Review of Technologies for Low-Cost Integrated Sensors

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Abstract—**This paper discusses the evolution towards integrated RFID-enabled wireless sensor network infrastructure using UHF and microwave frequencies. Inkjet-printed technology on flexible paper substrates and the integration (assembly) of sensors, wireless modules, discrete components and power sources is proposed as a solution for low-cost, light-weight, and environmental friendly method for RFID-enabled sensors and Wireless Sensor Nodes (WSN). Three examples are given to demonstrate the usability of such method: UHF RFID-enabled temperature sensor, Zigbee wireless module for location finding and sensing applications, and finally an RF- Certificate of Authenticity (RF-COA) for anti-counterfeiting applications.**

Keywords: antenna, inkjet printing, paper substrate, RF-COA, ultra-high frequency (UHF), sensor, wireless.

I. INTRODUCTION

RFID has the potential to bring many benefits to several applications. This is especially the case with RFID enabled sensors where the real time monitoring is important such as in perishable foods, tire pressure monitoring, and medical applications. These applications are on a global scale and RFID-enabled sensor tags to be deployed in massive amounts. Four different scenarios: logistics/supply chain, automotive, healthcare monitoring, and navigation systems; where a full deployment of RFID-enabled sensors, benefit in increased visibility, traceability, flexibility, and added security. Such applications are but not limited to the following list [1]:

- Warehousing systems
- Item management and security
- Asset tracking
- Logistics and supply chain
- Industrial production and automation
- Work in progress (WIP) tracking
- Container identification
- Meat industry
- Store keeping and order processing
- Access Control: people with disabilities, warehouse employees, and hands free access
- Ticketing and public transportation
- Medical applications

All of these applications could benefit from integrating a sensor for continuous (state) monitoring. Sensors are used in everyday objects and are available to measure almost every physical parameter. Temperature, pressure and gas detection are probably the most common measurements related with our daily life, as well as in many industrial processes and material supply chains. Applications include cars, machines, aerospace, manufacturing and robotics. There are also innumerable applications for sensors of which most people are not aware such as touch-sensitive elevator buttons and lamps which dim or brighten by touching the base. As example temperature sensors could be integrated with RF tags for perishable food monitoring, accelerometer could be utilized for health monitoring of assets in tracking applications, and pressure sensors could be utilized in tire pressure monitoring. In addition, low-cost indoor location finding could be made possible with the integration of RF modules (such as zigbee), which allows that.

A wireless sensor is a device that combines the capabilities of a sensor and an RF or wireless device and hence is capable of sensing, processing data, transmitting and/or communicating to other wireless device(s). In addition to the basic RFID automatic Identification capabilities, wireless sensors can bridge identification and sensing technology through their integration. The aim is to create a system that is capable of not only tracking, but also monitoring (condition). With real-time cognition we may create a secured "intelligent network of RFID-enabled sensors." However, like any newly developed technology, challenges occur that hinder its large-scale practical implementation. This paper discuses the technologies that are aimed towards low-cost development of wireless sensor modules. These include:

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- Low cost materials such as paper substrate [2]. Other low cost material like Liquid Crystal Polymer (LCP) can as well be used with minor modifications of the design and development process [3,4].
- Direct write methodologies for fast fabrication and immediate prototyping. Of such methods is the inkjet printing [5] of conductive inks as is explained in III. B. This process is proposed to replace the metal deposition/etching and which requires a clean room facility.
- Evolution towards higher frequencies: 2.4 GHz WiFi and higher frequencies.

Examples given in this paper will focus on: 1) a fully tested temperature UHF sensor and 2) a system on package solutions for zigbee modules which could find applications in location findings, sensing, and identification and 3) RF Fingerprinting Physical Objects for Anti-counterfeiting Applications.

The featured designs in this article show an evolution from several previous work [2,6] that use passive RFID tags which are limited by short reading and identification capability only, single layer inkjet printing UHF sensor which uses a dipole antenna and which also suffers from some interference between the radiator and the electronics due to the lack of shielding between them, and finally use higher frequencies such as 2.4 GHz band for faster rates.

II. Wireless Sensors

A block diagram for such an RFID enabled sensor is shown in Fig. 1 below [7]. An antenna acts as an interface between the sensor device and the environment. Without loss of generality, the separate blocks in Fig. 1 represent the Integrated Circuit or Microcontroller. This microcontroller in turn is composed of the Digital Logic and MODEM that performs the modulation-demodulation of analog or digital signals with a final goal of producing a signal that can be transmitted easily and decoded to reproduce the original digital data, an **E**lectronically **E**rasable **P**rogrammable **R**ead-**O**nly **M**emory or **EEPROM** block, a non-volatile memory technology similar to that found in computers and other electronic devices that stores small amounts of data that must be saved when power is removed. EEPROM is currently used by RFID Gen2 Protocols. An analog to digital converter (ADC) is responsible for converting the analog data captured by the sensor into digital data that can be used by the microcontroller to be transmitted. In the receiving mode, there is a voltage multiplier that converts the AC low voltage signal into a high voltage DC signal that feeds into the Digital Logic lock as shown in the diagram.

A suggested module of an already existing RFID tag operating at UHF frequencies and that is planned to include sensing capabilities is shown in Fig. 2. High Efficiency Antennas at UHF frequencies are characterized in general by their dimensions which vary from half a wavelength at the operating frequency (such as 15 cm around 900 MHz in one dimension) or by having some monopole, squared or rectangular configurations, which in such cases would be a better candidate to fit the host electronics, power supply, and sensing devices.

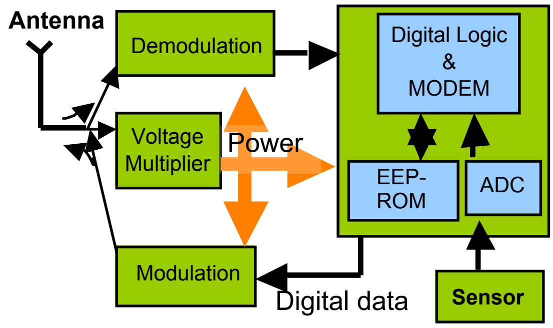

Figure. 1. The components of an RF tag with sensing capability.

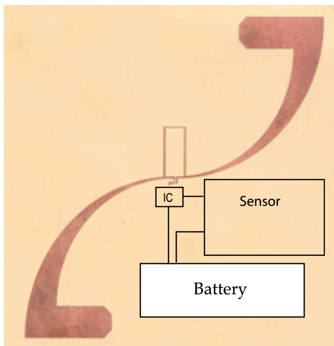

Figure. 2. Suggested outline of integrated RFID antenna with IC, sensor and power supply.

III. Technologies for Low Cost Integrated Sensors

A. Materials: Paper as an Ultra Low Cost Solution for Direct Write Fabrication Methods for Frequencies up to 10GHz

There are many aspects of paper (as a material) that make it an excellent candidate for an extremely low-cost substrate for RF applications and other applications where mass deployment is required such as RFID and wireless sensor networks (WSN) [2]. Paper, an organic-based substrate, is widely available. The high demand and the mass production of paper make it the cheapest material ever made. From a manufacturing point of view, paper is well suited for reel-to-reel processing, thus mass fabricating RFID inlays on paper (to name an example) becomes more feasible. Paper also has low surface profile and, with appropriate coating, it is suitable for fast printing processes such as direct write methodologies instead of the traditional metal etching techniques. A fast process, like inkjet printing, which is discussed in more detail in the next section, can be used efficiently to print electronics on/in paper substrates. Lastly, paper is one of the most environmentally friendly materials and the proposed approach could potentially set the foundation for the first generation of truly "green" RF electronics and modules.

RF characterization of paper becomes a critical step for the qualification of the paper material for a wide range of frequency domain applications. The knowledge of the dielectric properties such as dielectric constant (ε_r) and loss tangent (tanδ) become necessary for the design of any high frequency structure such as RFID antennas on the paper substrate, and more importantly, if it is to be embedded inside the substrate. Precise methods for high-frequency dielectric characterization for this frequency range are Transmission Line and Resonant Techniques. In an extensive literature review, dielectric properties of paper beyond few hundred megahertz were not available.

The properties of the benchmarking paper substrates were studied in the UWB frequency range [8] through the use of the split-post dielectric resonator technique and were performed by the Electromagnetics Division at the National Institute of Standards and Technology (NIST), Boulder, CO, USA. Several cavities covering the band from 1GHz to 10GHz were utilized. Each blank paper sample was cured first in a thermal oven for 2 hours at 120 degrees to mimic the curing process of the printed ink. The results for the extracted relative permittivity of the 10mil thick cured paper are shown in Fig. 3. The measured dielectric loss tangent or tanδ values were bounded between 0.06 and 0.07 for the whole frequency range.

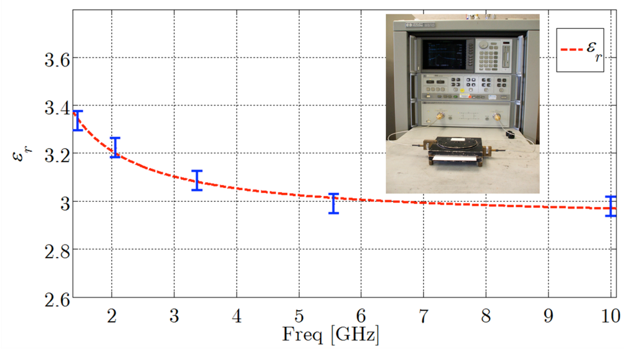

Figure 3. Characterization of paper material through the split ring resonator method.

B. *Inkjet Printing*

Modern inkjet printers operate by propelling tiny droplets of liquid down to several pL. This new technology of inkjet printing utilizing conductive paste or ink may rapidly fabricate prototype circuits without iterations in photolithographic mask design or traditional etching techniques that have been widely used in industry. Printing is completely controlled from the designer's computer and does not require a clean room environment. A droplet's volume is one of the parameters that determine the resolution of the printer, for an example a droplet of 10 pL gives ~ 50μm minimum thickness or gap size of printed traces/lines. In addition to that, the ink material, the substrate, the curing processes as well as the voltage waveform used on the jetting nozzles all play a role in the resolution, accuracy, and success of the inkjet printing.

The cartridge or print-head consists of a Piezo-driven jetting device with an integrated reservoir and heater. A detailed description of the Inkjet printer used in this work is shown in Fig. 4. The inkjet-printing is done in a horizontal bar-by-bar printing using a print-head or cartridge "DMC-11610" which has a nominal drop volume of 10 pL.

Inkjet Printing, unlike etching which is a subtractive method by removing unwanted metal from the substrate surface, jets the single ink droplet from the nozzle to the desired position, and therefore, not creating waste and result in an economical fabrication solution. A microscopic picture is shown in Fig. 5 emphasizing a featured size of 50 μm. Silver nano-particle inks are usually selected in the inkjet-printing process to ensure a good metal conductivity. After the silver nano-particle droplet is driven through the nozzle, a sintering process is found to be necessary to remove excess solvent and to remove material impurities from the depositions. The sintering process also provides the secondary benefit of increasing the bond of the deposition with the paper substrate.

After the printing process takes place, it is essential to cure the prototype in order to increase the conductivity of the silver ink. Curing is simply done by heating the fabricated antenna, so that the printed silver ink nano-particles melt and a good percolation channel is created for electrons to flow. The curing is performed in a high precision industrial oven, at a constant temperature of 100°C for 10 hours. The curing must be performed immediately after the printing, because the silver ink begins to oxidize which may result into permanent poor conductivity and efficiency of the antenna trace. It has to be noted that the maximum temperature that paper substrate can endure is 150°C. The conductivity of the printed ink was studied through the use of the Signatone Four Point Probe (www.signatone.com). To ensure good conductivity, three layers of ink were printed, and then treated in a thermal oven as described earlier. The resulting ink thickness was measured using the Wyko profilometer (www.veeco.com). The resulting thickness was around 3 μm with a consistent measured conductivity in the range $9\text{x}10^6$ [S/m] – $1.1\text{x}10^7$ [S/m]. In addition, DC characterization was performed in order to test the silver epoxy and the integration of SMD devices. Fig. 6 shows a photograph of the test setup highlighting a 1.6Ω DC Resistance measurement by the multimeter for the trace with a 1Ω SMD Resistor assembled in the center of the trace using silver epoxy. This proves that such connections using epoxy can be made with losses that are tolerable. It is recommended to use inkjet printing at lower frequencies for such reasons.

The savings in fabrication/prototyping time that inkjet printing brings to RF/wireless circuits will be critical to the ever changing electronics market of today, verifying its feasibility as an excellent prototyping and mass-production technology for next generation electronics especially in RFID, wireless sensors, handheld wireless devices (e.g.4G/4.5G cell phones), flex circuits, and even in thin-film batteries.

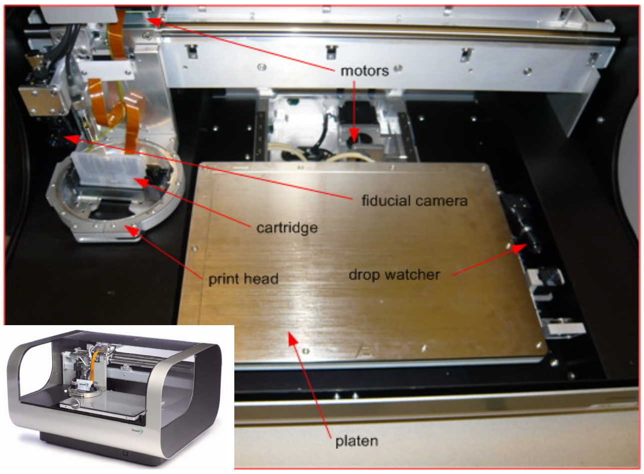

Figure 4. Details of Dimatix Material Printer DMP 2800.

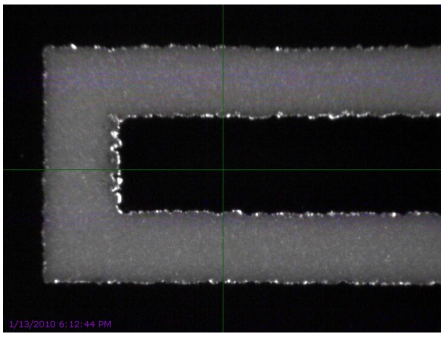

Figure 5. Realized feature size of 50 µm.

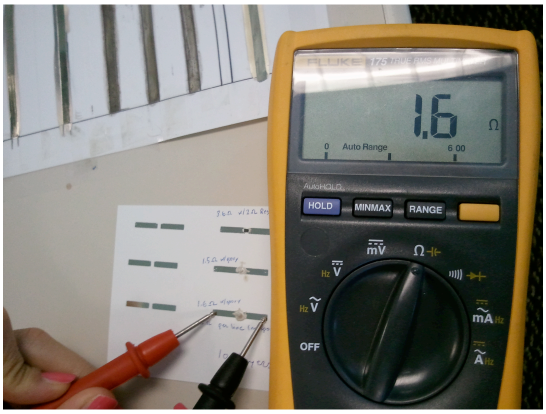

Figure 6. DC characterization for inkjet printed traces with epoxy and SMD 1Ω Resistor.

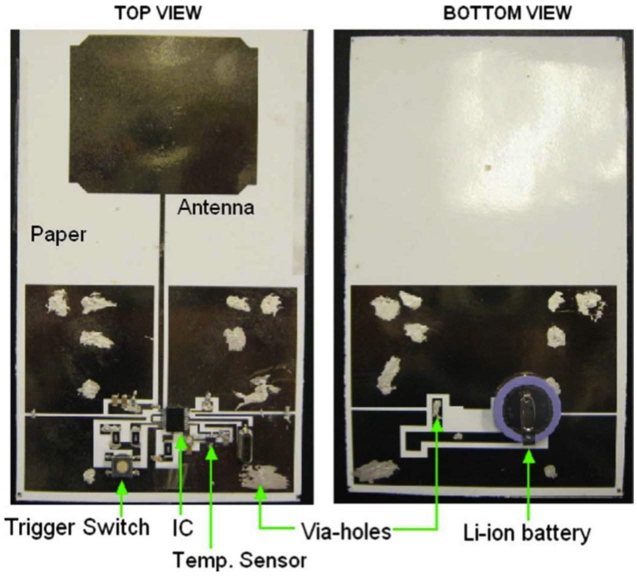

Figure 7. Top (left) and bottom (right) photographs of the UHF RFID-enabled wireless sensor.

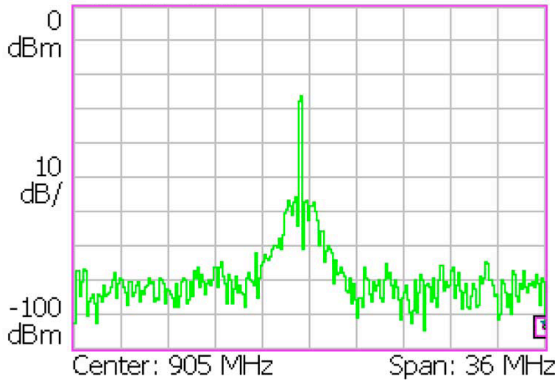

Figure 8. Snapshot of RTSA (Power vs. Frequency) for UHF RFID-enabled wireless sensor module at a distance of 1.83 m.

IV. Examples of Wireless Integrated Sensors

As a proof of concept for the technologies mentioned in III, this section demonstrates three examples: UHF RFID-enabled wireless sensor, a Zigbee wireless module for location finding and sensing applications, and an RF-COA.

A. *UHF RFID-Enabled Wireless Sensor*

As an example for the inkjet printing on paper substrate and the integration of sensors, Fig. 7 shows a UHF RFID-enabled sensor [9,10]. The top layer contains the printed antenna and most of the circuit components for the module. While the bottom layer contained a Li-ion cell and the power supply traces, which were routed to the top layer through drilled vias. Those vias were formed mechanically using a 400-µm microdrill bit manufactured by LPKF A.G., Garbsen, Germany. Fiducial marks printed along the borders were used to ensure that the top and bottom layers of the monopole-based wireless sensor module were aligned properly. The drilled via-holes were then filled using silver epoxy.

The monopole antenna shown has a planar coplanar waveguide (CPW-G)-fed wideband structure with a rectangular radiator to achieve a more compact and wideband design that could be easily printed. It uses its ground planes as a radiating surface, which can also be used to shield any circuitry behind it. This antenna was matched to an impedance of 60.1-j73.51 ohms, which corresponds the Integrated Circuit (IC) impedance to which it is matched. The simulated return loss for the entire structure showed good wideband resonance of about 220 MHz around the design frequency of 904.4 MHz. The maximum directivity obtained was 2.6 dB for both **E** and **H** planes. As a result of the operation of the sensor node, a reading of -26 dBm was obtained by the Real Time Spectrum Analyzer (RTSA) at a distance of 2 m, which shows excellent transmission from this sensor node, and the proof of concept of a 3D-paper based module.

Next, the UHF RFID-enabled sensor module in its SENSING mode was evaluated. The ASK modulated sensor information transmitted out by the module at different temperatures is measured by the RTSA as illustrated in Fig. 9. The transmitted sensor data shows good agreement with the measurements carried out with the digital IR thermometer, which has an accuracy of 2.5 C.

This section illustrated the success of the marriage of the two low-cost strategies: paper substrate and inkjet-printing. In addition the assembly of the components utilized silver epoxy, and that was characterized and described in III. B. Next section talks about a system level solution for modules that require a higher level of functionality.

B. Zigbee Wireless Module for Location Finding and Sensing Applications

Fig. 10 shows the suggested outline for the planar zigbee module [3]. A differentially fed Antenna is interfaced to the chip through one of its 56 pins on the top layer as depicted in Fig. 11 and Fig. 12. Jennic JN5148 wireless microcontrollers [11] is proposed in this design due to its ultra low power consumption and low cost for wireless sensor networking applications based on the IEEE802.15.4 standard. IEEE802.15.4 standards define (in the 2.4 GHz band) 16 ZigBee channels, with each channel requiring 5 MHz of bandwidth, and so an 80 MHz operational bandwidth is required for this Antenna. Fig. 13 shows the S_{11} plot for the antenna on 10 mil (~250 um) thick paper substrate covering well above the required bandwidth as described by the -10 dB line. It is to be noted that the data shown in Fig. 13 takes into consideration the simulation of the entire module as shown in Fig. 11, which shows the integrated antenna and the circuit layout used for signal routing plus their ground (DC ground). Furthermore, the simulation assumes a matching network consisting of an LC circuit in order to create a 50 Ohm match. Fig. 14 shows the directivity of the antenna at 2.4 GHz indicating good coverage for location finding applications.

The module was inkjet printed on paper substrate. This required very precise and detailed settings as described in III. B. The smallest dimension that was inkjet printed is ~125 um and pertains to the gaps/traces of the QFN package wireless zigbee microcontroller.

This wireless module is also in compliant with Time of Flight ranging engine and with easy programming is appropriate for indoor continuous monitoring or location finding. In addition, this module also supports the integration of on-board sensors, which can be utilized for several sensing applications.

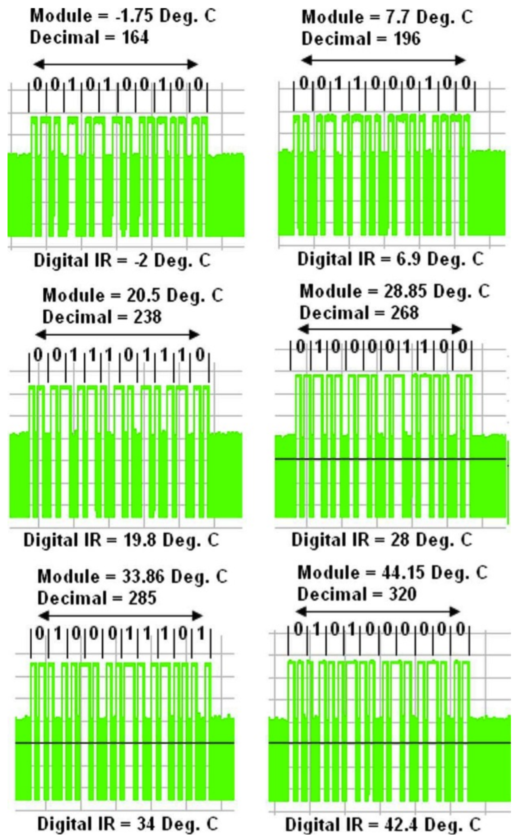

Figure 9. ASK modulated temperature sensor data of monopole-based module captured by the RTSA at room temperature (power versus time). Module: sensed temperature transmitted from module and captured by RTSA. Digital IR: temperature measured by the digital IR thermometer.

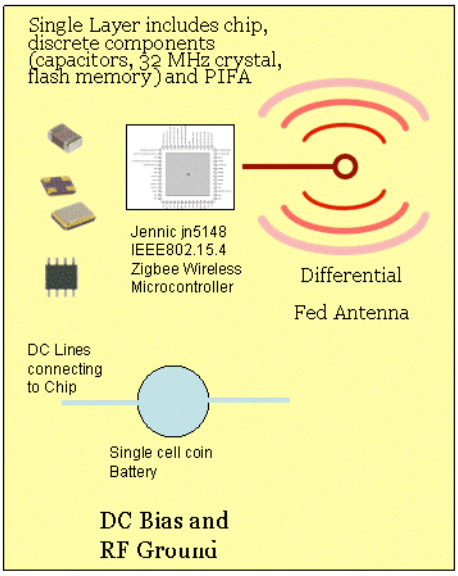

Figure 10. Outline of components for the Zigbee wireless module.

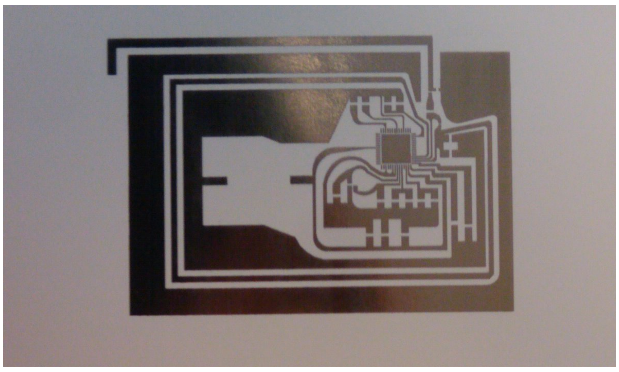

Figure 11. Photograph of the inkjet printed wireless module on paper substrate.

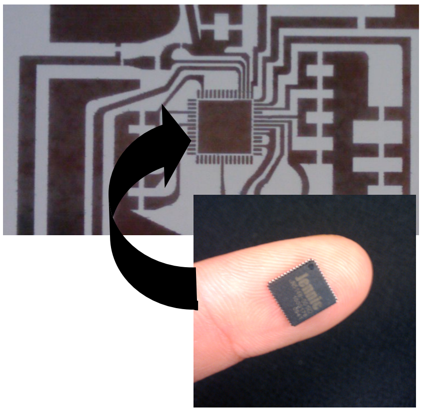

Figure 12. Photograph of the inkjet printed wireless module on paper substrate.

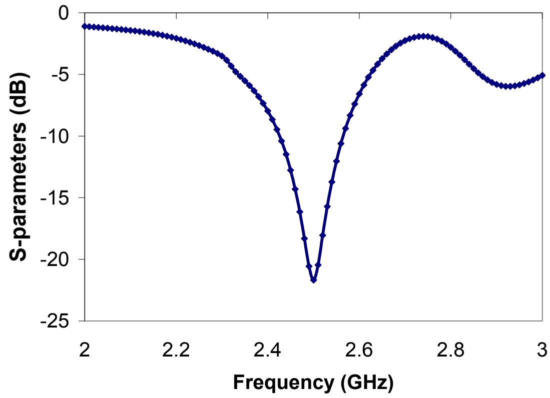

Figure 13. S_{11} for the antenna plus module.

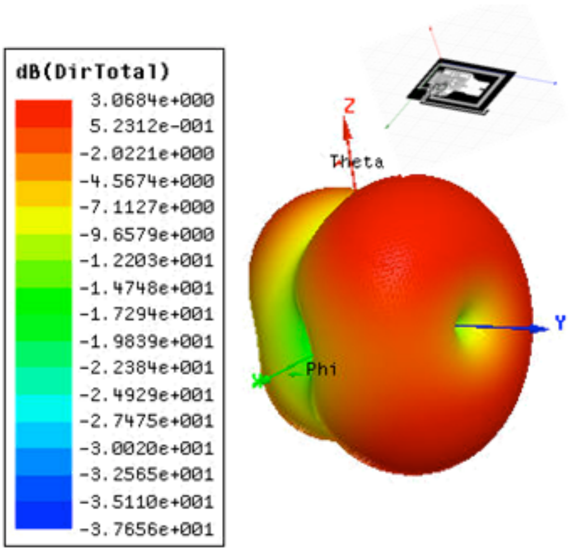

Figure 14. Directivity of the antenna simulated at 2.4 GHz.

C. RF Fingerprinting Physical Objects for Anti-counterfeiting Applications

The inadequacy of the traditional, digitally encoded RFID tags in combating counterfeiting, an illegal trade action where the seller fools the buyer into believing that the merchandise is authentic, has prompted researchers to investigate new hardware-enabled technologies that can complement the remote identification functionality of typical RFIDs in an effective and very low cost way. A complete such RFID anti-counterfeiting solution is the RFID-CoA [12]; a system that aims to render typical RFID tags physically unique and hard to near-exactly replicate by complementing them with random 3D scattering structures, which serve as certificates of authenticity (CoA). Fine aspects of this system include a completely passive operation, interoperability with any RFID tag technology of any frequency band without requiring any RFID reader software modifications and a cost comparable to that of typical, passive RFID tags.

The fundamental idea is to complement an RFID tag with an inexpensive physical object that behaves as a certificate of authenticity in the near electromagnetic field so that this "super-tag" is not only digitally, but also physically unique and hard to near-exactly replicate. Each RFID-CoA instance is associated with an object, whose authenticity the issuer wants to vouch. It can be created as a random constellation of small, randomly 3-D-shaped conductive and/or dielectric objects that exhibits a distinct behavior in its near field when exposed to RF waves over a particular RF spectrum. This enables, on one hand, the extraction of the data about the product in the far field and, on the other hand, the verification of its authenticity within its near-field with a virtually impossible false alarm. For the first generation of physical RFID-CoA objects, we relied upon inkjet printing technique (on paper substrate) as a means of a very fast, low-cost, and in-house process. The final 3-D structure, shown in Fig. 15b can be created by tightly stacking multiple 2-D CoAs, shown in Fig. 15a, one on top of each other.

The unique near-field response, or "fingerprint", of the certificate instances is extracted as a set of S_{21} curves by our re ader prototype, shown in Fig. 16, in the 5 to 6 GHz frequency range. In particular, the extraction of the unique RF fingerprint of a certificate is done as follows. RF power is radiated from a particular element of the antenna array, then it is scattered and reflected by the conductive material of the instance placed about 2 mm away from the array and, finally, it is received by another antenna element. Each one of the S_{21} curves of the RF fingerprint corresponds to a single coupling of a pair of antenna elements that is selected by digitally controlling RF switches. A single such element of the 5 by 5 antenna array is a folded microstrip patch antenna with a resonant frequency of 5.15 GHz. During the readout, it is ensured that the placement of the RFID-CoA instance is fixed and geometrically unique, using short plastic poles, shown in the upper left corner of Fig. 16, the relative position of which is non-symmetrical on the array's plane.

As a means to verify the reader's performance in extracting the near-field frequency response of the RFID-CoA physical structures reliably and with an as highest entropy as possible, Lakafosis et al. [12] have conducted a number of tests, namely, uniqueness among different instances, repeatability robustness for same instances, variation in conductive material density of the certificate, and 2-D to 3-D projection attacks. The results of this performance analysis demonstrate that uniquely authenticated "super" RFID tags, in the form of badges of a small dielectric profile directly affixed onto objects or in the form of carefully attached product tags, can prove a valuable tool against the ever-increasing action of counterfeiters.

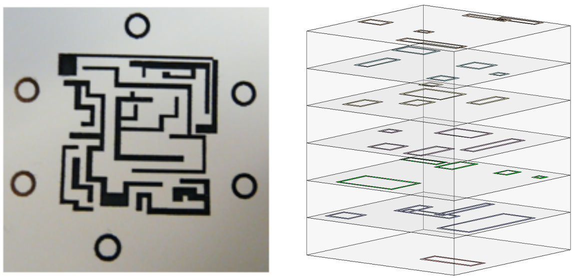

Figure 15. a) Inkjet-printed, single layer NF-CoA of rhombic loops on paper substrate. b) 3D-stacked NF-CoAs of rhombic loops.

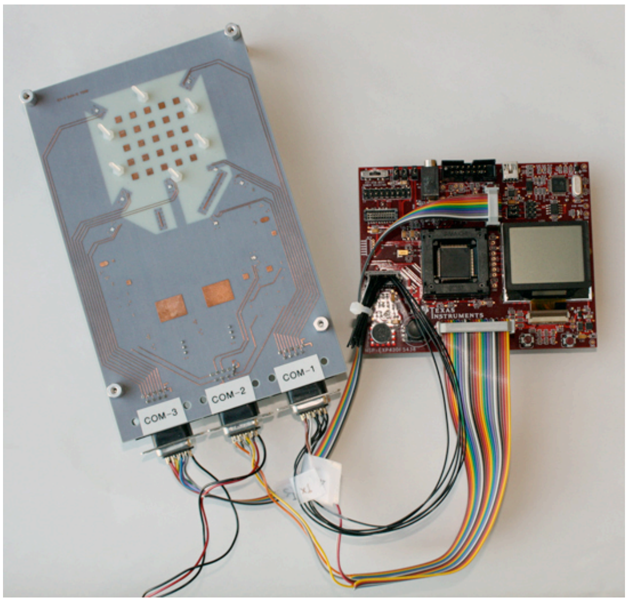

Figure 16. The Super High Frequency RF plane (left) and the Digital Control plane (right) of the RFID-CoA reader.

V. CONCLUSIONS/FUTURE WORK

The evolution towards low-cost, integrated RFID-enabled wireless sensors and enhanced authentication wireless electronics using UHF and microwave frequencies has been demonstrated. The examples given utilize inkjet-printed technology on flexible paper substrates as well as the integration (assembly) of sensors, wireless modules, discrete components and power sources as a solution for low-cost, light-weight, and environmental friendly method for RFID-enabled sensors and WSNs. Future work includes the completion of the Zigbee wireless module and which is planned to be presented in the final manuscript and at the conference.

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