A Battery-less, Wireless Mote for Scavenging Wireless Power at UHF (470-570 MHz) Frequencies

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***Abstract*—In this paper, a novel power scavenging mote to harness wireless power in the UHF frequencies between 470 and 570 MHz is presented. A broadband monopole antenna prototype inkjet printed on a paper based substrate is used transduce the incident wireless power from its Electromagnetic wave form to a RF AC signal. A conjugately matched voltage multiplier and RF transformer are used to rectify and store the RF input power in a low leakage capacitor for powering on a microcontroller unit and wireless transceiver end-device thereby making the entire operation of this mote battery-less.**

Keywords-component:RF, Power Scavenging, Voltage Multiplier, Antenna, monopole, inkjet printing, wireless.

I. Introduction

The last couple of decades have seen an explosion in the use of wireless technologies in everyday products. The advent of blue tooth and WiFi technology since the 1990s have led to a plethora of devices from computers to smart phones utilizing them to connect to the world wide web or other accessories such as speaker, microphones, printers etc. Cellular connectivity around the world has also mushroomed manifold with 95% and 45% of the population owning cell phones in developed and developing countries respectively as of 2007, and which continues to rise. In addition the switch from Analog TV to Digital Terrestrial Television over the air in most countries is also expected to be completed by 2011. These ever expanding applications have results in a perpetually increasing power content present in the wireless spectrum at UHF frequencies starting at 400 MHz till 3.5 GHz.. In countries where DTV has been implemented, significant amounts of continuous wireless power have been observed to be present in the low UHF bands between 400-700 MHz that appear to be perpetually on in urban areas. A potential application of such a perpetual source of power could be to turn on ultra low power wireless motes that could be used for a range of applications. Advancements in semiconductor technology have in recent years led to developments ultra low power embedded microcontrollers such as the TI EZ-430 and Microchip PIC12F series of Microcontroller units (MCU) and transceivers that consume microamperes to milliamperes of current respectively. Powering on either of these 2 components using such an omni-present and ambient power source in the UHF wireless spectrum that can penetrate through most walls make it ideal for a whole range of applications indoors and outdoors. Combined with an embedded Microcontroller/processor chip with its built in ADCs, and data communication interfaces (SPI, I2C, USART-RS232) such a wirelessly powered platform could make it ubiquitous for a vast array of applications related to remote sensing, localization, metering, alarms, security etc.. In this paper we present one such mechanism that can be used for harnessing the wireless power present in the UHF spectrum in order to realize such ubiquitous devices.

II. Power Scavenging Mechanism

A. RF Voltage Multiplier

The end goal of this project is to develop a wireless power scavenging platform that would utilize the ambient power currently found in the existing wireless spectrum to power up a wireless mote comprising of a microcontroller and a transceiver. Based on wireless spectrum measurements carried out in downtown Tokyo, a perpetual ambient source of wireless power was found in the frequency band from between 470-570 MHz currently used for Analog (470-495 MHz) and Digital TV (520-570 MHz) broadcasts. These lower UHF bands offer superior propagation characteristics in terms of low attenuation through air and walls and also experiences lower parasitic loses through circuit components. The end device that would be powered on using wireless power would be a wireless sensor mote comprising of a microcontroller unit (MCU) and a transceiver. A review of microcontrollers and transceiver technology currently manufactured by a host of IC companies show them to have the lowest operating voltage range of between 1.8V and 3.6V [1]. In order to completely eliminate the use of a battery, the wireless mote prototype was equipped with a low leakage super capacitor that was trickle charged with wireless power. Super capacitors have significant advantages over batteries through their significantly higher number of recharge cycles, low leakage, low cost and cleaner disposal. The drawback with capacitors is their unregulated voltage, which in the absence of proper supervision may discharge quickly rendering the end device powerless. Lack of supervision of the charge-discharge mechanism of the capacitor into the end device may also cause it to under go unnecessary power-on-resets (POR). In such a scenario, the MCU would turn on once the capacitor reached its turn on voltage drawing current from the capacitor immediately causing the capacitor to discharge. Without sufficient voltage margin, the capacitor voltage would drop to below the turn on voltage of the MCU shutting it down before it can complete its firmware routine. With capacitors as power storage devices, there is always a risk of the MCU entering a state of constant PORs without finishing its functioning. Preventing such a state has to be achieved through the proper design and calibration of the PMU circuit, which in essence is a voltage trigger analog switch that is set to a voltage sufficiently higher than the turn on voltage of the MCU but lower than the max operating voltage of the MCU along with proper firmware design. The operating time of the wireless mote would be the discharge time of the capacitor from the PMU triggered turn on voltage to the turn off voltage of the MCU at 1.8V.

In order to ensure that the ambient wireless power in the UHF band between 470-570 MHz is transformed to a voltage of 1.8V and higher required across the capacitor at a fixed distance from the power source, a topology comprising of a multistage RF voltage multiplier was used as shown in Fig 1. RF schottky diodes were used for the RF charge pumps given their lower forward voltage drop compared to conventional silicon based PN diodes. Parasitic effects due to packaging currently limit the forward voltage of the diode to between 100mV and 400mV between forward currents of between 0.1-100mA respectively [2] which means any voltage received across the antenna terminals below this voltage would result in the antenna seeing an open impedance towards the circuit that would cause all the incident wireless power to be reflected back without turning on the device. In order to avoid this scenario at a given distance from the wireless source, a RF transformer was employed between the antenna and the voltage multiplier to help transform the incident wireless power to a higher voltage thereby ensuring a trickle charge into the end capacitor. A low voltage zener diode with an avalanche voltage equal to the max operating voltage of the end device or MCU was connected in shunt across the capacitor to prevent excessive current flow through the end device, which would occur if the power scavenging mote was within close range of the UHF wireless power source. Given the low trickle charge seeping in from the wireless source, the zener diode was carefully selected to have minimum leakage.

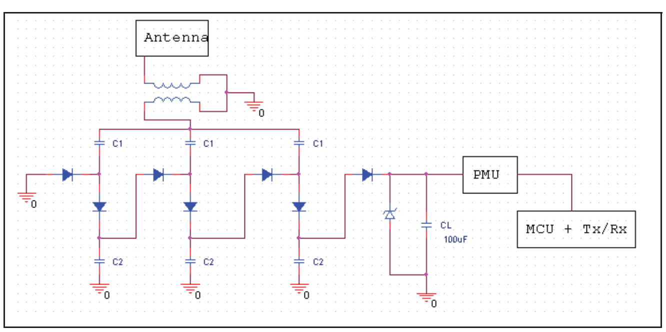

Figure 1. Schematic of voltage multiplier cicruit.

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The measured impedance looking into the towards the RF power scavenging circuit between 400 and 500 MHz can be seen in Fig 2. The impedances were measured with the trickle charge having charged the storage capacitor (100uF) to 1.8, 2.2 and 3V. Fig 3 shows that once turned on, the impedance of the power scavenging circuit stays fairly consistent at 1.1-j40 ohms while the charge tank capacitor is charged to between 1.8 and 3.0V which is the operating range of the end device. Using this impedance, an optimum antenna was designed to match to the conjugate of this circuit impedance for efficient wireless power scavenging at 520 MHz which is the center frequency of the intended wireless source.

B. Antenna

According to the 2 ray beam tracing and direct line of sight Friis formulas [3], a high enough antenna gain is required to maximize wireless power transfer from the UHF signal source and power scavenging wireless mote. In order to achieve the correct trade off between gain and bandwidth, a monopole based structure was used for the antenna to transduce the incident EM power into its usable RF AC form. For lab tests, the linear structure of the monopole provides better efficiency than other comparable forms such as patch antennas that suffer from lower efficiencies when printed over thin substrates. Also unlike dipoles, monopoles give out a single ended signal form, which is perfect for the RF voltage multipliers designed. IN addition the ground plan on a planar monopole antenna can be very conveniently used to shield the radiating part of the structure against parasitic coupling by the scavenging circuit or any mounts nearby. [4]

For quick prototyping and testing the monopole antenna was fabricated on an organic paper based substrate using an inkjet printing technique. Unlike wet etching or milling, inkjet printing uses electrostatic potential to deposit charged ink solvents from inkjet cartridges onto a paper based substrate. Fourteen nozzles on the print head each 254um apart jet out controlled amounts of ink on the paper based substrate resulting in a uniform deposition for improved conductivity as shown in Fig 3.

An inkjet cartridge with a spray volume of 10pL was used to spray 15 layers (~15um conductor thickness) of the conductive ink to increase the conductivity antenna structure. The antenna was annealed at a temperature of 120 degrees Celsius for 8 hours to allow the dispersed conductive nano particles for form conductive bonds increasing the metal conductivity further. Given the low temperature tolerance of paper to etreme high temperatures produced by soldering irons, conductive silver epoxy was used to connect an SMA connector to the antenna for antenna measurements as shown in fig 4 [5].

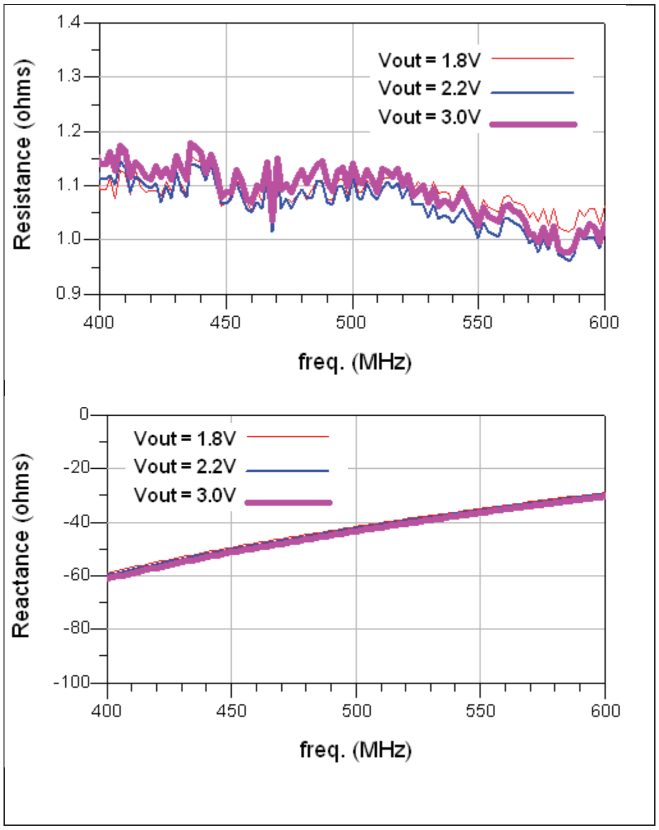

Figure 2. Measured input impedance of power scavenging circuit.

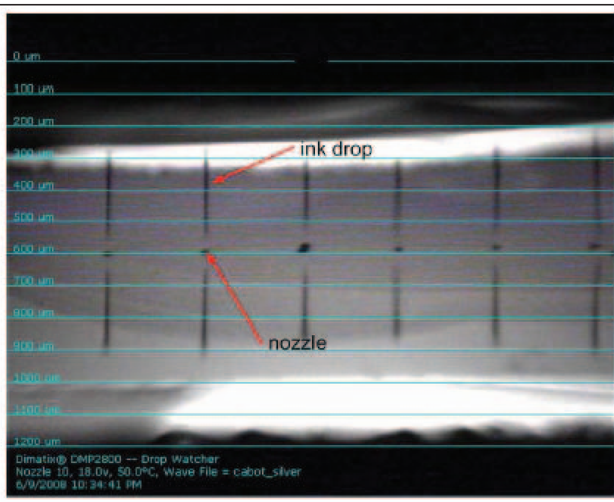

Figure 3. Conductive ink printed out of a series of nozzles on print head.

The radiating element of the monopole was tapered for increased bandwidth and compactness. Its tapering microstrip feed was optimized to lower the resistive part of the antenna structure's input impedance to as close to the impedance of the power scavenging circuit without compromising its radiation gain. The peak antenna gain obtained for the antenna for its lowest real impedance was 2.07 dBi. A matching network had to be designed to reduce any further impedance mismatches between the power scavenging voltage multiplier circuit and the antenna. The tapered structure also provides more broadband antenna impedance helping in making the matching more broadband between the antenna and the power scavenging circuit. The antenna was simulated for a paper based substrate using the HFSS EM solver by Ansoft. The antenna designed along with its simulated radiation pattern is shown in fig 5. A working prototype of the power scavenging circuit along with the antenna is shown in fig 6.

Figure 4. Silver epoxy used to connect SMA receptacle to Antenna microstrip feed.

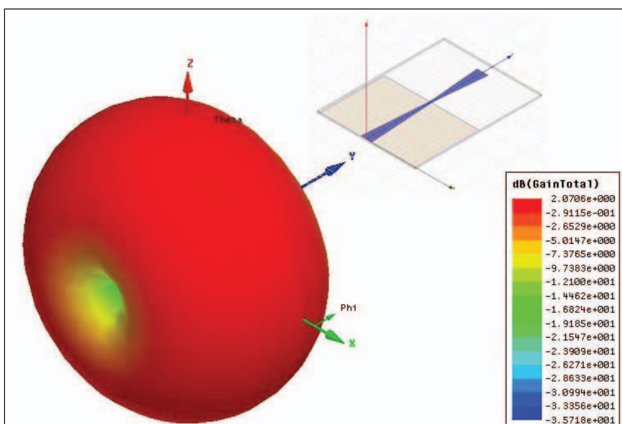

Figure 5. Radiation pattern of the tapering monopole structure simulated using Ansoft HFSS.

The measured impedance looking towards the antenna from the input of the power scavenging circuit once optimally matched is shown in figure 5 below. The measured antenna impedance at 520 MHz attained was 1.01 + j45.75 ohms, which offers a fairly good conjugate match to the optimum impedance required by the power scavenging circuit at 1.1-j40 ohms as shown in fig 2.

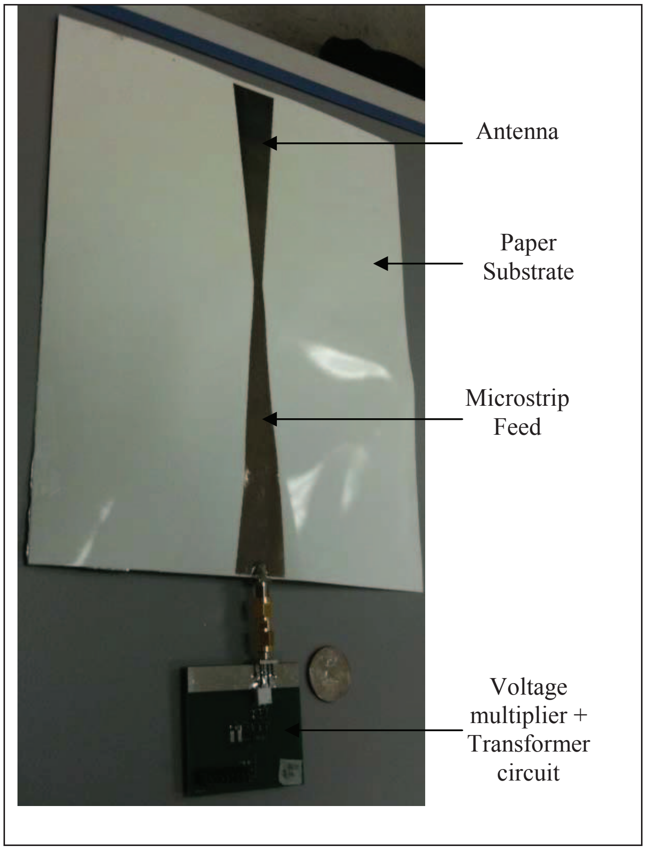

Figure 6. Working prototype of the UHF wireless power scavenging Mote.

III. CONCLUSION

In this paper, a prototype utilizing an inkjet printed monopole conjugately matched to a low power, high output, multistage voltage multiplier is showcased as a potential power scavenging platform to hardness wireless power present in the UHF band between 470-570 MHz emanated as part of TV broadcasts. Wireless power trickled into a supercap is shown as a potential replacement for batteries in powering on embedded and ultra low power wireless applications.

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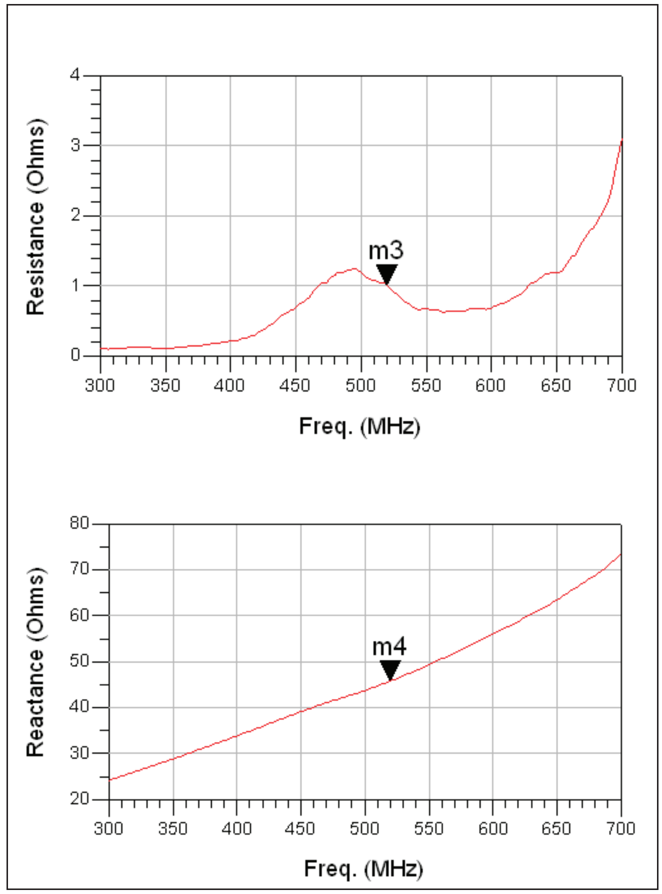

Figure 7. Measured Antenna Input Impedance conjugately matched to the voltage multiplier circuit.

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