Antenna-based "Smart Skin" Sensors for Sustainable, Wireless Sensor Networks

Hoseon Lee†, George Shaker‡, Vasileios Lakafosis†, Rushi Vyas†, Trang Thai†, Sangkil Kim†, Xiaohua Yi†, Yang Wang†, Manos Tentzeris†
Georgia Institute of Technology†
University of Waterloo‡
hoseon@ece.gatech.edu

***Abstract*- This paper introduces antenna-based "smart skin" sensors that are integrated with RFIDs for wireless sensor networks. Furthermore, the paper shows wireless energy harvesting capabilities to enable battery-less, or sustainable, wireless sensor networks with "smart skin" sensor nodes. These sensors are highly applicable for industrial applications: carbon-nanotube-based gas sensor, pressure sensor, and strain sensor. The low-profile, flexible sensors can be attached to surfaces as a "smart skin" with various sensing capabilities. These antenna-based sensors have the unique property of having a dual function of sensing and communication within a single device, which thereby enables RFID functionality to be integrated. Utilizing wireless sensor networking, it is possible to increase range and area of sensing. All prototypes have been designed, fabricated, and measured, the results of which show high sensitivity.**

I. INTRODUCTION

Smart sensors have been researched and developed extensively over the years for various industrial applications. However, the types of smart sensors can vary greatly depending on the definition, specification, and application of the smart sensors. In this paper, we introduce different types of "smart skin" sensors, whose scope has been defined by two important factors that are common. The first is that the sensors are antenna-based sensors, in which the sensors have the inherent capability of wireless communication while at the same time being able to sense a target parameter such as gas, stress, or pressure. The second factor is that these sensors are "smart skin" sensors that are flexible and have low profile, which can potentially be attached to any surface. This has been achieved by utilizing inkjet printing fabrication techniques as well as using flexible material such as photopaper and Rogers RT Duroid substrate. In the following sections, the gas sensor, stress sensor, and pressure sensor will be introduced, in that order.

To realize a wireless sensor network with smart sensors requires a lot of power due to the mass number of sensor nodes. However, this problem can be solved by the use of energy harvesting and ultra-low power integration platforms for mass wireless sensor networks, such as RFID, WISP, or Zigbee protocols. By circumventing the problem of having a battery, a truly "sustainable" wireless sensor network can be realized. Sections V and VI will address how this can be integrated with the "smart skin" sensor nodes.

II. RF WIRELESS GAS SENSOR

The gas sensor is realized based on the concept of the impedance change of a thin film of carbon nanotubes (CNT) when a particular gas is present. However, these single-walled nanotubes (SWNT) can be functionalized with a polymer called poly aminobenzene (PABS) which allows the SWNT to be more sensitive to ammonia gas than other types of gases.

Based on this concept, a prototype sensor was designed based on a patch antenna with a stub that is loaded with inkjet-printed PABS-SWNT. Previous work on CNTs include characterization of single strands of SWNT, resonators loaded completely with CNT, or simulated or theoretical work of CNT loaded antennas [1,2]. Here we introduce a prototype with controlled ammonia gas measurement results based on a RF surface impedance model from electromagnetic characterization results. [3,4]

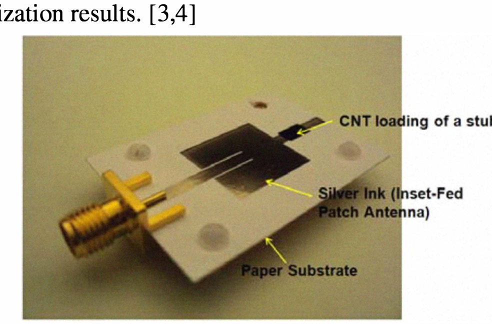

Fig. 1. Patch antenna based gas sensor integrated with a thin film of inkjet-printed carbon nanotube in the stub load, all printed on paper substrate. [3]

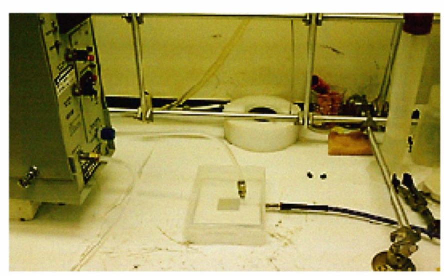

Fig. 2. Closed system measurement setup using a gas generator and ammonia permeation tubes. [3]

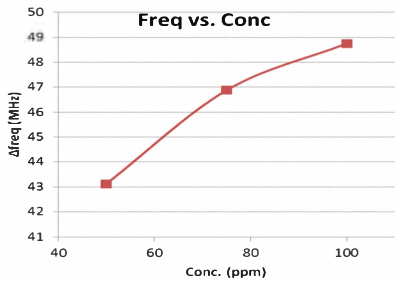

Fig. 3. Return loss frequency shift as a function of concentration indicating more shift with higher concentration of ammonia gas. [3]

The patch antenna (Fig. 1) has an inset feed and a stub with a 1mm gap that is loaded with PABS-SWNT. The sensor was measured in a closed cell under a fume hood (Fig. 2), with a controlled introduction of ammonia gas using a gas generator. The coax cable is connected from the sensor to a PNA and the frequency shift was recorded for different concentrations. The results in figure 3 show that with higher concentrations, the frequency shift of S11 is higher.

The sensor is based on a patch antenna design which enables RFID integration for a fully wireless gas sensor.

III. RF Wireless Strain Sensor

The wireless strain sensor, is a “smart skin” that detects the strain on metal surfaces on bridges, buildings, airplanes, and other heavy infrastructure. The concept is based on the conventional strain gauge that detects the change in resistance of a folded foil, that changes shape when stress is applied.

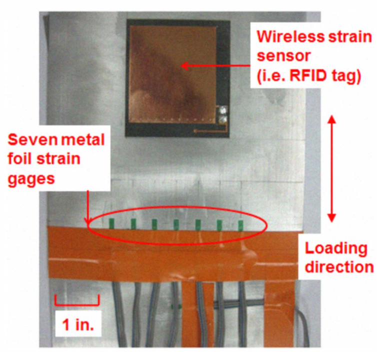

Fig. 4. Wireless strain sensor with conventional strain gauges. [5]

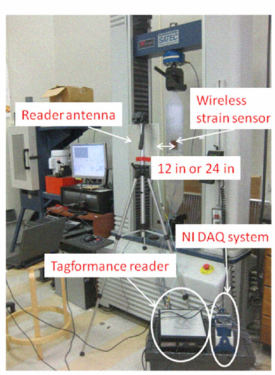

Fig. 5. Measurement setup with Tagformance RFID reader and servo hydraulic machine for tensile testing. [5]

To develop a wireless strain gauge, a patch antenna was used due to the concept that the S11 resonant frequency of a patch antenna will shift if the width and length of the patch is stretched due to strain. For this a flexible Rogers RT Duroid 5880 was used due to its good elasticity characteristics. An NXP RFID chip was integrated with the patch as shown in fig 3. on the left. [5]

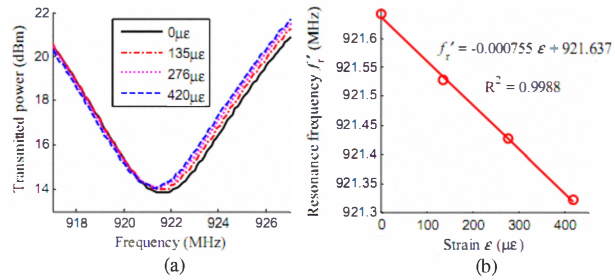

Fig. 6. Measurement plot of frequency shift of transmitted power as a function of strain. (a) Average transmitted power threshold. (b) Resonance frequency versus strain. [5]

The measurement was performed by placing the wireless strain sensor along with conventional strain sensors on a flat aluminum test specimen, which was pulled using a servo hydraulic machine for tensile testing. The tensile strength was swept from 0 microstrain to 420 microstrain, and the frequency shift was measured using a Tagformance RFID reader, as shown in Fig 6 (a). In addition, linear regression is conducted to the four data points in Fig. 6(a). The slope coefficient, -0.000755, shows that the strain sensitivity is -755Hz/με for the wireless strain sensor [5].

The measurement results clearly indicate a linear shift in frequency correlating to a linear shift in strain. Integrated with RFID technology, this sensor can enable a much more cost effective and convenient way of measuring the stress on bridges and bridges for safety checkups.

IV. RF Wireless Pressure Transducer

The wireless pressure transducer is different from the stress sensor in that the pressure transducer detects the amount of pressure applied perpendicular to the sensor, as opposed to the stress sensor which relies on the tensile stress that stretches the sensor.

The design consists of a parasitic upper patch antenna coupled in the broadside with an active lower patch antenna through an air gap. The upper patch is supported

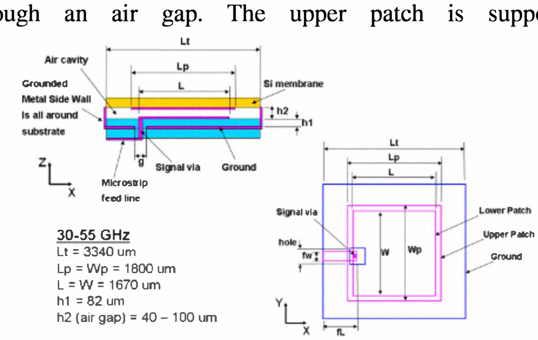

Fig. 7. Design of pressure sensor. [6-7]

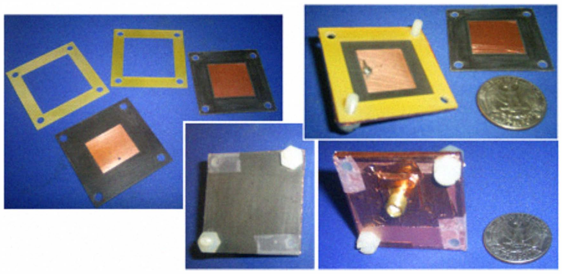

Fig. 8. Return loss measurement results showing 500MHz shift in S11 for 788um reduction in air gap height.

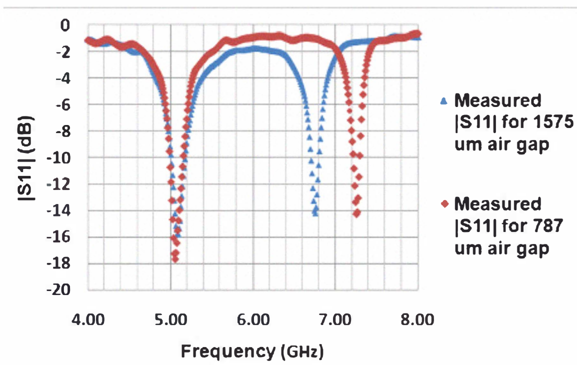

Fig. 9. Return loss measurement results showing 500MHz shift in S11 for 788um reduction in air gap height.

mechanically by a thin membrane whose deflection can be induced by a pressure difference between the air cavity and the surrounding (Fig. 7). The stacked patch configuration is a dual frequency resonator (Fig. 8). The pressure sensing is accomplished by the change of the air gap which results in a shift of the higher resonant frequency of the stacked patch configuration, while the lower resonant frequency remains unchanged. Thus, the lower frequency band can be utilized as a communication channel while the upper band is the indicator for pressure change.

The pressure sensor was designed to operate at 30-55GHz [6-7], but a prototype at 5-7GHz was fabricated to show the proof-of-concept. The initial air gap height was 1,575um which was reduced to 787um, resulting in a resonance shift of nearly 500MHz as shown in Fig. 9.

V. Energy Scavenging

Given the wide deployment of the smart antenna based skins, increasing the range of such individual devices can yield significant benefits in reducing the number of interrogating readers thereby reducing costs and overhead. Range increases currently are achieved through boosting the transmitted return power from these skins typically using a power amplifier. Power amplifiers powered on using batteries can create significant logistical, cost and environmental overheads. However, given the limited duty cycle transmits required by most smart skin application, power scavenging techniques can be effectively utilized to boost the smart skin range. In this section, we present a novel method of boosting the range through the use of green powering technologies such as solar cells to power on active electronics. In [1], a method to power on a wireless transmitter and embedded microcontroller using a solar cell and limited size solar cell array in an asynchronous manner is presented. The solar powered prototype is shown in figure 1 below. The solar cells are allowed to charge up a super capacitor to a pre-determined voltage level set by a power management unit (PMU) at which point it turns on the embedded microcontroller and wireless transmitter to carry out the sensing and wireless transmissions in the process discharging the super capacitor.

The wireless transmitter can be configured to send out a

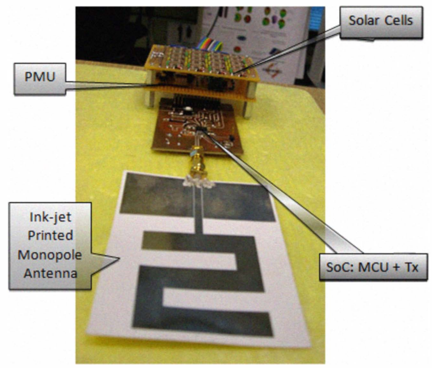

Fig. 10. Prototype for energy harvester.

couple of data packets between the points when the super capacitor discharges from 3.8V to 2.7V [8]. The total transmit time available is dependent on the the super capacitor used and the voltage threshold set by the PMU. Through the proper use and design of a super capacitor (300-600uF range) and PMU, the required transmit time of tens of millisecond repeatable every couple of seconds can be easily obtained during daylight hours as shown in figure 2 below.

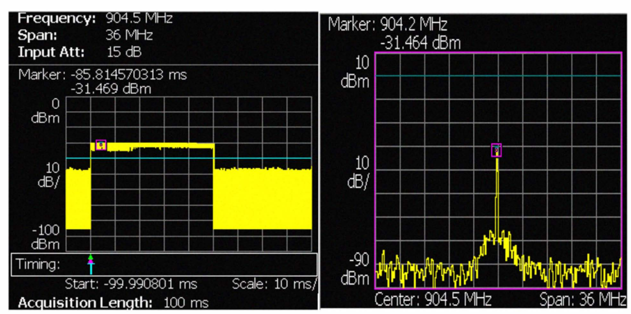

Fig. 11. Return loss measurement results showing 500MHz shift in S11 for 788um reduction in air gap height.

Upon completion of communication, the MCU would disable the wireless front end and put itself in "sleep" mode consuming microamps of current thereby allowing the already discharged charge tank capacitor to replenish itself using solar energy and repeat the process once it got to the threshold voltage [8]. To enhance the range and ensure that the majority of the harnessed solar power goes towards the wireless transmission, an optimized antenna matched to the Power amplifier in the wireless front end was used. Field tests carried out with this antenna show wireless ranges of 500 feet.

VI. WIRELESS SENSOR NETWORKING

The "smart skin" sensors can be implemented with ultra low cost integration platforms for mass wireless sensor networks, such as RFID, WISP, and Zigbee protocols. For example, the RF wireless strain sensor was integrated with an NXP RFID chip and tested using a Tagformance RFID reader. Another example shows a wearable temperature sensor integrated with a TI CC2500 module. The TI CC2500 module is low cost, low power 2.4 GHz RF transceiver which is designed for low power wireless applications in the 2.4 GHz ISM band. The original chip antenna of the commercial TI CC2500 module is substituted by inkjet-printed antennas to improve the communication range of the module on the human body while keeping the same power level. The communication range is successfully increased by factor of three by using new antenna designs for wireless body area networks (WBANs) applications compared to conventional monopole antenna (Fig. 12). This work can be easily extended to Zigbee protocol which is small, low power communication system based on an IEEE 802.15 standard. Therefore it is proper for low data rate, long battery life and personal security applications such as wearable sensor networks.

However, these mass wireless sensor networks can be realized with virtually no additional power although wireless sensor networks require a lot of power and with the energy scavenging explained in section V. The complete system would include the RFID-enabled antenna-based "smart skin" sensors, that can be integrated with WISP, Zigbee, or RFID protocols, that have wireless energy scavenging capabilities that provides the necessary power to activate each sensor node.

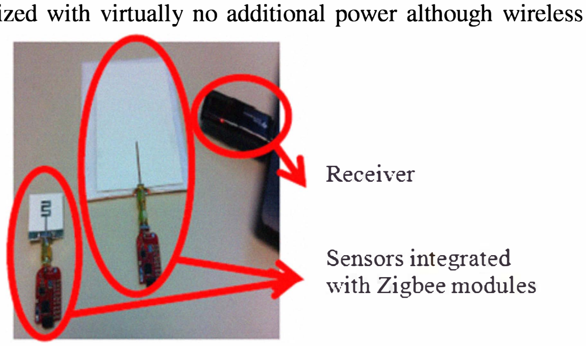

Fig. 12. Implemented sensor nodes for wearable temperature sensor application. a) Meandered monopole antenna b) Monopole antenna on the EBG plane for WBANs applications

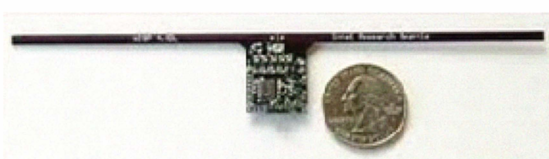

Fig. 13. A Wireless Identification and Sensing Platform (WISP) prototype tag[9]

The capability of gathering, storing, and processing large amounts of data collected from the smart skin sensors described above in a centralized, efficient and low-cost way without involving the human in the loop is becoming more and more critical as we move on to the ubiquitous cognition era. Toward that goal, we have demonstrated [10] that it is possible to deploy Wireless Sensor Network (WSN) nodes in between prototype sensors and the Internet. Under this approach, the WSN motes are not anymore the lowest-level network devices in the infrastructure hierarchy; their primary task is not as data generators, which role is almost entirely taken over by the smart skin sensors, but as data routers that relay the sensed information through wireless multihop links to one or more gateways.

Although we have managed to establish communication between the RF front-end module of the aforementioned solar-powered RFID tag and the commercial TI CC1000 transceiver-based MICA2 WSN mote using a very simple but power efficient protocol [11], the role of the WSN mote can also be assumed by 802.15.4 / Zigbee nodes, DASH7 nodes, Oracle Sun Spot nodes and others. For those smart skins whose electromagnetic sensing mechanism is not exclusively carried out under the remote sensing principle but can be done locally, a simple low-power consuming transmitter can be attached to successfully "speak" to the WSN nodes. This means that, from the networking reference layer design perspective, not only should there be physical layer (PHY) compliance in terms of carrier frequency and proper modulation of the RF transmission by the smart skin sensor but also that the transmitted packet has to be properly bit encapsulated link layer-wise [medium access control (MAC)].

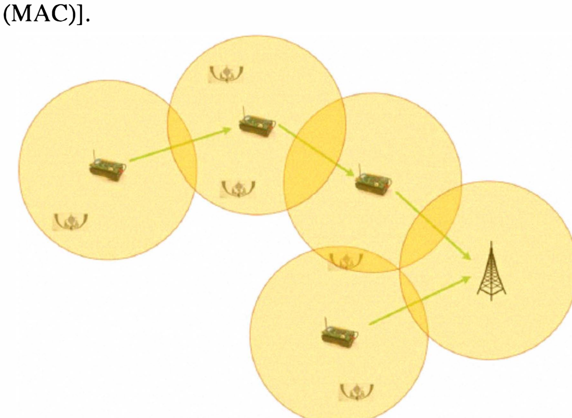

Fig. 11. An example of WSN topology.

Regarding the power efficiency of both the smart skin and the WSN node operation, it is always desirable to minimize the power consumption of the radio transmission. Instead of transmitting high strength signals over long single-hop wireless links, it is more power efficient to relay packets a number of times over lower-strength shorter links, as discussed in [12]. At the same time, as long as the WSN nodes are located within direct radio range of others, hopping effectively extends radio communication over higher ranges overcoming non line-of-sight and path loss effects. Moreover, their multi-path topology is inherently self-healing allowing the network functionalities to be sustained without any interruption due to potential WSN node failures.

VII. Conclusion

"Smart skin" sensors have been introduced that have the unique dual functionality of both sensing and wirelessly transmitting the sensed data. The low profile and small form factor allows for a wide range of placement possibilities, and the RFID chip integration enables compatibility with various protocols from RFID readers, WISP, and Zigbee for mass wireless sensor networks. Coupling the sensor nodes with the wireless energy scavenging capabilities, these wireless sensor networks can truly be ubiquitous, sustainable, "smart" sensor networks.

Acknowledgements

The authors wish to thank IFC/SRC (Interconnect Focus Center/Semiconductor Research Corporation, FHWA (Federal Highway Administration) and NSF (National Science Foundation) ECS-0801798, for their support in this research effort.

References

[1] S. Chopra, A. Pham, J. Gaillard, A. Parker, and A.M. Rao, "Carbon nanotube-based resonant-circuit sensor for ammonia," Applied Physics Letters, vol. 80, no. 24, pp. 4632-4634, June 2002.

[2] O.K. Varghese, P.D. Kichambre, D. Gong, K.G. Ong, E.C. Dickey, and C.A. Grimes, "Gas sensing characteristics of multi-walled carbon nanotubes," J. Sensors and Actuators B Chem., vol. 81, pp. 32-41, 2001.

[3] H. Lee, G. Shaker, K. Naishadham, J. Song, M. McKinley, B. Wagner, M. M. Tentzeris, "Carbon Nanotube Loaded Antenna-Based Ammonia Gas Sensor," IEEE Transactions on Microwave Theory and Techniques, 2011.

[4] H. Lee, G. Shaker, K. Naishadham, M. M. Tentzeris, "A Novel Highly-Sensitive Antenna-Based "Smart Skin" Gas Sensor Utilizing Carbon Nanotubes and Inkjet Printing," IEEE Antennas and Propagation Society International Symposium, 2011

[5] Xiaohua Yi, Terence Wu, Yang Wang, Roberto T. Leon, Manos M. Tentzeris, Gabriel Lantz, "Passive Wireless Smart-Skin Sensor using RFID-Based Folded Patch Antennas," International Journal of Smart and Nano Materials, vol. 2, issue 1, 2011

[6] T. T. Thai, G. R. DeJean, M. M. Tentzeris, "A Novel Front-End Radio Frequency Pressure Transducer based on a Millimeter-Wave Dual-band Resonator for Wireless Sensing," IEEE International Microwave Symposium, pp. 1701-1704, Boston, MA, June 2009.

[7] T. T. Thai, G. R. DeJean, M. M. Tentzeris, "A Novel Ultrasensitive Millimeter-Wave Pressure Transducer Utilizing a Si Membrane and a Stacked-Patch Configuration," IEEE Antennas and Propagation Society International Symposium, pp. 1-4, Charleston, SC, June 2009.

[8] R. Vyas, V. Lakafosis, M. Tentzeris, "Enabling Localization in WSNs with Solar-Powered End Devices", IEEE conference on Sensor Networks, Ubiquitous and Trustworthy Computing (SUTC), pp 155-160, May 2010

[9] Mary Catherine O'Connor, "www.rfidjournal.com/article/print/4613," 2010

[10] Lakafosis, V.; Rida, A.; Vyas, R.; Li Yang; Nikolaou, S.; Tentzeris, M.M.; , "Progress Towards the First Wireless Sensor Networks Consisting of Inkjet-Printed, Paper-Based RFID-Enabled Sensor Tags," Proceedings of the IEEE , vol.98, no.9, pp.1601-1609, Sept. 2010

[11] Lakafosis, Vasileios; Vyas, Rushi; Tentzeris, Manos M.; , "A localization and position tracking solution utilizing solar-powered RFID tags," Antennas and Propagation (EuCAP), 2010 Proceedings of the Fourth European Conference on , vol., no., pp.1-4, 12-16 April 2010

[12] Lakafosis, V.; Tentzeris, M.M.; , "Implementation of multi-hop routing protocols for the dramatic range enhancement of wireless sensor networks," Antennas and Propagation Society International Symposium, 2008. AP-S 2008. IEEE , vol., no., pp.1-4, 5-11 July 2008