Towards a Smart Wireless Integrated Module (SWIM) on Flexible Organic Substrates Using Inkjet Printing Technology for Wireless Sensor Networks

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ABSTRACT: Wireless sensor networks (WSNs) have potential military, industrial, biomedical, environmental, and residential applications. However, implementing sensor networks and realizing their potential faces various challenges. Sensors nodes should be small in size, ultra-low-power, and WSNs should be comprised of large quantities of sensor nodes [1][2]. These challenges emphasize the need for low-cost and eco-friendly substrates suitable for mass production of wireless sensor nodes. Organic substrates is one of the leading solutions to realize ultra-low cost and eco-friendly sensor networks [3]. This paper presents the first IEEE 802.14.4 and ZigBee complaint wireless sensor node on organic substrates. The wireless node is a System-on-Package (SoP) solution operating at 2.4GHz with a printed Planar Inverted-F Antenna (PIFA) on organic substrates using inkjet printing technology. A prototype is realized on FR-4 substrate and used to compare traditional manufacturing techniques with an inkjet-printing solution on paper, which is promising in the large scale manufacturing of ultra-low-cost eco-friendly “green” wireless sensor networks.

INTRODUCTION

Realizing the potential applications of WSNs requires sophisticated and efficient communication protocols, low-power consumption, and low-cost [1][2]. Furtheremore, sensors nodes should be small and deployed in large quantities [2], which emphasizes the need for low-cost and eco-friendly substrates suitable for mass production. Organic substrates use is one of the leading candidates for ultra-low-cost, small, and eco-friendly packaging of Radio Frequency (RF) devices [3]. Among some of the most recent developments, wireless System-on-Package (SoP) solutions have been presented by embedding chip components in organic substrates [4]; Ultra Wide Band (UWB) modules with antennas using organic substrates have been designed [5]; wireless transmitters using embedded passives on organic substrates operating at 27MHz have been realized [6]; and techniques for packaging of miniature biomedical sensors on organic substrates have been presented [7].

Paper is the cheapest and most widely used organic substrate in the world; additionally, paper is recyclable and made of renewable raw materials [8] which offers an environmental friendly solution. Various papers have been published in the area of printed electronics, with inkjet printing characterization results offering promising RF characteristics [3]; consequently, sensor-enabled RFID tags on paper that communicate with WSNs have been already demonstrated with a data transmission frequency of 904.4 MHz [3][9]. Inkjet-printing is a growing technology of interest that transfers the circuit design pattern directly onto the substrate via silver nanoparticles without material waste or traditional printed circuit board (PCB) etching techniques, which in turn offers an economical manufacturing technique [3].

This paper presents the design of a Smart Wireless Integrated Module (SWIM), the first IEEE 802.14.4 and ZigBee compliant wireless sensor node on paper using inkjet printing technology. Smart because when paper is used as an active material in sensors and actuators, it is called “smart paper” [8]. Although vias on organic substrates such as liquid crystal polymer (LCP) have been already presented [10], a dual-layer design with no vias or traces on the bottom layer that can be efficiently printed on paper is presented. First, we demonstrate a prototype which is realized and tested on FR-4 substrate with a swivel antenna to compare traditional manufacturing methods and antennas with inkjet printing on paper, and to assure correct functionality of the wireless module. Then, we migrate the FR-4 module to paper-based design with an entirely printed Planar Inverted-F Antenna (PIFA). The final design of the paper module with the printed antenna is described, and finite element HFSS simulations of the RF parameters of the antenna are presented.

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SYSTEM LEVEL DESIGN

The presented SWIM is a SoP wireless sensor node solution operating at 2.4GHz with low-power consumption, in-system programing, and a printed PIFA antenna. As it can be noted in Fig. 1, a System-on-Chip SoC solution was chosen to implement the module. The CC2431 is a SoC tailored for IEEE 802.14.4 and ZigBee applications. IEEE 802.14.4 is a standard defined for WSNs focusing on low-power operation and applications which do not require high-rate communication. ZigBee is built upon IEEE 802.15.4 and is suited for sensor and control applications focusing on low-cost and low-power design of both star and mesh network topologies [11]. The SoC solution features an 8051 Microcontroller Unit (MCU) with a 128KB in-system programmable flash and 8 KB RAM, an eight-input 12-bit ADC, a radio based on the CC2420 RF transceiver, and an analog temperature sensor among other features.

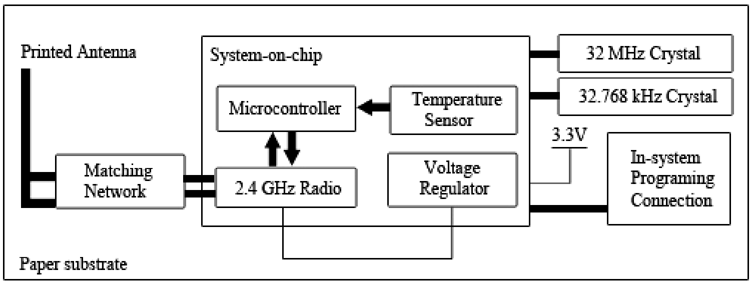


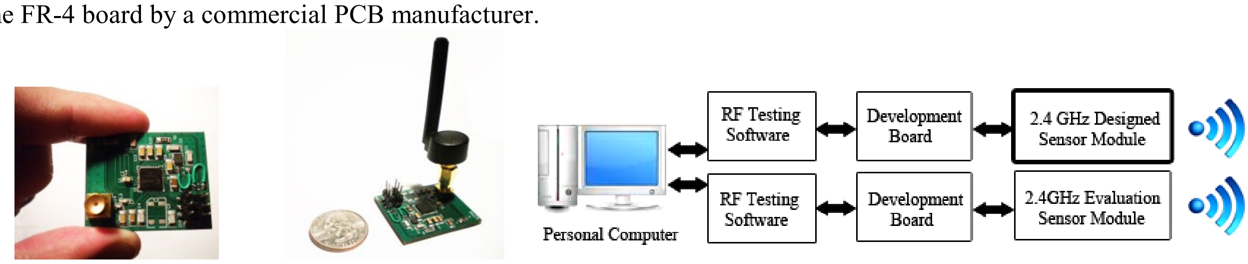
Fig. 1 System level design of wireless sensor module on organic Substrate

The SoP is powered by an external 3.3V power supply, and the SoC voltage regulator is decoupled with external components to provide a regulated 1.8V power supply to the RF transceiver. The RF module uses an off-chip resistor as a precision passive component for current reference generation. The on-chip analog temperature sensor output is one of the inputs of the ADC multiplexer, so the MCU can be configured to read and broadcast the sensor readings. The SoC requires a 32 MHz crystal, and an optional 32.768 KHz crystal is added to improve power efficiency by allowing the SoC to switch clocks and enter various power consumption modes. An off-chip biasing resistor acts as a precision passive for current reference of the 32 MHz crystal oscillator. Programing and debugging of the chip is accomplished by a proprietary synchronous two-wire interface with a clock and a data line which also requires control of the SoC reset pin. Finally, a matching network described in [12] consisting of three inductors and one capacitor to match the differential impedance of the RF module to a 50Ω antenna is used. Additional components of the SoP include loading capacitors for the crystal oscillators and decoupling capacitors.

PROTOTYPE INTEGRATION

FR-4 Module Integration

The realization of the SoP on FR-4 can be seen in Fig. 2(a). The FR-4 prototype has all the components and traces on the top PCB layer, and the bottom layer is a solid copper pour acting as a ground plane. The top and bottom ground planes were coupled using via holes, which can be later removed in the paper module integration. Two surface mount or wire jumpers were needed to realize the module on one layer. The PCB design was realized using Altium Designer, and the FR-4 board by a commercial PCB manufacturer.



(a) (b) (c)

Fig. 2 (a) Designed FR-4 prototype (substrate is 33x38x1.57mm), (b) FR-4 prototype with commercial swivel antenna next to a 25 cents coin, (c) FR-4 and paper module prototype testing setup

Assembly was conducted manually using a microscope to place the components on their respective location over lead-based solder paste. A reflowing oven was used to attach the components to the board. As noted in Fig. 2(b), a 50Ω Titanis 2.4 GHz Swivel antenna was used in the first prototype as a point of comparison between a commercial antenna and an inkjet-printed antenna solution.

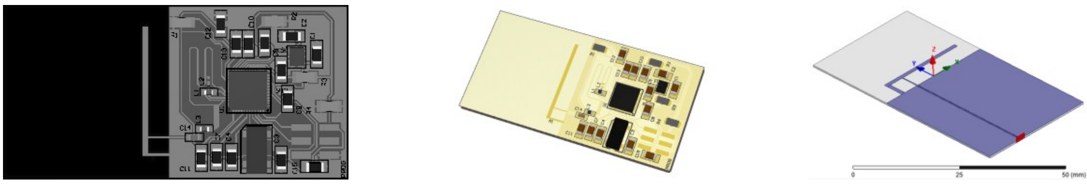
FR-4 Module Testing

The SmartRF Studio software was used to evaluate and configure the FR-4 prototype. As seen in Fig. 2(c), an evaluation wireless sensor module (CC2430EM) based on the CC2430 which also supports IEEE 802.14.4 and ZigBee was used to communicate wirelessly with the FR-4 prototype. The modules were positioned at 22cm of each other, each using a Titanis 2.4 GHz Swivel antenna. Both modules were set to transmit and receive 100 consecutive network packets with a random hexadecimal message on the 0x0B IEEE 802.14.4 channel with and transmit power of 0.6dBm. The FR-4 prototype correctly modulated, sent, and received the messages with an average RSSI measurement of -23.1dBm. The CC2430EM had an average RSSI measurement of -23.9dBm.

INKJET-PRINTED WIRELESS SENSOR NODE

Module Design

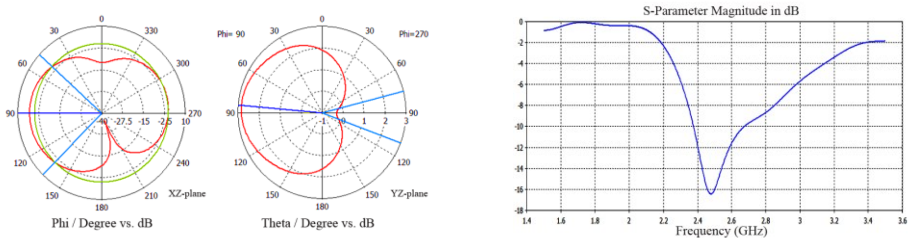
Fig. 3 shows the PCB design of the inkjet-printed module in Altium Designer, and the antenna design in Ansoft's HFSS. Demonstration of the FR-4 prototype is the basis to migrate the design from FR-4 to paper substrate. The paper module has the same PCB design of the FR-4 module with the exception of the printed antenna, a slightly modified matching network, and the removal of via holes for which the SoC ground pad is now connected through the unused pins of the chip. The matching network described in [12] will need to be adjusted to work on paper. The passive components can remain the same, while varying the thickness and width of the transmission lines to accommodate for the dielectric properties of paper described in [13]. An optional matching network that requires less variation is described in [14]. The proposed variation, obtained by using [15], is an estimated 50 mil width for the balun-to-antenna connection. The estimate was found using a 3.3 dielectric constant, 0.07 tangent loss, and 0.5mm substrate thickness [13]. The minimum trace width of the PCB is 0.254mm, and the minimum clearance between traces is 0.22 mm; this resolution has been already demonstrated in the laboratory, although the resolution depends on the ink material, the substrate, the curing processes as well as the voltage waveform used on the printer [9].



(a) (b) (c)

Fig. 3 (a) Paper-based module design with printed antenna in Altium designer, (b) Rendering of paper-based module with printed antenna in Altium Designer, (c) Printed antenna in HFSS

The antenna is a printed PIFA on 0.5mm thick paper. The antenna was designed in HFSS as seen in Fig. 3(c). The S11 simulated recordings for the center frequency of the antenna were -16.4 dB, as shown in Fig. 4(b), and the realized gain is 2.8dBi as noted in the radiation patters in Fig. 4 (a). The size of the feed is 0.254x3.6mm, the shorting pin is 3.6x19.24mm, the radiator is 23.5x1 mm, and the distance between the shorting pin and the radiator is 4 mm. The paper material used for the simulation has a 3.3 dielectric constant and 0.07 tangent loss [13]. For the simulation, it is assumed that a matching network has been already realized, and a 50Ω wave port is used as exitation. The assembly technique suggested is described in [3], which replaces lead-based solder paste with conductive epoxy and does not require reflowing.



(a) **(b)**

Fig. 4 (a) Simulated radiation patterns of printed antenna, (b) S11 parameters of printed antenna

CONCLUSIONS

In this paper, the design of the first IEEE 802.14.4 and ZigBee compliant wireless sensor module on paper using inkjet-printing technology is presented. The module is a 31x60mm SoP solution operating at 2.4GHz with a printed PIFA antenna. A proof-of-concept FR-4 prototype is designed, realized, and tested. Then, we migrated the FR-4 prototype to a paper-based design with a printed Planar Inverted-F Antenna (PIFA). The printed antenna was designed and simulated on paper substrate in HFSS with a realized gain of 2.8dBi and return loss at the resonant frequency of -16.4dB. Results show that inkjet printing is promising in the mass production of ultra-low cost eco-friendly wireless sensor networks.

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