RFID—A Unique Radio Innovation for the 21st Century

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In 1948, the *Proceedings of the Institute of Radio Engineers* published Harry Stockman's seminal work on "communication by means of reflected power," which many consider as the first paper on radio-frequency identification (RFID). The paper concluded by expressing the expectation that "considerable research and development work has to be done before the remaining basic problems in reflected-power communication are solved, and before the field of useful applications is explored." It is only appropriate that after more than 60 years following the publication of this work by its progenitor, in this special issue, the PROCEEDINGS OF THE IEEE review current developments towards the realization of the goal outlined by Stockman.

This special issue explores the state of the art across the RFID technology landscape from hardware, to systems, as well as applications and support for innovative business models.

Indeed, while RFID technology has been around for decades, it is only in the last ten years or so that considerable progress in technology and standardization, resulting in large-scale manufacturing of high-performance RFID system at affordable prices, has reignited interest in RFID, and has significantly extended the scope of possible applications. To a certain extent, addressing the main problems associated with RFID technology itself has been only the beginning of this process, as similarly extensive breakthroughs have been and are still required within associated information systems so that they can take advantage of the technology. For example, while it has become technically and economically feasible to tag a wide variety of manufactured artefacts for some time now, enterprise

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IT systems have been unable to cope with such detailed information and the high volumes of data generated as a result of IDs that are unique for each item. As a result such systems have already undergone considerable development so as to simply be able to record such information, with further work required in the future.

Stockman also correctly anticipated that applications would play a central role in taking RFID technology forward. While the first generation of RFID involved the concurrent reading of one or a small number of tags that moreover carried only a simple identifier, today's novel applications are making greater demands on tags, readers, middleware, infrastructure, and IT in terms of affordability, performance, and flexibility. Notable among them are the initiatives by the Department of Defence and Wal-Mart in supply chain operations, which have played a central role in increasing awareness, and in highlighting the business value and the challenges in deploying RFID. By tracking assets, supplies, and personnel, many enterprises are increasingly experimenting with new business models to integrate RFID within their digital ecosystems.

While innovation in basic RFID and supporting technologies continues to advance the field, the marketplace also plays a central role by eliminating the less viable options. To be sure, this interplay between the research community and the engineering and business community has been instrumental in the development of RFID, and in this special issue, we aim to represent both sides and their concerns.

RFID is increasingly seen as far more than a simple and effective automatic identification technology. Academic and industrial proponents view RFID as the cost-effective technical solution for the development of open, shared, universal ubiquitous computing infrastructures thus pioneering the next paradigm in computing. From this point of view, RFID is seen as the core ingredient that enables the coupling of physical entities and digital information into cyberphysical systems and is widely expected to bring about pervasive computing One of the main challenges towards the realization of this vision, often also expressed using the term internet or web of things/artifacts,[1] is the provision of networked services that support interaction between conventional information systems and such augmented natural objects and manufactured artifacts.

This special issue explores the state of the art across the RFID landscape from hardware, to systems, applications, and support for innovative business models.

The first two papers consider techniques that can lead to improvements of RFID tag performance across applications. Moretto *et al.* employ modeling and simulation to investigate the loading effect and its implications for RFID tag antenna performance. In particular, they propose an optimal model of shunt resistance and calculate boundaries for this effect with regard to distance from the reader, which imply support for larger tag memories, on-tag encryption, and improved performance in hostile environments. Bolomey *et al.* introduce the concept of transfer impedance to characterize RFID systems. Furthermore, they employ two metrics to assess the performance of RFID tags, and illustrate their application in several case studies. They conclude by demonstrating how their model can be used in practical situations to investigate the tradeoffs for RFID tag design in specific applications.

Furthermore, Dardari *et al.* survey the application of ultrawideband technology to RFID considering specific opportunities for improved area coverage, better resilience to interference, higher multiple-access capability, and higher ranging resolution that can facilitate more accurate localization.

The following three papers consider the case of RFID-enabled wireless sensor networks. Roy *et al.* examine how sensors can be integrated into tags, with emphasis on enhancements to link and multiple-access layers, and support for advanced power management. The paper reports on two key innovations introduced by the authors, namely, a programmable tag powered through energy harvesting and a software-defined RFID reader. Bhattacharyya *et al.* discuss a scheme that allows RFID tags to be used as low-cost sensors by mapping a change in some physical parameter of interest to a controlled change in RFID tag antenna electrical properties. The paper provides three application types for which this class of RFID sensing is well suited, including temperature threshold sensing, displacement sensing, and fluid level sensing. Lakafosis *et al.* consider the case of printed electronics on flexible and paper substrates. They highlight their unique capabilities and the benefits of using paper as the ultra-low-cost, conformal, and environmentally friendly substrate for mass-scale and ubiquitous implementation of such applications, thus eliminating the need of expensive RFID reader infrastructure.

Merilampi *et al.* also consider the use of printed electronics for RFID. Specifically, they investigate the effect of the conductive ink layer thickness on the performance of printed ultra-high-frequency (UHF) RFID tag antennas. The relationship established between performance characteristics and ink thickness provides a basis for tradeoff optimization between the cost and read range requirements in certain applications.

Hande *et al.* present a piezoelectric vibration energy harvesting design for active RFID tags. Vibration data from high-value assets used during disaster relief have been analyzed and their results provide a comprehensive description of their prototype including system form factors, efficiency, and lifetime.

Nikitin *et al.* demonstrate how by using hollow metal heating, ventilating,

[1] http://www.iot2010.org/, http://www.computerworld.com/s/article/96416/RFID_Getting_From_Mandates_to_a_Wireless_Internet_of_Artifacts

and air-conditioning (HVAC) ducts can provide a potential communication channel between passive UHF readers and tags. HVAC ducts behave as electromagnetic waveguides with much lower signal attenuation compared to free-space propagation and the authors have been able to achieve a 30-m read range for standard tags with free-space range of only 6 m.

Chen *et al.* propose a novel EPC application level events (ALE) compliant logical reader abstraction defined on spatial zones and implemented by combining tracking information from passive RFID and positional information from active RFID. This approach allows for fine-grain, near-real-time tracking of high volumes of assets within large spaces, at significantly lower infrastructure cost.

Sani *et al.* presented an implantable RFID for medical applications paying special attention to its communication range and antenna design. Their research demonstrates that a passive tag solution allows only for a limited communication range due to the electrically small size of the antenna and nulls in the radiation pattern. Active tags are found to have distinct advantages in this domain.

Gentili and Iadanza address the problem of positive patient identification within a pediatric intensive care unit. They implement a tracking and identification system using IEEE 802.11 and active RFID technologies. The system appears to result into a substantial improvement according to the total risk priority number methodology, a technique employed by carers to assess patient risk, when compared to a non-RFID system.

Michael *et al.* discuss different alternative futures for RFID from establishing a rather simple alternative to bar code tagging to fulfilling its full potential as a core ingredient for the internet of things. They outline a vision for an RFID product service system, the kinds of smart applications that are likely to emerge in the future as a result of this, and the role of data management capabilities in planetary-scale systems.

Finally, Baker *et al.* report on a recent empirical study dealing with the RFID investment decision. The study examines the factors that affect this decision in the case of early RFID adopter and nonadopter companies. While the adoption cost remains a primary concern, the opportunity for strategic benefits in decision making is seen as a key factor for RFID adoption.

This collection of papers brings out the state of the art, the technical and engineering challenges that are faced by the field, the directions taken by the academic and the industrial community, and the opportunities in technology, standards, and business. RFID has gone from a niche industry now to becoming part and parcel of underlying technology in consumer and enterprise spaces. The future of RFID is expected to be even more exciting including intelligent tags, tags that can scavenge energy from the environment, readers and tags that can create meshes of self-organizing intelligent networks, embeddable tags, etc. We hope that this collection of papers forms the genesis of intellectual thought leadership discussions that go on to create a vibrant, viable, and sustainable RFID community. ■

ABOUT THE GUEST EDITORS

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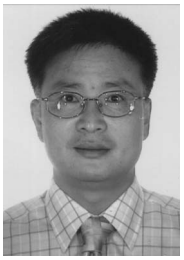

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Dr. Chu received the Best Paper Award in Excellence for Applied Research at the 2004 Wireless Telecommunications Symposium.