UHF IoT Humidity and Temperature Sensor for Smart Agriculture Applications Powered from an Energy Harvesting System

Adnan Nadeem
Frederick Research Center, Nicosia, Cyprus
School of Electrical Engineering & Computer Science, National University of Sciences and Technology, Islamabad, Pakistan
anadeem.msee19rimms@seecs.edu.pk

Nosherwan Shoaib
School of Electrical Engineering & Computer Science, National University of Sciences and Technology, Islamabad, Pakistan
nosherwan.shoaib@seecs.edu.pk

David Chatzichristodoulou
Frederick Research Center, Nicosia, Cyprus
RF and Microwave Solutions LTD, Cyprus
eng.cd@frederick.ac.cy

Loukia Vassiliou
Agricultural Research Institute, Nicosia, Cyprus
loukia.vassiliou@ari.gov.cy

Symeon Nikolaou
Frederick Research Center, Nicosia, Cyprus
Electrical Engineering Department, Frederick University, Nicosia, Cyprus
s.nikolaou@frederick.ac.cy

Abdul Quddious
KIOS Research and Innovation Center of Excellence, University of Cyprus, Nicosia, Cyprus
quddious.abdul@ucy.ac.cy

Photos Vryonides
Frederick Research Center, Nicosia, Cyprus
Electrical Engineering Department, Frederick University, Nicosia, Cyprus
p.vryonides@frederick.ac.cy

***Abstract*—This manuscript presents a novel UHF IoT humidity and temperature sensor module that is powered from an integrated energy harvesting (EH) system. The module is intended for smart agriculture applications. The sensing module is powered from the collected RF energy that is harvested by a meander monopole antenna operating at 915 MHz (US UHF band) and therefore the use of a battery is not required. The rectifying voltage doubler converts the received RF energy into DC while the Power Management Unit (PMU) boosts-up and stores the rectified voltage providing a regulated output voltage of 1.8V to the RFID tag IC (ROCKY100) and 3.3V to the microcontroller unit (MCU) and the humidity and temperature sensor IC. The communication RFID antenna uses the European UHF frequency band centered at 868 MHz. When the RFID tag IC is supplied with 1.8 V from the PMU it operates in semi-passive mode and it effectively increases its communication range. The ROCKY100 is EPC C1G2 compliant and is compatible with power harvesting modules and SPI communication to support external low-power sensors and actuators. In addition, a capacitive digital humidity and temperature sensor (HTS221) is used as the sensing module for soil measurements. The process of measuring the relative humidity and temperature of the soil is controlled with a Texas Instrument mixed signal microcontroller that possesses two SPI interfaces that allows it to communicate with the RFID IC and the sensor in parallel. Upon receiving a SPI directed read request from the RFID reader, the ROCKY100 SPI bridge requests the value of the last measurement from the microcontroller and the humidity and temperature measurements taken by the HTS221 IC are sent to the RFID reader. The use of harvested wireless energy as a power source makes the demonstrated module a potentially batteryless and thus a "Green" sensor.**

Keywords—RF energy harvesting, RFID, Rectenna, PMU, MIMO antenna, Humidity sensors.

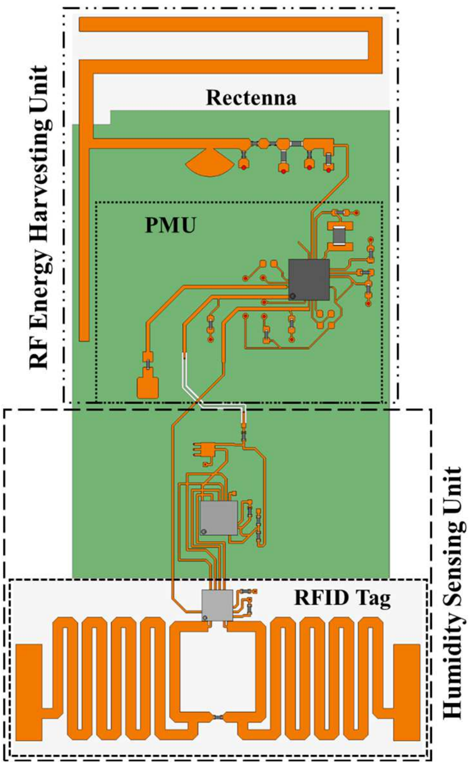

Fig. 1. Layout of the proposed energy harvested supported sensor module intended for agriculture applications. The RF ground is presented in green color.

I. Introduction

One of the main advantages of 5G networks is the integration of low cost compact wireless sensors [1] that were traditionally forming local networks in a limited area, with the internet, and consequently with any other communication

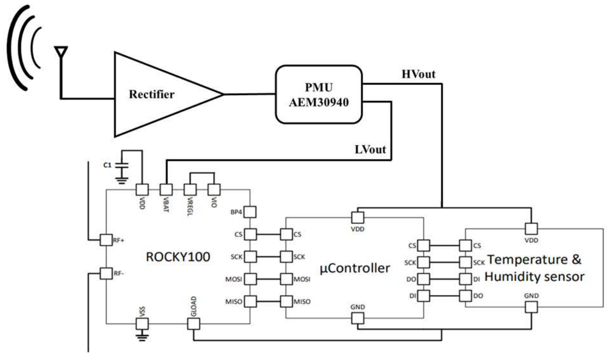

Fig. 2. Schematic of the IoT UHF sensing module

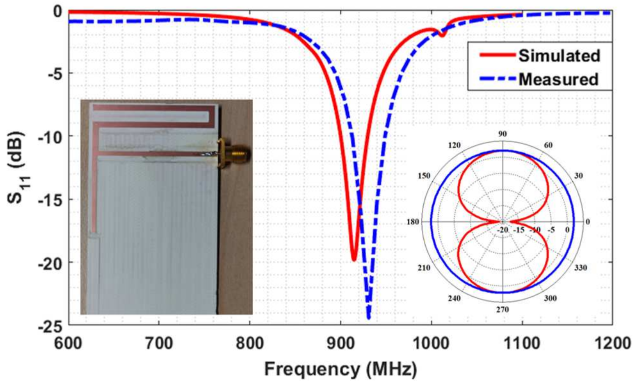

Fig. 3. S_{11} plot of the UHF meander line monopole antenna with fabricated prototype and an omnidirectional radiation pattern.

network. The Internet of Things (IoT) allows the communication of an isolated device with any other device on the web. IoT allows the wireless communication of devices such as humidity or temperature sensors [2] which are widely used in agriculture and the collection of large amount of data that can be stored and processed at will. The integration of technologies such as Artificial Intelligence (AI) with a vast amount of data, collected from distributed IoT sensors is what drives Smart Agriculture [3] which aims to increase food productivity that is required in order to support the continuously growing planet population. What limits the extensive use of IoT sensors is their cost, and their need to be battery operated. Especially for agriculture sensors where the sensors are usually embedded in soil, the soil contamination from the disposed batteries is a major disadvantage. In order to replace the battery the use of an energy harvesting system [4] is proposed. This technology allows the exploitation of wireless energy that is transmitted from a designated transmitter in close proximity and is a green source of energy with zero environment impact.

UHF RFIDs have been used in combination with a variety of sensing applications [5-7] because UHF is a globally recognized standard, and mostly because of the low frequency and the limited free space loss which result in enhanced reading range. An example of a passive UHF tag for humidity sensing was presented in [8]. In several cases the reading range of a passive tag is insufficient; therefore, an active RFID may be needed which implies the use of a battery. In cases where the battery replacement is inconvenient or even impossible the use of wireless energy harvesting systems or otherwise wireless power transfer systems, may be used [9]. In most cases a wireless sensor should be compact in size. The use of high efficiency UHF antennas which are needed for the energy harvesting system dictates that the antenna size is large and in turn it defines the overall size of any wireless sensor module. In order to keep the antenna size as compact as possible, a number of antenna miniaturization techniques may be used [10]. Some of these methods are implemented for the proposed design.

The current manuscript presents the implementation of a digital humidity and temperature sensor that is integrated with a UHF RFID antenna to implement an IoT wireless sensor. On the same board an Energy Harvesting (EH) system that consists for a second UHF band rectenna and a power management unit (PMU) is used in replacement of a conventional battery, thus implementing a battery-less IoT humidity and temperature sensor, intended for Smart Agriculture applications. The combination of the UHF semi-active RFID based humidity and temperature sensor with the UHF EH system, presents a new approach with enhanced reading range compared to what has been reported in the recent past [11].

II. Sensor System Implementation

The proposed sensing module consists of two main units, a) the RF energy harvesting unit and b) the humidity sensing unit depicted in Fig. 1. The schematic diagram of the wireless sensor implementation is demonstrated in Fig. 2. As can be seen, the Power Management Unit (PMU) provides voltage to the RFID IC from the low output voltage pin (1.8 V), and it supplies a higher voltage (~ 3.3 V) to both the microcontroller and the sensor IC from a second high voltage pin. The proposed sensing module is designed on Rogers 4003C laminate with 0.813mm thickness. For the design and optimization of the sensor commercially available full wave and circuit analysis software was used.

The microcontroller is used to collect the digital signal from the sensor's measurements and provide Serial Peripheral Interface (SPI) bridge between the RFID tag and the sensor. The microcontroller is configured in order to periodically read and transmit the measured values of the temperature and humidity in a continuous mode. The capacitor C_1 is included in the device in order to support the current peaks during measurements. Upon receiving a SPI directed read request from the UHF RFID reader, the RFID tag's SPI bridge requests the value of the last measurement from the microcontroller. The microcontroller provides the humidity and temperature values to the RFID tag through the SPI bridge and thus the reader receives a unique identification number (tag ID) plus the updated digital signals of the humidity and temperature measurements of the associated sensor.

The RF energy harvesting unit consists of a rectenna (combination of the receiving UHF antenna and the rectifier) and a PMU. The purpose of the rectenna is to collect the transmitted RF energy and convert it to useful DC power. The RF energy harvesting antenna collects the RF energy at 915 MHz and delivers it to the rectifier for the rectification. The implemented voltage doubler rectifier is able to convert the received RF power into DC with maximum RF-to-DC efficiency of 63%. It is well known that the rectifier's efficiency is non-linearly dependent on the input power level and on the termination load [12]. The implemented rectenna is terminated with a commercially available PMU with stable input impedance. The PMU provides two regulated output voltages LVout at 1.8V and HVout at 3.3V. The RFID tag IC

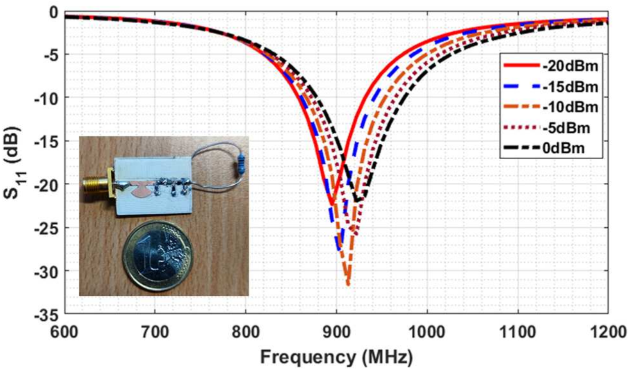

Fig. 4. S_{11} plot of the UHF rectifier for different output power levels versus frequency with its fabricated prototype compared to 1 euro coin to demonstrate its compact size.

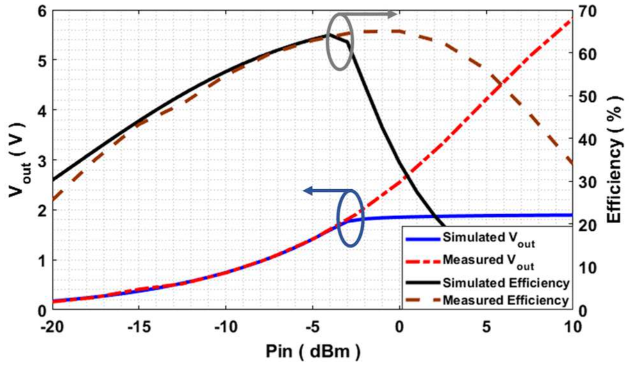

Fig. 5. Measured and simulated rectifier's output voltage and efficiency plot versus different power levels; output voltage plot is labeled on left axis while efficiency plot is labelled on right axis.

requires 1.8V to operate in semi-passive mode that can improve the sensitivity of the RFID tag IC from -14dBm to -24dBm. This sensitivity improvement can effectively increase the communication range of the RFID tag without the use of a battery cell since the required DC voltage is provided by the EH system. The microcontroller and the sensor IC both require 3.3V and are directly powered by the PMU. With minimum available power at the input of the rectifier equal to -12.5 dBm, the rectifier can supply the minimum required cold-start voltage to the PMU that in turn provides a regulated 1.8V at its output. This voltage is effectively applied to the RFID IC which operates into semi-passive mode and as a result the read range can be enhanced by 8.5m.

A. UHF Rectenna and PMU Circuit

The RF energy harvesting antenna is a monopole antenna that exhibits omni-directional pattern that is suitable for RF energy harvesting applications. It has a meander line structure intended for compact size and is matched to 50Ω line through an open stub and a straight uniform transmission line. In addition, it exhibits a fractional bandwidth of more than 3.1 % with simulated gain of 1.35 dBi. The fabricated prototype was measured, and the results are in good agreement with the simulation results as illustrated in Fig. 3. The offset is due to fabrication tolerances, but the antenna is still matched at 915 MHz frequency with S_{11} better than-10dB.

The most challenging task in the design of a rectifier is to achieve a sufficiently wideband matching. The major research challenges are related to the fact that rectifiers are nonlinear devices, and they tend to have significant variations in the achieved RF-to-DC efficiency when the incident power, or the termination load change [13]. With this in mind, the chosen rectifier topology is the voltage doubler since it causes the peak efficiency at low input power levels. The rectifier is designed to have high efficiency for input power levels from -20 to 0 dBm. The measured S_{11} of the rectifier for different input power levels vs frequency is plotted in Fig. 4. The rectifier demonstrates a maximum efficiency of 63% and more than 50% efficiency for low-input power levels as illustrated in Fig. 5. Furthermore, a voltage higher than 400 mV at -15 dBm is produced ensuring the minimum DC voltage for the PMU's cold start. Skyworks SMS7630-079 Schottky diodes are used for the rectification circuit exhibiting good efficiency at low-power levels whereas coil-craft inductors are used for impedance matching. The lumped elements are preferred in order to keep the rectifier area as small as possible.

The commercially available AEM30940 is used as the Power Management Unit (PMU) IC. It is capable of a cold start with waking up voltage 380 mV, while it can store energy in an optional rechargeable battery or capacitor and it provides two regulated DC voltage supplies at it's two outputs. The integrated PMU can operate with input DC voltages ranging between 50 mV to 5V subsequently to the cold start. The two output DC voltage supplies are suitable for either low power microctroller units (1.2-1.8 V), or even for a communication transceiver when the high output voltage (1.8-4.1 V) is used. For the used RFID IC, the PMU's low voltage output is used while for the humidity and temperature sensing IC and the microcontroller IC, the high voltage output is used.

III. Humidity Sensing Circuit

The humidity sensing circuit consists of the actual humidity and temperature sensor which is the commercially available HTS221 IC, and a microcontroller. The humidity sensor is controlled by a microcontroller that provides its readings to the RFID IC. For the communication with the reader, a meander-shaped dipole UHF antenna is used.

A. UHF RFID Tag

The European 865-868 MHz band is considered for the RFID tag antenna design. A meander shape dipole shape is considered for the antenna design to make the size compact and provide with an omni-directional radiation pattern. The ROCKY100 tag IC is used for the RFID tag design that supports external sensors and has a serial port interface (SPI) interface to connect it with external sensors and communicate with them. The IC operates in a fully passive mode back reflecting the received energy from the RFID reader. However, it can also support an external power source, where the IC can operate in semi-passive mode and therefore achieve longer communication range because the sensitivity of the RFID IC improves from -14dBm to -24dBm. In the semi-passive mode, the RFID IC is supplied by the output pin of the PMU. The ROCKY100 RFID IC includes the necessary power supply management circuitry to supply external sensors or actuators at the cost of deterioration of the chip sensitivity that will affect its read range. Thus, the MCU and the sensing IC are powered directly by the PMU of the EH system. The RFID tag IC has configurable general purpose input/outputs (GPIOs) to communicate with the external device, trigger operations and retrieve data prior to backscattering the obtained answer to the reader. The RFID tag IC uses Phase Shift Keying (PSK) modulation to backscatter data through

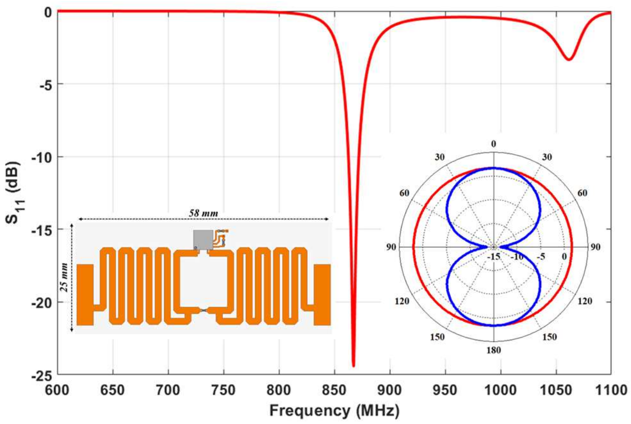

Fig. 6. Simulated S_{11} (dB) of EU UHF RFID tag antenna with its schematic design and a typical omni-direction radiation plot.

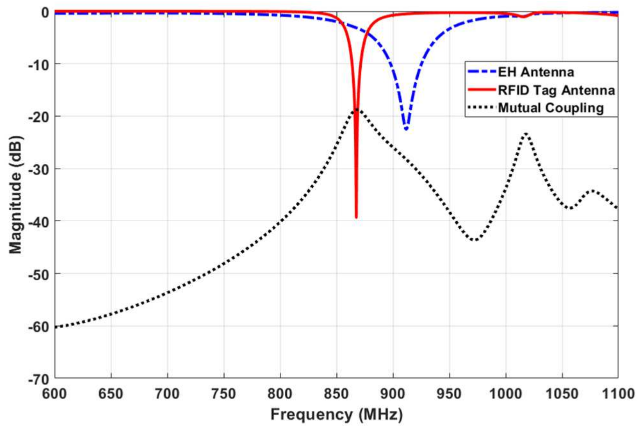

Fig. 7. Humidity sensing MIMO module S-parameters plot: S_{11} curve of the RFID tag antenna; 915 MHz EH antenna with the blue dotted-dashed curve. The mutual coupling is presented by the S_{21} black dotted curve.

the reverse link and demodulation of Amplitude Shift Keying (ASK) symbols in the forward link.

The RFID IC has an impedance of 51-j460 Ω in passive mode and an impedance of 14-j456 Ω when operating in semi-passive mode. To conjugately match the tag IC an inductive loop is used, and meander lines are used to increase or decrease the resonating frequency of the tag antenna. The matching of the tag antenna mainly depends upon the inductive loop that cancels the imaginary part of the IC and the meander lines that can shift the resonance frequency. The spacing between the meander lines also affect the matching. When the number of turns increases, the gap needs to be reduced and vice versa, in order to improve the matching. The real part of the impedance is controlled by the T-shaped brick at the end of two arms of the dipole tag. The increase of the width of the bricks results in reduction of the real part of the impedance. On the contrary reducing its width results in an increase of the real part impedance.

The tag antenna is well matched at the intended UHF band and presents S_{11} better than -24.4 dB and realized gain of 1.16 dBi. The tag antenna has a relatively compact size of 58 x 25 mm^2. The narrowband reflection coefficient along with the omnidirectional radiation pattern and the layout of the meander UHF dipole can be seen in Fig. 6.

The combined EH unit with the sensing module presents a MIMO system where two different antennas are closely operating and resonating at two distinct frequencies. In MIMO systems, the mutual coupling is of main concern. To avoid mutual coupling two distinct frequency bands are considered i.e., the EU UHF band (865-868 MHz) for the RFID tag antenna and the US UHF band (902-928 MHz) for the EH antenna. Moreover, the orientation of both antennas is chosen so that the mutual coupling between the two antennas is kept as minimum. The RFID tag and the EH antennas were co-simulated along with the entire sensing module including all the parasitics. The s-parameter simulation results are presented in Fig. 7 while the slightly perturbed radiation patterns are demonstrated in Fig. 8. Interestingly, the MIMO system has improved S_{11} for the UHF RFID tag while the EH antenna's S_{11} remains practically the same. The S_{21} plot represents the mutual coupling between the two antennas and is less than -15dB throughout the entire band, something that ensures that the two antennas do not affect each other's performance. The radiation patterns of both antennas are presented in Fig. 8, where Fig 8(a) plot refers to the RFID tag radiation pattern and Fig 8(b) presents the polar radiation pattern of the EH antenna. The MIMO system presents 1.13 dBi and 1.79 dBi simulated gain for the RFID tag antenna and the EH antenna respectively.

B. Humidity Sensor and Microntroller

For the actual humidity and temperature sensing, the commercially available HTS221 IC is used, and it is integrated on the same board that also includes the RFID IC and a microcontroller which synchronizes the communication between the sensor IC and the wireless communication RFID IC. The used humidity and temperature sensor has reading range between -40^o and +120^o exceeding any practical range that can be used for any agriculture application. At the same time humidity from 0% all the way up to 100% can be detected and the reported accuracy is ±3.5% rH. A polymer dielectric capacitor is actually used to convert the varied capacitance into humidity. The sensor IC needs to be powered with a power supply between 1.7 and 3.6 V, and this voltage is provided from the PMU of the EH system. The sensor IC consists of the analogue sensors and the analogue to digital converter which communicates the digital signal to a microcontroller (MCU). The communication is accomplished through I^2C/SPI (Inter- Integrated Circuit)/(Serial port interface). For the physical implementation of the customized communication traces a milling machine is used and the design intended to accommodate the small traces and the required lumped components (R,L,Cs) in the smallest possible area.

Texas Instruments MSP430FR2433IRGET mixed signal microcontroller is used as the preferred MCU. The defined configuration allows for periodic updates of the sensor readings. It MCU IC has two SPI interfaces which are exploited to communicate with both the Sensor IC and the RFID IC which will eventually send the readings to an RFID reader. The used MSP430FR2433IRGET MCU is a member of a low-cost family of MCUs especially designed for sensing and measurement applications since their design is supported by very low-power modes which ensure extended battery life. In the presented case the entire system is batteryless since it is powered from the wireless EH system that provides DC power to the ROCKY100 RFID IC, and also the regulated voltage to the MCU is provided by the PMU. The power and communication interfaces between the involved ICs are depicted in Fig. 2. The entire microcontroller with the memory cells and its peripherals is packaged in a compact 4×4 mm^2

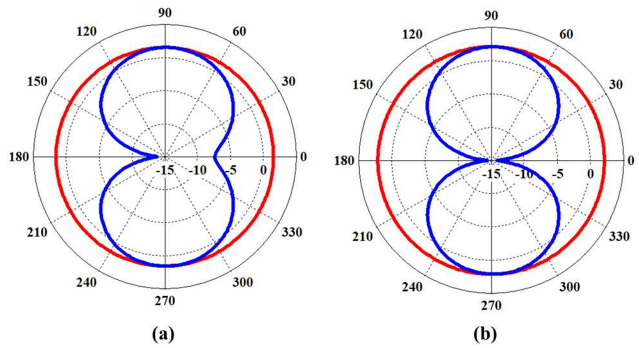

Fig. 8. Radiation patterns of MIMO antennas. (a) Radiation pattern of RFID tag antenna (b) Radiation pattern of EH antenna

QFN package. The MSP430 uses ultra-low-power Ferroelectric Random Access Memory (FRAM) technology which combines the low-energy fast writes/reads and the flexibility, of the traditional RAM with the non-volatility that is the characteristic of flash memory.

IV. Conclusions

A UHF IoT UHF humidity and temperature sensor powered from an RF energy harvesting system, suitable for smart agriculture applications, is presented in this paper. The humidity and temperature sensing module uses power from the PMU of the RF energy harvesting system power up the RFID IC, the digital sensor and the microcontroller. The semi-passive mode of the UHF tag results in improved read range of 8.5m without the need of a battery. The humidity and temperature of the soil are measured using a digital capacitive HTS221sensor. Through the SPI and I^2C interface pins, the sensor transfers its digital data to the RFID IC through the microcontroller. The sensor data is transmitted to the interrogating RFID reader along with the tag ID through the RFID UHF meander dipole upon request. The entire system is powered using an integrated energy harvesting system as long as the available power at the rectifier is more than -15 dBm.

Acknowledgment

This research was co-funded by the European Regional Development Fund and the Republic of Cyprus through the Research and Innovation Foundation, under the projects, INFRASTRUCTURES/1216/0042-(RF-META) and EXCELLENCE/ 0918/0365 (ICARUS).

References

[1] D. Chatzichristodoulou, A. Quddious, L. Vassiliou, N. Shoaib, P. Vryonides and S. Nikolaou, Additive Manufacturing Techniques for 5G IoT Antennas and Sensors, in proceedings of the conference on ‘15th European Conference on Antennas and Propagation: (EuCAP’ 2021)’, Germany, 2021, pp. 1-5.

[2] Y. Junho, J. Lee, and Y. Kwon, Humidity-Sensing Chipless RFID Tag with Enhanced Sensitivity Using an Interdigital Capacitor Structure, in proceedings of the conference on ‘Sensors’, 2021.

[3] A. Khoa, M. M. Man, T.-Y. Nguyen, V. Nguyen, and N. H. Nam, “Smart Agriculture Using IoT Multi-Sensors: A Novel Watering Management System,” Journal of Sensor and Actuator Networks, vol. 8, no. 3, p. 45, Aug. 2019.

[4] A. Quddious, S. Zahid, F. A. Tahir, M. A. Antoniades, P. Vryonides and S. Nikolaou, Dual-Band Compact Rectenna for UHF and ISM Wireless Power Transfer Systems, IEEE Transactions on Antennas and Propagation, vol. 69, no. 4, April 2021, pp. 2392-2397.

[5] S. Palacios, A. Rida, S. Kim, S. Nikolaou, S. Elia, MM Tentzeris, "Towards a Smart Wireless Integrated Module (SWIM) on flexible organic substrates using inkjet printing technology for wireless sensor networks", 2012, IEEE International Workshop on Antenna Technology (iWAT).

[6] J. Zhang and G. Y. Tian, "UHF RFID Tag Antenna-Based Sensing for Corrosion Detection & Characterization Using Principal Component Analysis," in IEEE Transactions on Antennas and Propagation, vol. 64, no. 10, pp. 4405-4414, Oct. 2016, doi: 10.1109/TAP.2016.2596898.

[7] A. Rida, L. Yang, T. Reynolds, E. Tan, S. Nikolaou and M. M. Tentzeris, "Inkjet-printing UHF antenna for RFID and sensing applications on Liquid Crystal Polymer," 2009 IEEE Antennas and Propagation Society International Symposium, 2009, pp. 1-4.

[8] S. Koley, S. Benouakta, F. Hutu and Y. Duroc, Passive UHF RFID Yarn for Relative Humidity Sensing Application, ‘13th European Conference on Antennas and Propagation: (EuCAP’ 2019)’, Poland, 2019, pp. 1-4.

[9] A. Costanzo, D. Masotti, G. Paolini and D. Schreurs, "Evolution of SWIPT for the IoT World: Near- and Far-Field Solutions for Simultaneous Wireless Information and Power Transfer," in IEEE Microwave Magazine, vol. 22, no. 12, pp. 48-59, Dec. 2021.

[10] S.Nikolaou, M.A.B.Abbasi, "Miniaturization of UWB Antennas on Organic Material", International Journal of Antennas and Propagation, vol. 2016, Article ID 5949254, 2016

[11] S. A. Imam, A. Choudhary and V. K. Sachan, Design issues for wireless sensor networks and smart humidity sensors for precision agriculture: A review, in proceedings of the conference on ‘International Conference on Soft Computing Techniques and Implementations: (ICSCTI’ 2015)’, India, 2015, pp. 181-187.

[12] Warda Saeed, Nosherwan Shoaib, Hammad M. Cheema, Muhammad U. Khan, "RF Energy Harvesting for Ubiquitous, Zero Power Wireless Sensors", International Journal of Antennas and Propagation, vol. 2018, Article ID 8903139, 16 pages, 2018.

[13] Fatima Khalid, Warda Saeed, Nosherwan Shoaib, Muhammad U. Khan, Hammad M. Cheema, "Quad-Band 3D Rectenna Array for Ambient RF Energy Harvesting", International Journal of Antennas and Propagation, vol. 2020, Article ID 7169846, 23 pages, 2020.