Current and Future Trends of RFID Systems Guest Editorial of the Special Issue on SpliTech 2021 and IEEE RFID-TA 2021 Conferences

THIS year, the IEEE JOURNAL OF RADIO FREQUENCY IDENTIFICATION (JRFID), decided to host a joint Special Issue collecting extended versions of papers coming from two international events. The former is the *IEEE International Conference on RFID Technology and Applications (RFID-TA) 2021*, virtually held in Delhi, India, on October 6-8, 2021. The latter is the *International Symposium on Advances in RFID Technology* organized within the *International Conference on Smart and Sustainable Technologies* (*SpliTech*), hosted in Split and Bol, Croatia, on September 8-11, 2021. SpliTech was technically co-sponsored by the IEEE and technically media sponsored by the IEEE Council on RFID (CRFID).

Authors from academia and industry participating at both conferences have common interests in sharing the recent advancements in the area of RFID from multidisciplinary point of views. Both conferences were held during the pandemic period, so they had an even more important role to connect researchers and scientists coming from all around the world.

The 11th edition of the IEEE RFID-TA Conference had a virtual format, by hosting more than eighty virtual speeches organized in thirteen technical sessions and one workshop. Advanced antenna solutions, novel backscattered-based systems, chipless, next generation RFID systems, and localization are some of the dealt topics. A special industry session on "IOT: the promise, the reality and the gaps that remain" gave a glimpse to the future of Internet of Things with experts from companies and academia. Two outstanding keynote speakers were hosted. Prof. Paolo Nepa presented a talk entitled "RFID readers and tags: when antennas matter" by giving a synthetic overview of requirements and design criteria for antennas of RFID tags and readers, as well as of the main challenges typically faced and solved by antenna designers. Prof. Shiwen Mao held a talk entitled "On RFID-based Human Activity Sensing", by discussing various technical challenges on fully exploiting RFID for human activity recognition and tracking. Besides, three special guests from Impinj, Inc., K. V. S. Rao, Pavel Nikitin, and John Kim, talked about "The history and evolution of RAIN RFID tag antennas" by covering the history of RFID tag antennas and their evolution up to the latest research developments. Competitions for the Best Paper Award and the Best Student Paper Award were also organized. The work by Phan-Huy *et al.* entitled "Ambient Backscatter Communications in Mobile Networks: Crowd-Detectable Zero-Energy-Devices" received the *Best Paper Award*. While the paper entitled "Cyber-Tooth: Antennified Dental Implant for RFID Wireless Temperature Monitoring" authored by Panunzio *et al.* received the *Best Student Paper Award*.

The *International Symposium on Advances in RFID Technology* was held with hybrid format by hosting four technical sessions. The main topics were related to wearable RFID systems, sensing and solutions for both society and industry, augmented RFID tags, and RFID applications. 27 oral speeches were presented by international authors. The Symposium hosted as keynote of the whole SpliTech Conference one of the pioneers of RFID sensing, Prof. Joshua R. Smith, with the speech titled "Perpetual Computing: Technologies for Banishing Batteries".

Among the papers of both conferences, 13 contributions have been extended and published on this Special Issue [A1], [A2], [A3], [A4], [A5], [A6], [A7], [A8], [A9], [A10], [A11], [A12], [A13], coming from Austria, Italy, Spain, U.K., Belgium, France, Finland, China, India, and Mexico. They address several topics such as novel antenna design, localization systems, augmented RFID systems, sensor fusion and next-generation systems, by giving an interesting overview of hot topics.

Summary of Special Issue Works: In the framework of localization systems, several solutions appear with different purposes [A1], [A2], [A3], [A4], [A5].

In [A1], Liu *et al.* proposed a widespread solution based on a robotic platform to perform tag localization. The phase and RSSI measurements are collected by a mobile robot carrying an RFID reader and multiple antennas. The stability of RSSI measurements is employed to determine reliable phase profile. The tag cross-range is estimated from the phase-curve minimum, while the down-range is derived by finding the integer number of wavelengths at the point of closest approach which fits the phase profile. 2D tag localization is determined thanks to straight-line trajectory of the robot, while 3D localization requires for L-shape trajectory. After estimating x- and y- coordinates, the height of the target can be calculated by considering the integer number of wavelengths at the point of the closest approach. Trajectories of antennas are gathered via Laser Imaging Detection and Ranging (LIDAR). An experimental analysis was carried out with 8 tags by performing five repeated tests in controlled environment. A 2D mean localization error of 12 cm was obtained, similarly to classical Synthetic Aperture Radar (SAR) methods. 32 tags were

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installed for 3D localization experiments and the localization error was of around 15 cm.

In [A2], Gil-Martínez *et al.* designed a novel frequency-scanning leaky-wave antenna (LWA) with commodity hardware to measure the Angle of Arrival (AoA) of the tag backscattered signal. The printed LWA is completely passive and compatible with commercial RFID hardware. The dispersive nature of the LWA combined with the selection of a proper high permittivity substrate allows the radiation of frequency steered directive beams. The system is based on four directive beams created by the two-port antenna and two RFID channels to estimate the AoA by amplitude-monopulse signal processing and angular pseudospectrum technique. The solution is simpler w.r.t. complex electronic scanning of phased arrays. By processing RSSI measurements, within the antenna Field-of-View of 130°, the Root Mean Square Error (RMSE) of AoA was of around 8° in the worst case of indoor scenario.

Surely, wireless motion capture systems are appealing solutions in the human-machine interaction panorama. In [A3], Merenda *et al.* proposed a device-free gesture identification system that recognizes different hand movements by processing RSSI and phase values from backscattered signals of RFID tags mounted on a plastic plate through Edge Machine Learning (EML) algorithms. Two reader antennas were installed in front and back the plastic plate with 16 tags. Antennas are alternatively fed and placed at a variable distance between 60 cm and 80 cm, each other. In the space between them, five hand gestures were performed, during which RSSI and phase data are collected. Three different algorithms, e.g. the Random Forest Classifier, the Support Vector Machine, and the Decision Tree Classifier, were compared by determining an accuracy up to 99.4%.

Also, sensor-fusion is a promising approach to implement localization systems. As an example, there is the system proposed by Merenda *et al.* in [A3], [A4], which combines ultrasounds with an RFID system. Positioning is determined by multiple distance measurements between reference points and sensors via ultrasonic signals. The RFID system performs the synchronization among emitter and sensors through the standard protocol features. The Time-of-Flight (TOA) detection is performed firstly by training off-line a Machine Learning model with peaks indexes of the received ultrasonic signal and the output of a cross-correlation based positioning system, as ground truth. In a second phase, the positioning is evaluated and tested on-board using the previously trained model on a microcontroller. Experimental results showed a mean positioning error below 25 cm in 95% of the test cases in a typical room for a moving target.

Finally, Di Giampaolo *et al.* [A5] proposed a Simultaneous Localization And Mapping (SLAM) system for mobile robots. The robotic platform is equipped with wheel encoders and an RFID reader which measures the phase of the signal backscattered by a set of passive UHF-RFID tags, deployed in unknown positions on the ceiling of the environment. The reference tag position must be estimated to create a reference map, within which the robot will be localized. A special kind of tag, *i.e.* TriLateration Tag (TLT), including three antennas close one each other was adopted. The solution is based on the range and bearing estimation of all detected TLTs, performed through a set of Multi-Hypothesis Extended Kalman Filters (MHEKF). Then, the range and the bearing information of the responding TLT is used in an EKF-SLAM algorithm which solves the SLAM problem. The proposed approach is more robust and computationally efficient with respect to other approaches available in the literature and it is particularly suited for large warehouses where RFID tags cannot be deployed too densely. An experimental analysis was carried out in an area of around 5 m^2 and the estimation error is usually smaller than 20 cm for a rectangular shape trajectory, by employing two TLTs.

As for the antenna design, several solutions have been proposed [A6], [A7], [A8], [A9], [A10].

Specifically, in [A6], a bi-directional coplanar-waveguide (CPW)-fed antenna with circular polarization (CP) was investigated as RFID reader for applications in the ISM band at 2.45 GHz. Authors proposed an antenna design composed by a CPW-fed monopole with a defected ground plane on which two stubs, one of which with an inverted-L shape, have been added to successfully tune the working frequency. The whole design is packed into a $60 \times 60 \times 1.5$ mm^3 one-side-printed FR4 substrate. An Arduino UNO-based open-source microcontroller setup has been used for studying such an antenna as an RFID reader antenna. Finally, a wireless module NRF24L01 working at 2.45 GHz with an external antenna acting as a tag has been used for measurement purpose. The solution appears to be attractive for a variety of IoT-based applications where bidirectional RFID coverage and integration with other technologies is required.

In [A7], the topic of rapid prototyping based on additive manufacturing (AM) was addressed, with the comparison of three promising AM/3D-printing technologies allowing the printing of conductive elements: Fused Filament Fabrication (FFF), Aerosol Jet® Printing (AJ®P), and Laser-Induced Graphene (LIG). To compare the techniques, the authors designed a UHF RFID tag and prototyped it with the three techniques and with a reference sample realized in Aluminum. The FFF tag was manufactured by extruding a conductive printable filament, named Electrifi, over an ABS printed substrate, used also for the AJ®P-made antenna. Conversely, the LIG tag was produced by laser-burning a Kapton® polyimide sheet. All the tested technologies have demonstrated to be suitable for realizing working prototypes, each one with its pros and cons and, as expected, with performance lower than the comparison sample. This has been especially true for the really appealing LIG case, which deserves further studies since it promises "green" and cost-effective antennas.

In [A8], Bansal *et al.* proposed a novel design for a platform-tolerant UHF RFID tag for tracking humans/materials at the construction site, using Artificial Magnetic Surface (AMC) meta surfaces. The novelties of the proposed tag lie in its improved radiation characteristics and stable high read range performance even when applied on items with different characteristics, like human body, metallic items, and so on. The aim was to develop a new approach to implement the Automatic Identification and Data Capture (AIDC) solution through a Middleware integrated with the UHF-RFID system, so guaranteeing an effective site management and access

control at the construction industry. Eventually, the authors discussed a test campaign in a real scenario environment which proved the potentialities of their design.

In [A9] the unconventional use of passive UHF RFID technology for creating music by means of a touch or a gesture was proposed. Two different textile prototypes, one based on touches, the other based on blocking/unblocking gestures, were introduced, realized, and tested. An RFID-based music player was also implemented to decode the reading/unreading of a specific ID and play music accordingly. Specifically, in the so-called Touch Prototype two electro-textile dipole antennas and three RFID chips were used. The touch of a specific copper pad guarantees the enabling of a specific ID and the consequent sound emitted by the music player. On the contrary, in the so-called Block Prototype, three commercial passive UHF RFID tags were applied to textile and simple gestures, including blocking, unblocking, and hovering over tags, are used to play music. The two devices were tested demonstrating a high input detection rate (95%-100%).

Finally, in [A10], Occhiuzzi *et al.* investigated the possibility to adopt the 5G 3.6 GHz frequency band for the next generation body-centric backscattering systems, by performing an experimental verification from the antenna perspective. The aim was to test if, as early studies suggested, the exploitation of the upcoming 5G communication infrastructure could overcome the limitations in bit rate and bandwidth and the need of a dedicated reading platform typical of the traditional UHF-RFID technology. For this scope, an epidermal antenna was hence designed, prototyped, and measured in real conditions, i.e., applied on the human body, by obtaining communication ranges up to 1.5 m when passive backscattering-based communication link was considered.

Three further contributions, extended and published in this Special Issue, deal with the macro topic of next generation RFID systems and their applications [A11], [A12], [A13].

Indeed, Basic *et al.*, in [A11], proposed an interesting and unusual application of wireless identification and communication exploiting the Near Field Communication (NFC) technology. The main goal is to enable the NFC-sensing of the status of batteries by integrating an NFC tag in a battery management system (BMS). The proposed NFC system guarantees the data communication while adds an authentication scheme for the battery pack validation, for anticounterfeiting reasons. To validate the approach, authors proposed a prototype of the whole system, reporting tests in terms of reading capabilities, security, and energy consumption.

Another particularly captivating application of the RFID technology is the one discussed in [A12] where Occhiuzzi *et al.* developed and tested a system for automatically evaluating the ripening of avocados in an industrial scenario. The novelty of the proposed automated ripening chamber is the use of passive UHF RFID tags to monitor the ripening level of fruits. The differences in the received backscattered signals, due to different ripening stages, are used to train an automatic classification algorithm based on Support Vector Machines (SVMs). The system is thus capable to discriminate between four different stages of ripening with an accuracy greater than 85%.

Finally, in [A13] a zero-power device is introduced to enable the concept of Crowd-Detectable Zero-Energy-Devices. Being capable of generating the required energy by means of solar and/or ambient light harvesters, the device can backscatter ambient waves for communication purposes. Authors prototyped the solution and tested it in proximity of different sources, such as TV, 4G, and 5G radiobase stations both in indoor and outdoor conditions, by demonstrating the appropriateness of the proposed approach.

In Closing: This special issue collected the extended versions of papers presented at *IEEE RFID-TA 2021 Conference* and the *International Symposium on Advances in RFID Technology* organized within the *International Conference on Smart and Sustainable Technologies* (*Splitech*). This leads to highlight the hot topics of the RFID community, worldwide.

We would like to express our appreciation to all the authors contributing to this IEEE JOURNAL OF RADIO FREQUENCY IDENTIFICATION Special Issue.

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APPENDIX: RELATED WORKS

[A1] Z. Liu *et al.*, "A phase and RSSI-based method for indoor localization using passive RFID system with mobile platform," *IEEE J. Radio Freq. Identif.*, vol. 6, pp. 544–551, 2022, doi: 10.1109/JRFID.2022.3179620.

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[A3] M. Merenda, G. Cimino, R. Carotenuto, F. G. D. Corte, and D. Iero, "Edge machine learning techniques applied to RFID for device-free hand gesture recognition," *IEEE J. Radio Freq. Identif.*, vol. 6, pp. 564–572, 2022, doi: 10.1109/JRFID.2022.3185804.

[A4] M. Merenda, L. Catarinucci, R. Colella, D. Iero, F. G. D. Corte, and R. Carotenuto, "RFID-based indoor positioning using edge machine learning," *IEEE J. Radio Freq. Identif.*, vol. 6, pp. 573–582, 2022, doi: 10.1109/JRFID.2022.3182819.

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[A9] A. Shaikh *et al.*, "Design and evaluation of passive RFID-based music player textile prototypes," *IEEE J. Radio Freq. Identif.*, vol. 6, pp. 622–628, 2022, doi: 10.1109/JRFID.2022.3199887.

[A10] C. Occhiuzzi, F. R. Venturi, F. Amato, A. Di Carlofelice, P. Tognolatti, and G. Marrocco, "Design and experimental characterization of on-skin loop antenna for next 5G backscattering-based communications," *IEEE J. Radio Freq. Identif.*, vol. 6, pp. 629–636, 2022, doi: 10.1109/JRFID.2022.3154630.

[A11] F. Basic, M. Gaertner, and C. Steger, "Secure and trustworthy NFC-based sensor readout for battery packs in battery management systems," *IEEE J. Radio Freq. Identif.*, vol. 6, pp. 637–648, 2022, doi: 10.1109/JRFID.2022.3170381.

[A12] C. Occhiuzzi *et al.*, "Automatic monitoring of fruit ripening rooms by UHF RFID sensor network and machine learning," *IEEE J. Radio Freq. Identif.*, vol. 6, pp. 649–659, 2022, doi: 10.1109/JRFID.2022.3174272.

[A13] D.-T. Phan-Huy, D. Barthel, P. Ratajczak, R. Fara, M. D. Renzo, and J. D. Rosny, "Ambient backscatter communications in mobile networks: Crowd-detectable zero-energy-devices," *IEEE J. Radio Freq. Identif.*, vol. 6, pp. 660–670, 2022, doi: 10.1109/RFID-TA53372.2021.9617328.

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