Inkjet-printed “Zero-Power” Wireless Sensor and Power Management Nodes for IoT and “Smart Skin” Applications

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Abstract

Nanotechnology and inkjet-printed flexible electronics, sensor and power management (PMU) nodes fabricated on paper, plastic and other polymer substrates are introduced as a sustainable ultra-low-cost solution for the first paradigms of Internet of Things (IoT), “Smart Skins” and “Zero-Power” applications. The paper will cover examples from the state-of-the-art of fully integrated wireless sensor modules on paper or flexible polymers. We will demonstrate numerous 3D multilayer paper-based and LCP-based RF/Microwave Structures that include embedded energy harvesters and PMU’s, that could potentially set the foundation for the truly convergent batteryless wireless Internet-of-Things networks of the future with enhanced cognitive intelligence and “zero-power” operability through ambient energy harvesting. Examples from wearable (e.g.biomonitoring) antennas and RF modules will be reported, as well as the first integration of inkjet-printed nanotechnology-based (e.g.CNT, graphene) sensors on paper and organic substrates. The talk will close with a discussion about the challenges for inkjet-printed high-complexity modules as future directions in the area of environmentally-friendly (“green”) RF electronics and “smart house” conformal IoT topologies.

Keywords—Inkjet-printed sensors, inkjet-printed electronics, paper substrate, RFID-enabled sensor, autonomous wireless modules, energy harvesting, zero-power, Internet of Things, ambient energy harvesting

1. Introduction

The late combination of sensor networks and RFID technologies have spurred numerous applications from logistics and Internet-of-Things to monitoring and security, all of which require a capability for large volume circuit production as well as the use of low cost fabrication methods on environmentally-friendly and low cost, flexible substrates, while energy autonomy is critical for operability in rugged environments and materials [1]. As a result, implementations of flexible passive microwave circuit components such as antennas, inductors, and transformers utilizing substrates such as paper, polyethylene terephthalate (PET) and textiles are receiving significant attention in the literature. Inkjet printing fabrication process, permits large-volume production and by allowing a resolution below of approximately 50um, has emerged as a popular alternative to traditional circuit board fabrication techniques, such as chemical etching and milling, finding increasing applicability in the electronics and sensors industries [1]-[3]. The possibility of the inkjet printing of a complete System-On-Substrate (SoS), based on multilayer flexible substrate modules and inkjet deposition of active devices remains a challenge, especially when it comes to operating at microwave frequencies. While inkjet printing of semiconducting polymers to develop organic thin film transistors (OTFTs) is still far from operation in the GHz frequency range, integration of off-the-shelf active electronic components onto flexible substrates provides an exciting alternative. The realization and integration design of active topologies, circuits and sensors on flexible substrates, combined with passive interconnects, transmission lines and antennas presents a significant challenge with few notable examples in the literature [1]-[4] and presents the object of this work. This paper presents state-of-the-art results of inkjet-printed wireless sensors on paper verifying their great potential in terms of environmentally friendly and sustainable technology.

2. Inkjet Printing and Paper Substrate

Inkjet printing technology has a lot of advantages in sensors especially for the agricultural applications. First of all, inkjet printing technology is an environmentally friendly and cost effective method due to the fact that it does not require the use of any hazardous chemicals to wash away unwanted metals on the substrate surface. It drops nano-particle ink on the desired positions so that there are no by-products because it is an additive fabrication method. Fast fabrication and ease of mass produce also help to

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lower the cost of the inkjet-printed electronics. The conductivity of the inkjet-printed silver nano-particle is typically above 1.1×10^{7} S/m which is high enough to utilize in microwave area. Electronics can be printed on virtually every substrate through surface functionalization including paper, plastics, glass, silicon wafers, wood and fabrics.

3. Inkjet-Printed Wireless Sensors

3.1 RFID-enabled Sensors

RFID-enabled sensors feature numrous advantages over conventional sensor system in terms of cost and implementation. Usually, the cost of RFID tag is very cheap and the system is simple (reader and sensor tag). Therefore it is possible to realize the RFID-enabled sensor system in low cost and over the vast agricultural field. In addition, RFID standards are compatible with existing wireless sensor networks (WSN) which results in ease of implementation [5]. In [6], an inkjet-printed RFID enabled sensor for touching and water level detection was introduced. It consists of two identical RFID tag for UHF band (915 MHz) but a sensing component is integrated with one of the RFID tag. The two tags return their unique IDs at the same frequency when they are illuminated by a reader because their resonant frequencies are the same. However the resonant frequency of the antenna with a sensor is shifted to the low frequency when the sensor is loaded by human finger or water. Using an one tag as a reference, the presence of the sensing target can be easily detected. In the same way, water level can be detected because the capacitance of the sensor (Fig 1) affects the resonant frequency of the RFID-enabled sensor. The meta-material inspired resonator cell is integrated to the tag in order to suppress the cross talk of the two tags. The sensor is a meander line which has self-resonant frequency around 915 MHz. Once a material with high capacitance or inductance meet the meandered line, the capacitance of the sensor changes which results in shifting of the resonant frequency of the tag.

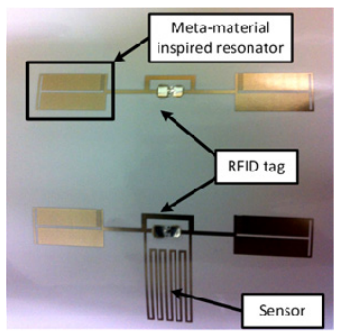


Fig.1 Inkjet-Printed Capacitive Sensor [6]

3.2 Inkjet-Printed RFID-Enabled Battery-Operated Wireless Temperature Modules

It is well known that one of the major packaging challenges of RF/Wireless sensors is their efficient and “rugged” integration with various power sources. In this section, various wireless delivery platforms to convey the sensed data are presented. Power considerations play an important role for logistical and environmental reasons. Increasing the operating lifetime and wireless range of such sensors require careful co-design of the wireless front end, including the antenna, embedded technology and its power interface. In this section, the authors present an active paper-based RFID tag for wireless temperature sensor platforms utilizing both battery and energy harvesting techniques to carry out sensing function over long ranges and lifespan. To investigate the feasibility of paper as a high frequency substrate for battery powered active RFID application, a microcontroller enabled wireless sensor module was realized on a photo-paper-based substrate. The system-level diagram of this wireless transmitter is shown in Fig. 2 below [3]. The microcontroller unit in the system samples the output of an analog sensor (in this case a temperature sensor), and encodes its digital form with the help of an integrated analog to digital converter. As a final step the MCU modulates the power amplifier (PA) in the integrated transmitter module in the same sequence as the bit encoded digital sensor data, thereby transmitting an Amplitude Shift Key (ASK) modulated signal out from the antenna. The transmission frequency of 904.4 MHz was generated using a crystal oscillator tied to the input of the Phase Locked Loop (PLL) unit of the transmitter. The data transmission was to be carried out at the unlicensed UHF frequencies around 900 MHz. In order to maximize the range of the wireless sensor, the integrated PA was characterized using a mechanical load pull system in order to determine its optimum impedance at which the longest possible range for a fixed battery powered supply can be achieved.

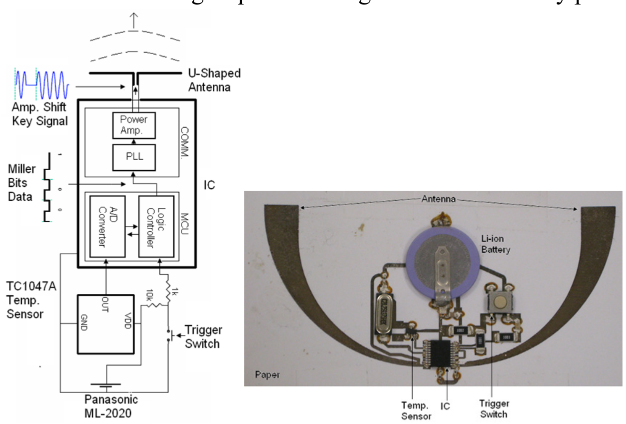


Fig. 2. Paper based Temperature Wireless Sensor Module.

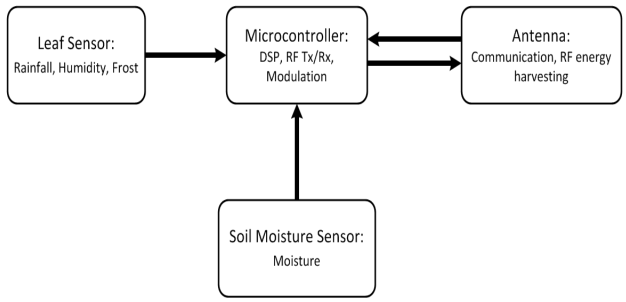
This optimum impedance looking out of the PA was determined at 3 different frequencies within the RFID bandwidth for the US and Europe. The center frequency impedance of about 60-j74 ohms was used to conjugately match the antenna to ensure maximum power transfer. A half wavelength dipole was chosen as the antenna structure for the wireless sensor module due to its radiation resistance of 75 ohms, which is close to the real part of the optimum load impedance (ZL-opt) as seen looking out from the PA at 904.4 MHz. A 10 pL cartridge was used to print the larger areas on the antenna and the RF ground planes/traces in the circuit layout to further increase conductivity. This was done to minimize the gap between adjacently sprayed silver particles enabling a larger overlap during the annealing process and ensuring better conductivity of the printed structure as shown previously to its maximum achievable range (between $1.4\sim2.5\times10^{7}$ S/m). The discrete IC components were mounted on the inkjet printed circuit layout and the complete device is shown in Fig. 14. To evaluate its performance, wireless link measurements were carried out using a Tektronics RSA 30408A real time spectrum analyzer (RTSA) connected to a UHF RFID reader antenna as an RFID reader. A measured wireless power of -48.1 dBm was obtained at a distance of 4.26 meters, which would yield a maximum range of 142 and 175 meters with a conventional RFID receiver, depending on their relative location. The transmitted sensor data shows good agreement with the measurements carried out with the digital infrared thermometer which has an accuracy of ±0.5 C; thereby providing proof of the feasibility of applying inkjet printing technology towards RF based sensing platforms in the UHF range.

3.3 Inkjet-Printed Agricultural Wireless Sensors

Recently, a low cost inkjet-printed sensor platform for agricultural application was proposed in [7]. The proposed sensor platform optimized to detect humidity, water contents in the soil and rain fall because the irrigation is one of the most important factor in recent agriculture. Its system level block diagram is shown in Fig.3. It is consists of leaf sensor, soil moisture sensor, microcontroller and antenna. The capacitance of the leaf sensor and soil moisture sensor varies depending on the humidity and water contents of the soil or near environment of the sensor platform. The microcontroller can detect the capacitance variation of the leaf sensor as well as the soil moisture sensor. It processes the collected data from the sensor, and broadcasts the information through the antenna. The antenna and microcontroller also can be utilized to collect ambient power in order to reduce the battery usage or power up the microcontroller. Unlike the conventional sensors, whole passive components are inkjet printed on environmentally friendly paper substrate. Plus, dense monitoring of soil moisture and detect rainfall over the vast agricultural field is possible due to low fabrication cost. The soil moisture sensor is buried in the ground to detect surface soil moisture and the leaf sensor, the microcontroller and the antenna are exposed to outdoor. The exposed components can be chemically coated such as silicon and parylene in order to extend the lifetime the sensor platform.

4. Conclusions

This paper has presented the dramatic impact of additive manufacturing techniques, such as inkjet printing, as well as of ambient energy harvesting to the realization of scalable low-cost “zero-power” IoT topologies. Various 2D and 3D integrated inkjet-printed wireless sensor and power management nodes have been discussed in terms of rugedness, readability, power autonomy and flexibility in a variety of conformal substrates, such as paper, organics and plastics. The presented topologies could potentially set the foundation for the truly convergent batteryless wireless Internet-of-Things networks of the future with enhanced cognitive intelligence and truly autonomous and eco-friendly operability.



(a)

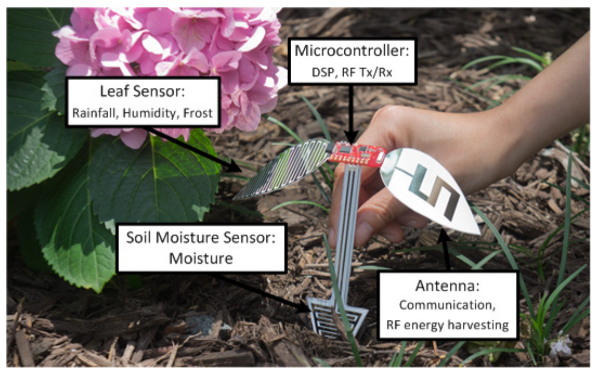


Fig 3. Inkjet-printed sensor platform for agriculture application: (a) block diagram, (b) proposed design [7].

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