in the third article and localization enhancements on the application layer in the fourth article. In general, DSP-enabled RFID systems are the key technology for novel features such as data encryption [2], sensing capabilities [3], and advanced localization [4], [5].

The first feature, by Arnaldo Oliveira, Nuno Borges Carvalho, João Santos, Alírio Boaventura, Rui Fiel Cordeiro, André Prata, and Daniel Costa Dinis, poses the exciting question: How can flexible UHF RFID readers be integrated into ubiquitous mobile and small devices? The authors propose and review low-complexity, all-digital transmission and reception methods, which require only a minimal RF front end for amplification and filtering. Generic digital interfaces perform an elegant, very-low-complexity but reconfigurable conversion between the analog and digital domains. Software-defined digital logic implements all RFID signal generation and reception functionality and thus enables a small-size, low-cost development toward novel application scenarios.

The second article, by Edward A. Keehr and Gregor Lasser, discusses all major aspects of a software-defined RFID platform that is sufficiently inexpensive for widespread application in the Internet of Things. The authors' goal is to substantially lower the entry threshold for RFID-enabled applications through a well-documented open source hardware and software project that is accessible to a wide range of engineers, tinkerers, and students. The article covers low-cost leakage cancellation, high-isolation antennas, system architecture and design, and fundamental limitations.

Third, Georg Saxl, Lukas Görtschacher, Thomas Ussmueller, and Jasmin Grosinger explore how software-defined RFID readers enable enhancements for UHF RFID system functionality in terms of localization and tracking as well as transmission security. They review wireless testbeds and their hardware and scope and propose a secure testbed that facilitates the rapid development and verification of low-power data encryption algorithms in conjunction with crypto-enabled tags. The second part covers a flexible localization testbed for showcasing positioning techniques. Its capabilities are demonstrated in a phase-based localization experiment with outstanding accuracy results.

Finally, the feature article by Matthias Gareis, Andreas Parr, Johannes Trabert, Tom Mehner, Martin Vossiek, and Christian Carlowitz covers signal processing methods for modern RFID localization based on synthetic aperture radar (SAR). The authors enable an unprecedented 3D position accuracy on the order of a few centimeters that complies with the EPCglobal class 1, generation 2 (Gen2) UHF RFID standard [6] and that uses commercial off-the-shelf tags. Large quantities of tags are localized in complex scenarios, such as a smart warehouse, where a fully automatic stocktaking robot travels along the shelves and establishes synthetic apertures for its antennas. To substantially reduce the computational burden of SAR processing, variable-grid and particle-based search techniques are employed to accelerate the tag positioning by a factor of 1,000 while retaining high accuracy.

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