

# Wireless Remote Localization System utilizing Ambient RF/Solar Power Scavenging RFID Tags

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**Abstract**— A novel hybrid batteryless tag design using ambient solar and proposed RF power is presented. The novelty of this system is that the RFID tag not only uses ambient RF/solar power to power itself, but also it uses it as triggering mechanism for initiating data communication. A remote localization system with very good accuracy utilizing this tag configuration and making use of RFID to Wireless Sensor Node communication is showcased as an end application with tremendous potential. **Index Terms** — Solar, RF, Power Scavenging, WSN, localization,

## I. INTRODUCTION

The idea of harnessing power found in the environment to power devices has been getting a lot of attention lately. Transducers that harness power from solar, RF, vibration (piezo electricity) and heat have been showcased recently. In addition, recent advances in low powered digital and analog electronics have made it possible to design and operate devices that depending on their application can use ambient power by itself or combine it with a battery assisted power source for a hybrid powered system. While the power density from these sources may not be enough to power a lot of high powered devices, a study of the power densities in them show their feasibility for use in wireless sensor modules. A measurement of the ambient RF energy carried out at the Georgia Tech Campus at 900 MHz is shown in fig 1. From the spectrum analysis around frequencies it can be seen that they cannot be used to continuously power wireless sensor modules that consume upto 40mW instantaneous power. But RF energy can be used to augment an additional more reliable power source to form a hybrid power source to wireless modules. Solar power densities reaching the surface of the earth average about  $1.3\text{kW}/\text{m}^2$  and can be used as a backup source to power a wireless sensor module. A system level diagram of such a wireless module is shown in fig 2 below.

An ideal application for such a power rationing system is remote localization that does not involve huge wireless data payloads to be transmitted. Localization is the process of determining the physical position of a node with a particular degree of accuracy in indoor or outdoor wireless sensor or ad hoc network fields. The physical location information of a user, device or mote can prove to be very useful in many applications, such as device tracking, involving location and bearing, geographic aware routing protocols, meteorological and environmental applications.

## II. SYSTEM

This paper presents an operational localization system that tracks the position of a remotely placed tag through lateration. Lateration is the method of estimating the position of the tag by using its distance from 3 or more anchor points whose exact location coordinates are known before hand. The anchor points were a wireless sensor network (WSN) made up of Crossbow's MICA2 wireless nodes. The distance of the tag from the anchor nodes were estimated from strength of the wireless signal transmitted from the tag as measured by Received Signal Strength indicator (RSSI) on the TI cc1000 [2] transceiver that the MICA2 motes used. RSSI measurements from the anchor node were pooled together on a central computer using the wifi interface that the MICA2 motes provided on which they were selectively parsed for computations that would triangulate on the tag.

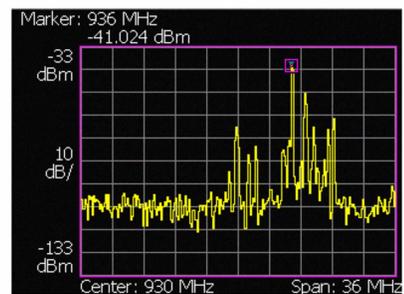


Fig 1. Ambient RF power at 900 MHz.

The tag not only used ambient light to power itself, but also used it as a triggering mechanism for initiating communication between itself and the anchor nodes thereby allowing for a completely stand-alone, battery-less asynchronous communication link from itself to the WSN used in the lateration. Section III describes the hardware design of the tag; Section IV describes considerations taken to establish a robust wireless communication link between the tag and WSN given the power limitations and Section V covers the localization techniques used and the results of its estimation using commercial mapping software.

## III. HARDWARE

The hardware system for the tag that was to be remotely tracked by the WSN was designed to meet the following criteria for successful lateration: Constant RF Power Output during each transmission, high rate of communication, Range,

Omni-directionality, Wireless link. The tag was made up of the following components: a palm-sized array of Solar cells, power management circuitry (PMU), an integrated 8 bit microcontroller chip (MCU), a wireless transmitter housed in the same MCU chip and an antenna.

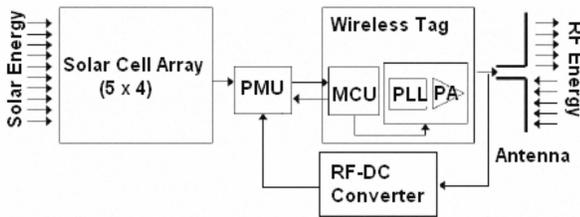


Fig 2. Proposed ambient RF & Solar Power Scavenging Tag.

The proposed RF power scavenging uses the antenna to channel in RF power and unlike the DC solar cell output is in AC form that requires the use of extremely low loss RF components for use in the RF to DC power conversion. Current investigation shows the forward voltage on most high speed Schottky diodes used in RF rectifiers and voltage multipliers introduce a good bit of loss in series thereby reducing the overall efficiency of the RF to DC converters. However, with the correct Antenna impedance and proper selection of low loss power converter topology and components, a trickle charge into the power storage device is possible.

Total ambient light power available in Atlanta was found to vary between 4.8 and 15mW for a palm-sized solar cell array of 20 cells in a parallel configuration. In comparison the wireless front end of the tag consumed a peak power of 48mW when the Power Amp is transmitting [1]. This solar energy if harnessed for a short period of time could provide enough energy to supply 48mW to the tag for the length of its operation. Given their longer recharge lifetimes combined with their cleaner disposability, super capacitors were used to collect this energy. The solar cells used were stacked GaAs cells and provided an output voltage of between 6 and 10V across the capacitor [1].

The Power management unit (PMU) was made up of discrete level FET switches that worked in conjunction with MCU firmware in controlling the power operation of the tag. Power in the form of charge stored in the super capacitors was allowed to build up to a pre-determined threshold level of 3.7V ( $V_{TH}$ ) till which time the PMU would keep the MCU in either “off” or “sleep” mode. This would prevent the MCU from turning on prematurely and turning on and off at the voltage point where it just turns on that was measured at 2.2V. Once the capacitor voltage had reached the threshold voltage ( $V_{TH}$ ) set by the PMU circuit, it would trigger the MCU on. Once “on”, the MCU of the tag would take over control of the operation of the tag [1].

The MCU was also programmed to power on the wireless front-end only when the tag was ready to transmit data since the MCU consumed between 540 and 480  $\mu$ A as compared to

15.65 and 15.37mA for the wireless front end for a charge tank voltage of between 3.8 and 2.7V at which point the wireless front end would shut off. Upon completion of communication, the MCU would disable the wireless front end and put itself in “sleep” mode consuming  $\mu$ amps 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 [1].

Having the PMU set the threshold voltage at which the tag turns on ensures that the transmission profile of the tag stays consistent each time it is triggered by ambient light irrespective of its intensity to communicate with the WSN thereby meeting one of the criteria for successful lateration of the tag. The maximum available transmit time is determined by the value of the amount of solar energy harnessed or conversely the charge tank capacitance ( $C_{TANK}$ ). A quick way of estimating the total transmit time ( $T_{xmit}$ ) available for a given value of charge tank capacitance is given in [1] and was estimated to be 42.23 ms for the charge tank capacitor of 637  $\mu$ F used in the prototype.

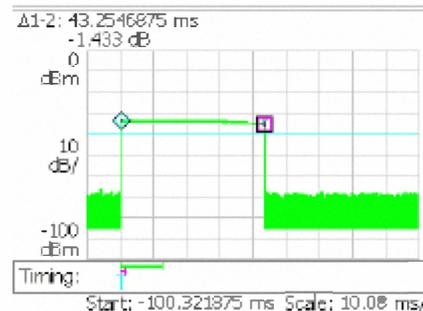


Fig. 3. Wireless transmission profile of the tag Captured by Real Time Spectrum Analyzer RTSA – Power vs. Time [1].

Table 1. Measured Rate of Wireless Transmissions

Light Intensity Exposed on Tag	Time Interval between consecutive Wireless transmissions
10.5 kLux	4.4 sec
20 kLux	2.7 sec
40 kLux	1.8 sec
70 kLux	1.4 sec

The wireless transmission profile of the tag as captured by a Tektronics RSA-3408A Real Time Spectrum Analyzer (RTSA) connected to an AN-400 RFID reader antenna is shown in fig 3. The measured wireless transmit time of 43.25ms was close to the theoretical value of 43.23ms. Lab tests carried out on the tag with a halogen bulb shows linearly proportionate relationship between light intensity and the rate of wireless transmissions as can be seen from Table 1.

#### IV. WIRELESS COMMUNICATION OF TAG WITH WSN

The data packets that were transmitted by the tag to the anchor nodes within its range in the WSN using FSK modulation at a center frequency of 904.3 MHz. comprised of

the following fields: Preamble, Sync, Addr, Type, Group, Length, Data, and CRC as shown in the RTSA measurement of fig 4. The first two fields are used for 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 [1]. The Data bits of the packets conveyed the RFID of the tag in order to help the WSN distinguish between one or more of the tags. The time to transmit one set of data packets was about 9ms, which given the total transmit time available for a charge tank capacitance of 637uF (transmit time of 43.23 ms) allowed for transmission of at least 4 set of data packets per energy duty cycle. 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 center 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 [2], which given the limited amount of power available per energy duty cycle can be useful [1]. The calibrated FSK modulation profile sent by the solar powered tag and the modulation profile of a MICA2 transmitter mote designed specifically for the MICA2 mote receiver both made by Crossbow as captured by the RTSA is shown in figure 5.

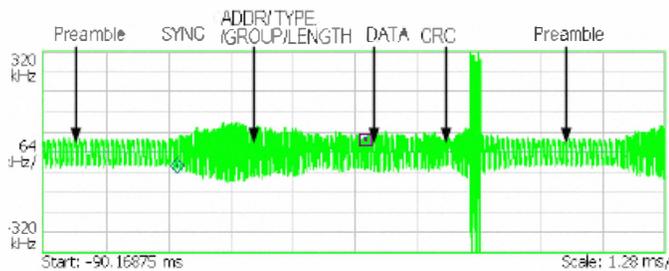


Fig 4. Wireless data sequence sent out by Tag.

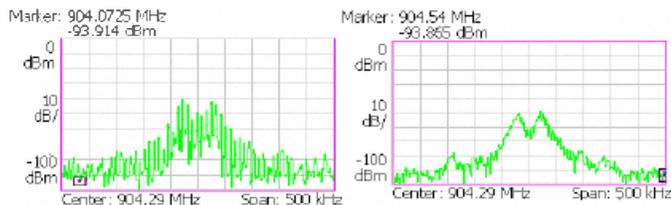


Fig 5. Calibrated Tag and Crossbow xmit FSK Modulation Profile.

A robust wireless link between the tag and WSN was further enhanced through the proper design of the monopole antenna with a gain close to 0dB while at the same time maintaining a conjugate match to the PA in the wireless front end of the tag thereby enhancing the range or conversely making the wireless link with the anchor nodes placed at pre-determined points more reliable [1]. The working tag prototype is shown in fig 6.



Fig 6. Working tag prototype.

## V. LOCALIZATION

In addition to the tag, the WSN setup was carried out to allow the anchor nodes to better receive the tag transmitted data, which would result in better localization estimation. The requirement for the clearance of at least the 80% of the first Fresnel zone is satisfied [4]. For the test bed setup used, where the average height of the motes above the ground is 3.5m and the height of the tag is around 1.5m, the value of the radius of the cross section of the ellipsoidal of the first Fresnel zone at the middle of the distance, typically 75m, is approximately 2.8m and the same value just 0.5m away from the mote side is around 0.3m.

The RSSI returned by the transceiver after the reception of a packet from another node can serve as an estimate of the aforementioned distances. In particular, the distance from the tag can be estimated by plugging this RSSI value along with the known effective isotropically radiated power (EIRP), which takes into account the transmission power, the antenna gain and the cables losses of the emitter, into the Friis equation for a particular path loss coefficient and model. The latter, of course, can be very sophisticated depending on the surrounding environment. In particular, after the successful reception from each anchor node of the beacon message transmitted by the tag, significant information, namely RSSI, unique tower id and time stamp, is appended and forwarded to a central location. All this message entries are imported into a Sqlite database, where they are validated by filtering out invalid entries. Then the filtered RSSI as explained later, is used for the distance calculation from a particular anchor node with the use of a free path or a two-ray tracing radio propagation loss model. The timestamp information availability enables the use of a timer function, which loads data from specific time intervals back in the past relative to the time the location estimate was initiated. Finally, the trilateration is performed as a database procedure calling [3] and in turn functions are called to display the returned WGS 84 latitude-longitude coordinates on Google Earth [3].

The attractive characteristics of this method are that neither additional hardware nor additional communication overhead is required. However, there are a few parameters that can degrade the accuracy of the RSSI approach. First, incorrect estimations are introduced when the RSSI is extracted from packets which have followed an indirect path due to multipath fading [4], regardless of whether they have been emitted from

an anchor node in line-of-sight with the receiver or not. Second, the fast-fading effect, as well as the dynamic nature of the environment, can result in serious oscillations in the RSSI measurements over time. Moreover, since the widely used inexpensive radio transceivers are in most cases uncalibrated, the actual transmission power can differ from the configured one and the measured RSSI value might not correspond precisely to the actual received signal strength. Nevertheless, the rather painful, and for some applications impractical, process of calibrating every node in the network can entirely eliminate these latter problems. In the framework of this work, efforts to alleviate the above degrading effects have been made before the trilateration is conducted. First, rigorous mapping of the RSSI values recorded at fine grained set distances from an anchor node and for known transmit power are conducted. Additionally, in order to remove the signal noise, the RSSI data is passed through Kalman filtering with the use of appropriate procedure language R functions [5].

### VI. LOCALIZATION RESULTS

In order to verify the feasibility of this technology for remote tracking applications, power and wireless link measurements were carried out between the tag and the commercial WSN node. However, in this paper we are emphasizing on the actual measurements of the location estimate error at different positions of the tag in the field covered by a number of anchor nodes. These 24 different predetermined positions are shown in fig. 7 with capital letters; the numbers correspond to the 8 anchor nodes, whose placement resembles to an asterisk topology. The diameter of the area covered by the overall topology is around 190m and the radius of the area RF covered by each anchor node is roughly defined to be 90m. An example of the localization estimate returned in Google Earth and compared to its real placement is shown in fig. 8. The mean, maximum and minimum estimate errors are summarized in table 2. The average error is reasonable when the tag is located in around the center of the topology. In contrast, the location estimate error increases as the tag moves more toward the periphery or even outside of the topology, where optimal coverage by multiple anchor nodes is not provided. This latter value, needs not been taken into consideration as the transmitter tag will always be considered to move in an area optimally RF covered.

Table 2. Localization Estimation Summary

mean value	38.56m	
max value	95.9m	for O
min value	1.62m	for G
mean value of green	24.52m	those in middle of topology
mean value of red	51.98m	those in periphery of topology

### VII. CONCLUSIONS

The first ever operational remote tracking system using a battery less, ambient power scavenging tag has been demonstrated. It is the first time reported that the ambient

solar/RF energy not only provides the necessary operation power of the tag, but it also functions as the trigger of the data communication. A successful solar triggered wireless link between the tag and WSN was successfully established providing excellent localization accuracy in a sustainable way.



Fig 7. WSN setup.

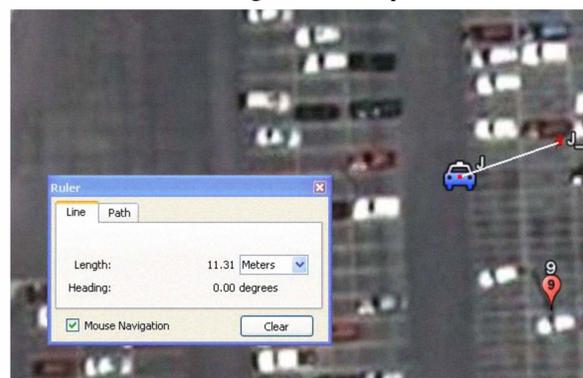


Fig 8. Localization Estimate Results

### ACKNOWLEDGEMENTS

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