

# **Inkjet-Printed Paper/Polymer-Based RFID and Wireless Sensor Nodes: The Final Step to Bridge Cognitive Intelligence, Nanotechnology and RF?**

*Manos M. Tentzeris, Amin Rida, Anya Traille, Hoseon Lee, Vasilis Lakafosis and Rushi Vyas*

School of ECE, Georgia Tech, Atlanta, GA 30332-250, USA

## **Abstract**

In this talk, inkjet-printed flexible antennas, RF electronics and sensors fabricated on paper and other polymer (e.g.LCP)substrates are introduced as a system-level solution for ultra-low-cost mass production of UHF Radio Frequency Identification (RFID) Tags and Wireless Sensor Nodes (WSN) in an approach that could be easily extended to other microwave and wireless applications. The talk will cover examples from UHF up to the millimeter-wave frequency ranges. A compact inkjet-printed UHF "passive-RFID" antenna using the classic T-match approach and designed to match IC's complex impedance, is presented as a the first demonstrating prototype for this technology. Then, Prof. Tentzeris will briefly touch up the state-of-the-art area of fully-integrated wireless sensor modules on paper or flexible LCP and show the first ever 2D sensor integration with an RFID tag module on paper, as well as numerous 3D multilayer paper-based and LCP-based RF/microwave structures, that could potentially set the foundation for the truly convergent wireless sensor ad-hoc networks of the future with enhanced cognitive intelligence, anti-counterfeiting capabilities and "rugged" packaging. We will discuss issues concerning the power sources of "near-perpetual" RF modules, including flexible miniaturized batteries as well as power-scavenging approaches involving thermal, EM, vibration and solar energy forms. The final step of the presentation will involve examples from wearable (e.g. biomonitors) antennas and RF modules, as well as the first examples of the integration of inkjet-printed nanotechnology-based (e.g.CNT) sensors on paper and organic substrates. It has to be noted that the talk will review and present challenges for inkjet-printed organic active and nonlinear devices as well as future directions in the area of environmentally-friendly ("green") RF electronics and "smart-skin" conformal sensors

## **1.Introduction**

RFID is an emerging and disruptive compact wireless technology for the identification of objects, and is considered as an eminent candidate for the realization of completely ubiquitous ad-hoc wireless networks. This technology has several benefits over the conventional ways of identification, such as faster data transfer, higher read range, the ability of RFID tags to be embedded within objects, the ability to read large amount of tags simultaneously and no requirements of line of sight [1]. Already, a large list of applications is currently utilizing RFIDs including supply chain and logistics, pharmaceutical e-pedigree, access control, parcel and document tracking, real-time location systems, automatic payment, vehicle identification and livestock tracking.

Compared with the lower-frequency (LF/HF) tags already suffering from limited read range (1-2 feet), UHF RFID tags see the widest use due to their higher read range (over 20 feet) and higher data transfer rate. The major challenges that currently hinder RFID practical implementation are: (1) cost, that has to be extremely low, especially for the RFID tags, in order to allow for mass-production amounts, (2) reliability, especially concerning tags/reader hardware and middleware, (3) regulatory situation, meaning that tags have to abide to a certain global regulatory set of requirements, such as Gen2 protocols defined by the EPC Global regulatory unit and (4) environmentally-friendly conformal materials, that could allow for the implementation of "green" and "rugged" RFID solutions. Recently, there have been research efforts reporting deployment of RFIDs and sensors on glass, flexible and polymer substrates, mostly utilizing screen-printing metallization mechanisms, but still the cost and the complexity of these modules is far from that required for a large-scale implementation of this technology, especially for sensing and cognitive intelligence applications.

## **2.PAPER: The cheapest substrate + INKJET PRINTING: The cheapest fabrication**

The first "green" ultra-low-cost organic substrate examined, on which the RFID tag circuitry and antenna were printed, is paper. There are many aspects of paper that make it an excellent candidate for an extremely low-cost substrate for RFID and other RF applications. First of all, the high demand and the mass production of paper make it the cheapest and most available 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 becomes more feasible. Furthermore, paper has low surface profile and, with appropriate coating, is suitable for fast printing processes such as direct write methodologies instead of the traditional metal etching techniques. As described in section III, a fast process, like inkjet printing, can be used efficiently to print electronics on/in paper substrates. In addition, paper can be made hydrophobic, and/or fire-retardant by adding certain textiles to it, which easily resolve any moisture absorbing issues that fiber-based materials suffer from. Last, but not least, paper is one of the most environmentally-friendly materials. Its high biodegradability, with respect to other ceramic substrates such as FR-4, allows it to turn into organic matter in land-fills in only a few months.

However, due to the wide availability of different types of paper varying in density, coating, thickness, texture, and implicitly, dielectric properties, dielectric RF characterization of paper substrates becomes an essential step before any RF “on-paper” designs. The knowledge of the dielectric properties such as dielectric constant ( $\epsilon_r$ ) and loss tangent ( $\tan\delta$ ) 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 include microstrip ring resonators, parallel plate resonators, and cavity resonators. The electrical characterization of paper has already been performed in [2] and results have shown the feasibility of the use of paper in the UHF and RF frequencies.

Unlike etching which is a subtractive method by removing unwanted metal from the substrate surface, inkjet printing jets the single ink droplet from the nozzle to the desired position, therefore, no waste is created, resulting in an economical fabrication solution. After the silver nano-particle droplet is driven through the nozzle, it is necessary to follow by the sintering process in order to remove excess solvent and to remove material impurities from the depositions. Another benefit provided by the sintering process is the increase in the bond of the deposition with the paper substrate. The conductivity of the conductive ink varies from  $0.4\sim 2.5 \times 10^7$  Siemens/m depending on the curing temperature and duration time. At lower temperature, larger gaps exist between the particles, resulting in a poor connection. When the temperature is increased, the particles begin to expand and gaps start to diminish. That guarantees a virtually continuous metal conductor, providing a good percolation channel for the conduction electrons to flow.

In the battle against counterfeiting, which accounts for between 7-8% of the world trade, traditional RFIDs with encoded digital information cannot be relied upon since they can easily be replicated. However, the proposed solution [3] that aims to address this problem is to complement an RFID with an inexpensive physical object that behaves as a certificate of authenticity (RF-CoA) in the electromagnetic field so that this tag is not only digitally but also physically unique and hard to near-exactly replicate.

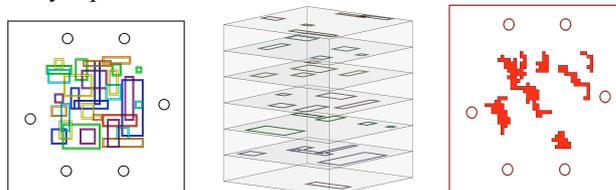


Fig. 1. a) Single Layer COA of rhombic loops. b) 3D-stacked RF-COAs of rhombic loops. c) RF-CoA as a random trajectory of pixels.

### 3. RFID-Enabled Sensor on Paper

The presented RFID-enabled wireless sensor module prototype using a dipole antenna was printed on a 2-D (single layer) photo-paper module [4]. The overall dimensions of the structure are: 9.5 x 6 cm and is shown in Fig. 2. The fabrication and assembly process is outlined in this section. In particular, the antenna and the circuit layout were printed and cured on paper using silver ink and the complete wireless sensor system comprising the TSSOP packaged integrated circuit (IC), including the MCU and the transmitter, its discrete passive components including a crystal oscillator, the TC1047 temperature sensor, and a Li-ion cell for “stand-alone” autonomous operation were assembled on it. The cost is below \$1, the range is above 300m and the temperature accuracy is better than 0.2C.

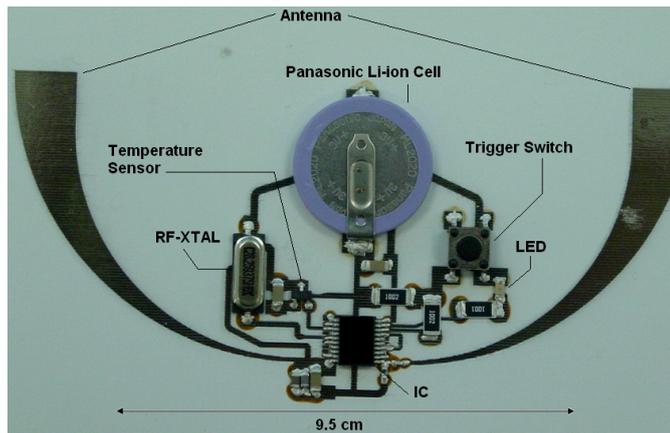


Fig.2 RFID-enabled wireless sensor transmitter using inkjet-printing on paper

To ensure maximum conductivity and antenna efficiency, the entire circuit was printed over with 12 layers of silver ink resulting in a conductor thickness of 12 microns. Next, the wireless sensor modules were assembled on the printed circuit. The assembly process on silver pads proved to be the most challenging aspect in the design process. Given the low temperature tolerance of paper, the electronic components used, and the relative weaker adhesion of printed silver pads on paper, soldering had to be ruled out. Multiple assembly methods were experimented in order to find a reliable alternative for mounting components, which include silver epoxies and conductive tapes. The entire assembly process had to be carried out in a multi-step process. This was because the conductivity of the silver epoxy had a direct correlation to its curing time and temperature, which contradicted with the limited temperature tolerance of the components used in the wireless transmitter. The impact of this module is by its ease in extending to a 3D multilayer paper-on-paper RFID/Sensor module by laminating photo-paper sheets. This is expected to reduce the cost of the sensor nodes significantly and eventually make the ubiquitous computing network a possible reality with a convergent ability to communicate, sense, and even process information.

#### 4.Integration of Power Scavenging

In addition to making RFID tags more environmentally friendlier materially, a separate effort to reduce its carbon foot print underway by eliminating batteries and encompassing power scavenging techniques from the environment is also presented. As a first step a battery-less solar powered tag has been developed that uses super capacitor along with a smart firmware and hardware controlled Power Management Unit (PMU) to power up an RFID tag has been developed as shown in fig 3. Unlike other solar powered devices the presented tag uses the solar power intermittently to charge the capacitor that when discharges causes the tag to wake up and communicate. This allows the system to use a much smaller solar cell array than existing systems that use solar cells to continuously power wireless devices. The solar powered tag communicates asynchronously with wireless Mica Mote receivers made by Crossbow that consume much less overall power then conventional RFID readers while syncing more amount of data at higher range. A working prototype of the solar powered tag is shown in fig 4.

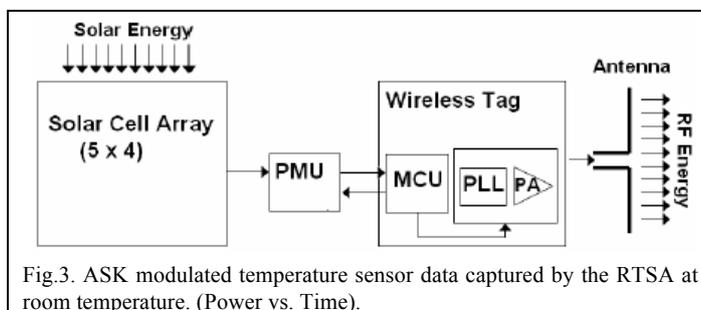


Fig.3. ASK modulated temperature sensor data captured by the RTSA at room temperature. (Power vs. Time).



Fig.4. ASK modulated temperature sensor data captured by the RTSA at room temperature. (Power vs. Time).

The asynchronous data bursts sent out by the solar powered tag as the super capacitor tank that's filled up with solar harnessed energy discharges as measured wirelessly by the real time spectrum analyzer is shown in figure 5 below.

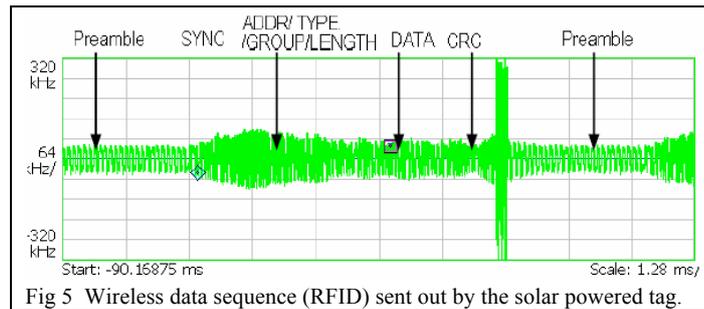


Fig 5 Wireless data sequence (RFID) sent out by the solar powered tag.

## 5. Conclusions

In this paper, inkjet-printed flexible antennas, RF electronics and sensors fabricated on paper and other polymer (e.g.LCP) substrates are introduced as a system-level solution for ultra-low-cost mass production of UHF Radio Frequency Identification (RFID) Tags and Wireless Sensor Nodes (WSN) in an approach that could be easily extended to other microwave and wireless applications. In addition, the authors briefly touch up the state-of-the-art area of fully-integrated wireless sensor modules on paper and show the first ever 2D sensor integration with an RFID tag module on paper, as well as the possibility of a 3D multilayer paper-based RF/microwave structures, that could potentially set the foundation for the truly convergent wireless sensor ad-hoc networks of the future.

## 6. Acknowledgments

The authors would like to acknowledge the support of NSF, NEDO, ODPP and IFC-SRC.

## 7. References

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