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Design and Characterization of a Novel Battery-less, Solar Powered Wireless Tag for Enhanced-Range Remote Tracking Applications

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Abstract— **In this paper, a novel wireless "Battery-less Solar Powered Wireless Tag" with an enhanced range of a factor of 3-5 with respect to other passive tags is introduced for remote tracking applications. Power and wireless link measurements carried out between the tag and a commercial wireless sensor network receiver verify the feasibility of this technology for remote tracking deploying very low cost multi-hop wireless communication. It is the first time that a communication between an RFID and a wireless sensor network is reported – based on the convergence/co-design of five different technologies - , thus tremendously enhancing the capabilities, as well as drastically reducing the implementation cost of RFID's, while leading to the first generation of truly "green" RF electronics.**

I. INTRODUCTION

As the demand for power-efficient broadband wireless electronics increases, the materials and integration techniques become more and more critical and face more challenges, especially with the ever increasing interest for "cognitive intelligence" and "ubiquitous wireless networks". This paper introduces a novel battery-less solar powered wireless tag for remote tracking application. A combination of different technologies, namely Photo-voltaics, basic analog circuit design, embedded systems, RF and Microwave/antenna design are utilized to establish an asynchronous wireless link between the solar powered tag and a commercial wireless (WSN) network mote using a simplified protocol in the absence of a regulated battery supply. The design utilizes super capacitors, which are much cleaner to dispose environmentally and have much higher recharge lifetimes compared to batteries. Specifically, a paper-based microcontroller-enabled wireless sensor prototype has been developed for the first time for the UHF frequency band (centred at 904.2 MHz).

Battery technology is considered the Holy Grail for a wide range of industries such as automobile, cellular communications etc. The economic and environmental costs of developing and discarding them are still high. While some applications absolutely require a regulated power source such as a battery, many applications through a slightly more involved co-design of different aspects in their hardware and software can be remotely powered using ambient renewable energy forms. Wireless networks present such an application.

II. SYSTEM LEVEL DESIGN

The fundamental problem with continuously powering an RFID tag was the scarce output power. The palm-sized solar cell array that was stacked in a parallel configuration was capable of generating a maximum of 15mW. The most power hungry portion of the tag which was the wireless front-end consumed a peak power of 48 mW in transmit mode. A comparison of the 2 numbers showed that while it was not possible to continuously power the tag with the solar cell array, in a relatively short period of time enough solar energy could be harnessed from the environment to supply the tag with just enough power for communication for a short period of time. Such discontinuity is acceptable for RFIDs which use asynchronous communication. A system level diagram of the tag is shown in Fig.1. The power source of the tag comprised of an array of Solar Cells configured to give out an open circuit voltage and current above a certain minimum value under different light conditions. The Solar Cell array was interfaced to the tag through a Power Management Circuit (PMU), which was in turn interfaced to the integrated 8-bit microcontroller unit (MCU) housed in the same chip as the Wireless front-end. Communication was carried out by the wireless front-end that comprised of a single-ended Power Amp (PA) connected at its output to an appropriately designed external printed monopole antenna.

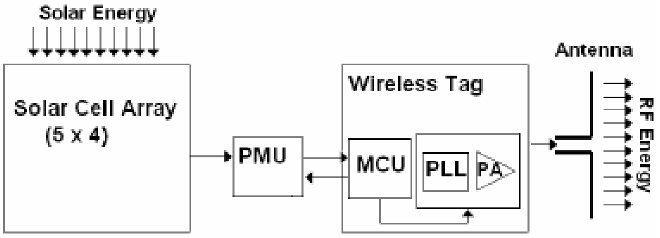

Fig. 1 System level diagram of solar powered wireless tag.

A. *Solar Cell Array*

The Solar cells were arranged in an array of 5 by 4 big enough to fit in a palm sized circuit board. Each solar cell unit was a stack-up of GaAs cells with open circuit voltage and short circuit current characteristics with respect to light intensity shown in Fig. 2 [1]. Measurements in Atlanta show light intensity to vary from 4,000 lux on a cloudy day to 60,000 lux on a clear sunny day. Light intensity measurements were performed using a LUX meter. From Fig 2, the open circuit voltage and short circuit current of each solar cell of the PV array would vary from between 7 to 10 volts and 0-80uA based on external light conditions. The parallel configuration of the solar cells would give a maximum short circuit output current of 1.6mA [2] while ensuring the same output voltage. Solar cells with a higher stackup that generate a higher output voltage were used based on the choice of the capacitor used in the Power Management unit. In the absence of batteries, the solar energy was to be collected in a capacitor (charge tank) for use by the tag. A higher solar cell output voltage across the capacitor would provide a faster charge-up time for different light conditions, which is important for more frequent communication by the tag as will be shown later. The drawback of configuring solar cells to produce a higher output voltage was that it would have to be regulated down to between 3 and 5.5 volts, which is the operating voltage of tag circuit. This was achieved through the setup of the PMU described in the following section.

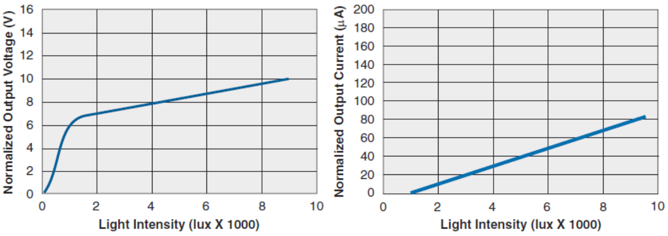

Fig. 2 Characteristics of single Solar Cell used in PV array [1].

B. *Power Management unit*

The Power management unit served as the interface between the solar cells and the tag. It was made up of super capacitors connected in parallel that served as the solar energy storage device. Power in the form of charge stored in the capacitors was monitored by the MCU in conjunction with discrete level FET switches that were also used to switch power to the system on or off. The PMU would keep the tag in either “off” or “sleep” mode till enough of the solar energy had been collected across the charge tank capacitors. Once the capacitor voltage had reached a certain user set threshold (V_{TH}), the PMU would trigger the tag on. Once “on”, the MCU of the tag would take over control of the operation of the tag.

The MCU firmware was designed to optimize power consumption of the tag and the MCU code was implemented to carry out data processing of the wireless data bits in as few instructions as possible to conserve power. In addition, the MCU was also programmed to power on the wireless front-end only when the tag was ready to transmit data. This was done keeping in mind that the MCU consumed only between 540 and 480 µA of current as the capacitor discharged from a threshold voltage of 3.8 to 2.2Volts, which is the voltage at which the MCU and tag shut off. On the other hand, the wireless front end along with the MCU consumed between 15.65 to 15.37mA as the charge tank discharged from the threshold voltage of 3.8 to 2.7 volts which was the threshold voltage at which only the wireless front end unit of the tag turned off. Upon completion of communication, the MCU would reset itself and the tag by discharge the charge tank capacitor to the turn off voltage of the tag through a voltage controlled MOSFET switch effectively resetting the tag. At this point the capacitor would start charging again from the Solar cell array with the MCU in low power sleep mode and repeat the process.

The three important parameters for the intended application of the tag are effective isotropic radiated power, total transmit time (i.e. number of times the Tag id is transmitted) and time interval between adjacent transmits. The effective isotropic radiated power, which is important for the triangulation of the tag, is determined by the Power Amplifier Output, that is a function of its bias that changes with the capacitor voltage and its output impedance which needs to be very close to the antennas impedance. Setting a fixed voltage threshold (V_{TH}) with the PMU ensures an identical PA output independent of the external light conditions. The maximum available transmit time is determined by the value of the amount of solar energy harnessed or conversely the charge tank capacitance. A quick way of estimating the total transmit time (T_{xmit}) available for a given value of charge tank capacitance is given by eq. 1.

$$T_{xmit} = -\ln(V_{OFF}/V_{TH})\,(R \times C_{TANK}) \qquad (1)$$

Where: V_{OFF} is the turn off Voltage of the wireless front end; V_{TH} is the threshold voltage set in the PMU; R is the mean load resistance of the tag operating between V_{TH} & V_{OFF} and C_{TANK} is the value of the charge tank capacitor.

For the tag prototype developed, the threshold voltage (V_{TH}) by the PMU was set to 3.8 volts and the tag’s turn off voltage was measured to be 2.7V. When transmitting using FSK modulation around a center frequency of 904.29MHz, the mean load resistance of the tag was measured to be 194 Ω. Using eq.(1) the total transmit time was determined to be 42.23 ms for the charge tank capacitor of 637 µF used in the prototype. The approximation in eq.(1) does not take into account the power consumed in the initial processing done by the MCU, which is less than 4% of the total power consumed and the power supplied by the solar cell as the charge tank capacitor discharges. The total wireless transmit time available for a charge tank capacitance of 637uF and a PMU threshold of 3.8V in the tag is shown in the wireless signal captured by a Tektronics RSA-3408A Real Time Spectrum Analyzer (RTSA) connected to an AN-400 RFID reader antenna in the form of power vs. time in figure3 below. The measured transmit time was observed to be 43.25ms, very close to the theoretically predicted value. The charge tank capacitance along with external light conditions would also set the time interval between adjacent transmits. For a capacitor of 637uF used, the time interval between adjacent transmits in the form of the tank capacitor voltage is shown in fig 4 below for light intensities varying from 10.5 to 70 kLUX. The light intensities were replicated in the lab with the help of halogen bulbs and may not represent the entire spectrum present in sunlight, therefore presenting the worst-case scenario.

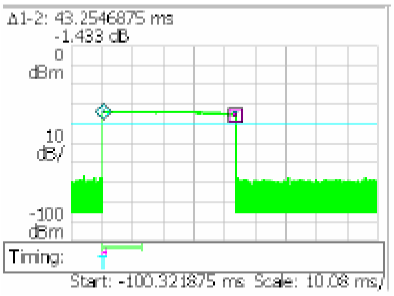

Fig. 3 Measured maximum wireless transmit time for charge tank capacitor of 637uF.

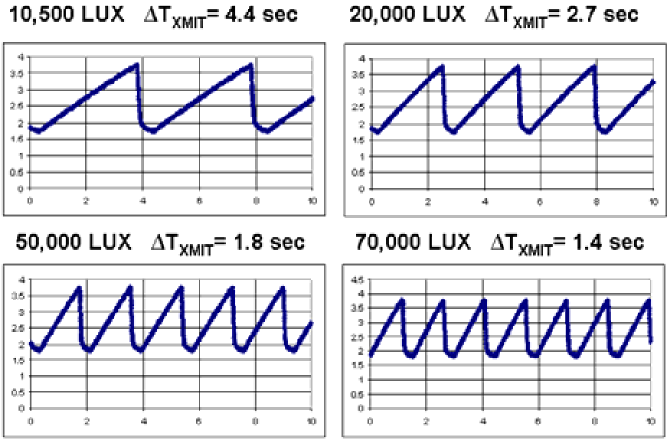

Fig. 4 Transmit time intervals for light intensities between 10.5 and 70kLux. Normal sunny noon ~ 30 kLux.

C. *Wireless Communication of RFIDs with WSNs*

For the remote tracking application, communication between a solar powered tag and commercial Crossbow's MICA2 WSN motes that served as the RFID reader was established thereby provide truly cognitive intelligence over extended physical distances on top of very low-cost and mature wireless infrastructures. The purpose of this communication was the extraction and the storage to a central base station of the received signal strength values of the packets transmitted by the tag and received by a number of relatively densely placed MICA2 motes. Afterwards, the aforementioned values along with the unique tag id, the unique mote ids and the predetermined GPS coordinates of the motes are used for the triangulation and, thus, the location estimation of the tag within the area, which is RF covered by the WSN nodes with a cost equal to a small fraction of that of commercial RFID readers.

The major requirement on the part of the tag was a constant RF radiated power that does not change with light conditions. This was achieved by the fixed trigger threshold of the tag set by its PMU circuit. In addition, because of the harmful effects to the wireless propagation of a number of parameters encountered in dynamic outdoor environments, such as fading, multipath, scattering etc., bit errors occur. At the physical level, one of the ways the bit errors between the tag and the receiver was noticeably minimized was by calibrating the Phase Locked Loop (PLL) of the tag so that its modulation profile around the centre frequency very closely matched to that required by the receiver MICA2 motes. This calibration also has the added advantage of requiring fewer number of preamble bits for the receiver to bit synchronize with the tag for Manchester bit encoding [3], which given the limited amount of power available per energy duty cycle can be useful. The calibrated fsk modulation profile sent by the solar powered tag and the modulation profile of a MICA2 transmitter mote optimally designed specifically for the MICA2 mote receiver both made by Crossbow as captured by the RTSA is shown in figure 5.

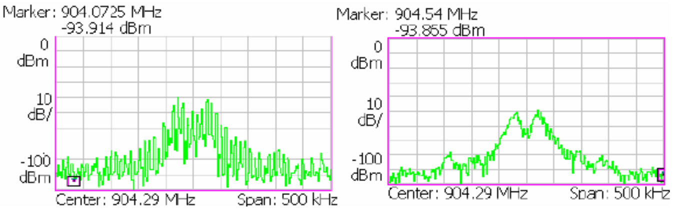

Fig. 5 Calibrated Tag and Crossbow transmitter FSK modulation profile.

The format of the packet sent from the tag, which is expected from the TI's CC1000 transceiver consists of the following fields: Preamble, Sync, ADDR, TYPE, Group, Length and CRC. The wireless packets sent by the tag as captured by the RTSA are shown in Fig.6. The first two fields are used for the synchronization of the receiver's clock and the latter field, Cyclic Redundancy Check, helps eliminate bit errors occurring within the sent bit sequence by successfully recognizing a corrupted packet and discarding it [3].

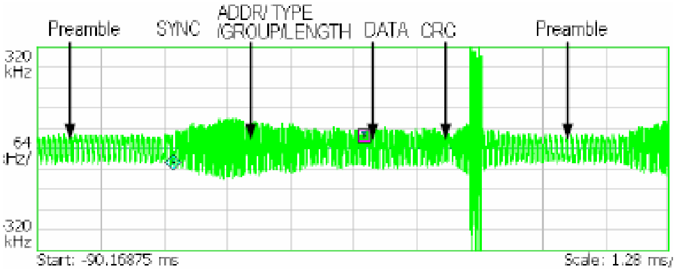

Fig. 6 Tag transmitted wireless data sequence captured by RTSA.

D. *Amplifier Characterization and Antenna Design*

The range of the solar powered tag to the MICA2 receiver is directly proportional to the amount of power transferred from the power amplifier (PA) to the transmitter front end to the antenna. Any impedance mismatch between the two can lead to the internal reflection of a part of the power intended to radiate out of the antenna, thereby minimizing range. Instead of designing the antenna to a 50 Ω match, it was decided to design it to the optimum impedance looking out of the amplifier in the transmitter to eliminate the need for a matching network To determine the optimum load impedance looking out of the PA in the wireless front-end, a load pull analysis was performed on it at 904.4 MHz. The optimum load impedance looking out of the PA at close to the transmit frequency of 904.4 MHz after accounting for bias circuit effects was determined to be 36.95-j71.77 Ω [4]. The most common antenna design for RFID tags are dipoles. However, for this solar powered tag a newly designed printed monopole structure was used. The primary benefit of this monopole is its use of ground plane [5], which in the present case can be very effectively used to EM shield the antenna radiating structure from the solar cell array and other parasitics that are introduced from mounting the tag on metallic objects like vehicles. In addition, monopoles have a wide input bandwidth and an omni-directional radiation pattern [6], which is used for triangulation calculations. The proposed structure for the antenna design was fabricated on paper using inkjet printed technology in-house and is shown as part of the working prototype in Fig 7. The fabricated antenna was found to have a measured input impedance of 37.3-j65.96, which was very close to the optimal impedance looking out of the PA resulting in a very high return loss of less than -10 dB over a bandwidth of almost 0.1GHz around the center frequency. The measured & simulated return loss and the measured range & radiation pattern of the antenna structured are shown in figs 8 and 9, respectively.

III. CONCLUSIONS

In this paper, we present the first ever wireless "Battery-less Solar Powered Wireless Tag" that can also communicate with wireless sensor networks for the first time reported. This RFID is based on the hardware/software codesign of five different technologies, and could set the foundation of ubiquitous ultra-low-cost RFID networks and the first generation of “green” RF electronics offering truly cognitive intelligence.

Fig. 7 Working prototype of Solar Powered Battery-less Tag

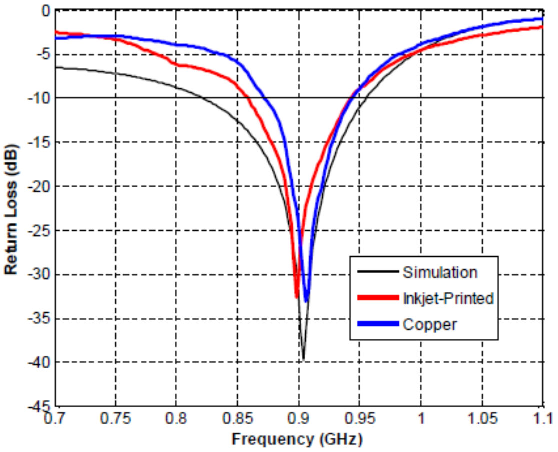

Fig. 8 Simulated & Measured Return Loss of the inkjet printed and copper based monopole antenna.

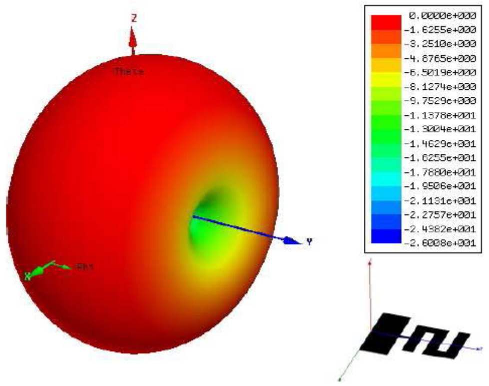

Fig. 9 Simulated 3D radiation pattern of printed monopole antenna.

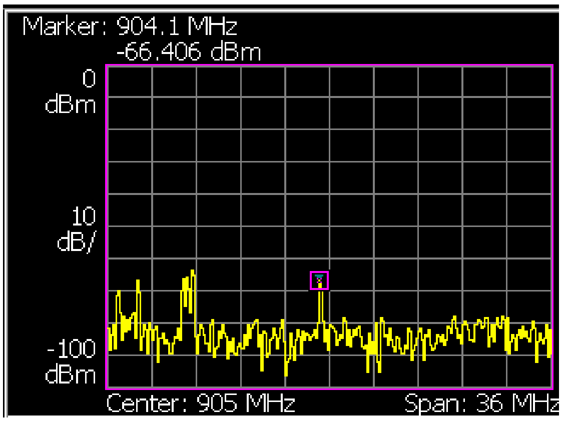

Fig. 10 RTSA measured tag signal at 500 feet.

REFERENCES

[1] Clare, “CPC 1832 Solar Cell,” *Data Sheet*, 2008.

[2] Green, Solar Cells: Operating Principles, Technology and Systems Applications, Bridge printery Pty. Ltd., 1992

[3] Texas Instruments “CC 1000”, Data Sheet, 2008.

[4] R. Vyas, A. Rida, L. Yang, M.M Tentzeris, “Design, Integration and Characterization of a Novel Paper Based Wireless Sensor Module”, *IEEE International Microwave Symposium*, accepted June, 2008

[5] H.W.Ott, Noise Reductaion Techniques in Electronic Syatems, 2nd ed. Wiley, 1988

[6] C.Balanis, Antenna Theory. New York: Wiley, 1997.