Novel Energy Harvesting Technologies for ICT Applications

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ABSTRACT

In this paper an overview of novel scavenging approaches for almost autonomous ICT applications will be discussed and evaluated in terms of efficiency, integrability, cost and applicability in rugged environments. Various frequencies of potential scavenged power will be tested and different electronic scavenging configurations will be presented and becnchmarked in comparison to commonly used approaches, such as solar cells or electromechanical couples. Their performance will be evaluated in metal-rich multipath indoor environments, as well as in multi-users outdoor and indoor rural and urban topologies.

Keywords—Electric/Magnetic field intensity, Energy Harvesting, Printed Electronics, Rugged environments

1. INTRODUCTION

The demand for low-cost, robust, flexible, reliable, low-power consumption and durable wireless modules, such as RFID-enabled sensor nodes [1], is driven by several applications, such as logistics, Aero-ID, anti-counterfeiting, supply-chain monitoring, space, healthcare, pharmaceutical, military and is regarded as one of the most important methods for realizing ubiquitous ad-hoc networks.

Paper material is one of the candidates that could potentially cause a breakthrough in the “green” wearable/ICT-attached electronics world due to its ultra low cost and environmental friendly characteristics. In addition, this approach could realize a truly “ubiquitous computing” network. From a manufacturing perspective, paper can go large reel-to-reel processing and so is a perfect candidate for bulk production especially when accompanied by a fast direct-write methodology such as inkjet printing. This can be done easily since paper has a low surface profile and with the appropriate coating it can host conductive paste on top of its surface which enables modules such as: antennas, IC, memory, batteries and/or sensors to be easily embedded in/on paper, as well as power sources in the form of batteries and/or power scavengers.

The ever increasing implementation and ramp-up of ubiquitous network services will necessitate the deployment of a large number of wireless sensors. Currently, batteries are the main power sources for sensor networks and mobile devices. Still, the use of batteries has two disadvantages: (1) the lifetime of the batteries is very limited even for low-power batteries, requiring the – many times impractical – battery replacement periodically, (2)the use of commercial batteries usually “overkills” the power requirements for uW sensor nodes, adding size, weight and featuring a very-low power efficiency, while creating the problem of environmental pollution due to the deposition of these batteries, as well as increases significantly the cost overhead of disposable nodes.. From the energy consumption point of view, the above will be major obstacles for the quick penetration of ubiquitous network services. This section investigates how to realize a sustainable sensor node without the need for battery supplies.

Energy harvesting [2] could be an alternative energy supply technology. Such systems scavenge power from human activity, ambient heat, light, RF, vibrations, etc. RF signals used for wireless communication systems will be the most suitable energy source because heat, light and vibration are not always available at every place. On the other hand, radio wave is ubiquitous in our daily lives. (TV/Radio, wireless LAN, mobile phone, etc.) However, it is very difficult to know how much of energy we can scavenge from RF signals in the real environment. With a simple EMC (Electro-Magnetic Compatibility) experiment [3] the authors have roughly calculated the power specifications of future sensor devices in ICT and µW Computing. Most commonly used wireless sensor nodes (e.g. RFID-enabled sensor nodes) consume dozens µW in sleep mode and hundreds µW in active mode. Since it is widely expected that the next generations of these nodes will consume significantly less power, power scavenging could be a very attractive option, especially in environments such as supercomputing rooms, with a large concentration of EM energy, and large railway stations, with multiple EM energy sources.

2. TYPICAL INKJET-PRINTED 3D WIRELESS SENSOR ARCHITECTURES ON PAPER

With the emergence of ubiquitous RFID-based applications, such as tagging of large, lossy bodies such as cars, that require a continuously acceptable wireless link quality as well as an effective scavenging (antenna receiving) area, most of the conventional planar RFID antennas suffer from multireflection/multipath effects; a three dimensional cubic antenna is the first step for autonomous “rugged” nodes. The aim of this effort is to create an almost omnidirectional radiation pattern with a miniaturized cubic antenna for the Real Time Locating as

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well as the continuing energy scavenging no matter how the node is oriented.

A non-uniform meander line structure that utilizes the folding of a half-wavelength dipole was used for the main radiating body. Meander line antennas for RFID applications have been discussed and developed in previous literature. Since passive RFID Tags Integrated Circuits (ICs) are characterized by highly capacitive impedances, inductive coupling was used in this structure to create a good match in the reactive impedance section in order to supply conjugate matching. The structure is shown in Fig. 1 where the size of each side of the cube is 32mm. Miniaturization was achieved by utilizing all sides of the cube and by using two antenna each occupying three sides. The radiation of the top antenna that is connected to the IC causes the bottom rectangular loop to couple with the bottom antenna, which also causes radiation. The result of the coupling of these two independent three-dimensional meander line antennas causes the input impedance to be matched at two different resonant frequencies. By varying the length of the meander lines and their proximity to one another, the cube can be designed for a specific dual band use, potentially allowing for the scavenging in both UHF and 900 MHz band. Scaling the cubic dimensions, scavenging could take place for 900/1800 MHz.The two antennas are symmetric with respect to a center cut plane or diagonal cut plane to the structure. The return Loss plot is shown in Fig. 2. The Impedance of the IC used was 73 – j113 Ohms. Fabrication using ink-jet printing on paper, folded into a cube can realize a very small low cost cubic RFID tag.

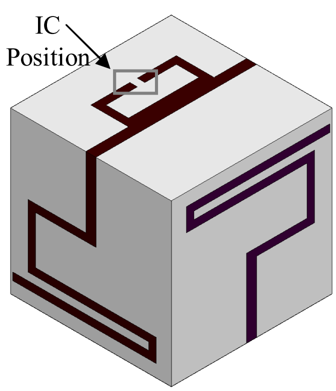

Fig. 1 Three dimensional RFID “Scavenging” Antenna using meander line configuration.

The next step in the investigation of the integrability of potential scavengers was the low-cost fabrication of the first wireless sensor module built and integrated completely on paper [1]. In particular, a microcontroller paper-based enabled UHF wireless sensor prototype has been developed. Inkjet-printing is a direct-write technology by which the design pattern is transferred directly to the substrate, and there is no requirement of masks contrary to the widely used traditional etching techniques. In addition, unlike etching which is a subtractive method by removing unwanted metal from the

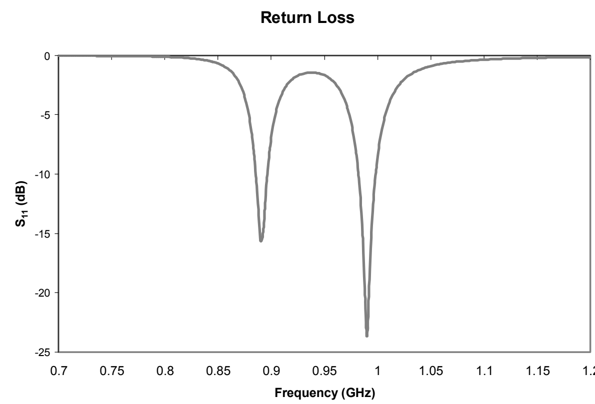

Fig. 2 S_{11} vs. frequency for the RFID Antenna of Fig.2.

substrate surface and which also uses chemicals such as the etchants throughout the fabrication process, inkjet-printing jets the single ink droplet from the nozzle to the desired position, therefore no waste is created, resulting in an economical fabrication solution. This aspect, together with the fact that the chemicals necessary for etching are eliminated, makes this approach environmentally friendly as well. The next plan will integrate an embedded supercapacitor, that could be used for the continuous recharging of the attached battery. This module could be easily embedded inside the 3D “cubic” scavenger.

The wireless sensor module on the paper is shown in Fig 3. A transmission frequency of 904.4 MHz was generated by a crystal oscillator that was connected to the input of the PLL unit of the transmitter. The data transmission was to be carried out at the unlicensed UHF frequencies around 900 MHz. The entire wireless system including the antenna and the traces for the components mounting was printed on a 2-D paper module and operated remotely using a 3V Li-ion cell. The antenna was designed to resonate at a center frequency of 904 MHz, where it would have an input impedance matched to the optimum output impedance of the power amplifier in the transmitter module. This aggregate impedance was determined after accounting for the shunt impedance introduced by the bias circuit and the series impedance introduced by the series coupling capacitor between the amplifier and the antenna terminals at 904 MHz.

The antenna shape chosen was a U-shaped tapered dipole in order to reduce the overall size while, especially that the traces for the sensors components were enclosed within the U-shape of the antenna while establishing a wide bandwidth near the center frequency that covers the UHF RFID frequency band in the US. The overall dimensions of the module are 9.5 x 5 cm. The Return Loss or S11 measurements for the center frequency for the antenna terminals was recorded to be -15.05 dB for the simulated structure using the full wave EM simulator HFSS and -12.45 dB measured using the ZVA-8 VNA. The radiation pattern was also measured using Satimo’s Stargate 64 Antenna Chamber measurement system and by using the NIST Calibrated SH8000 Horn Antenna as a calibration kit for the measured radiation pattern at 904 MHz, and is shown in figure 5. The discrete passive components, the temperature sensor, and a Li-ion cell for "stand-alone" (autonomous) operation were assembled on paper.

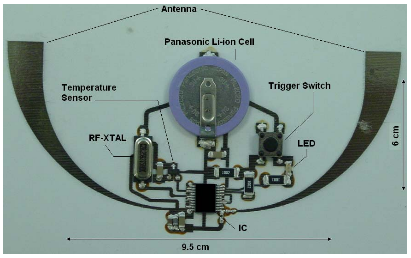

Fig. 3 Wireless Sensor transmitter prototype on paper substrate using silver inkjet printing technology.

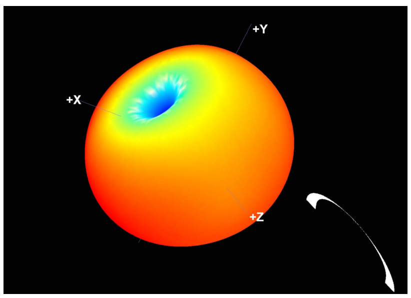

Fig. 4 Measured radiation pattern of U-shaped antenna including all metal traces of the module.

One of the major concerns of WSN's is the limited lifetime of the batteries. The cost of replacing batteries in the nodes can be relatively high especially in remotely located nodes. The same issue is of major importance in active and semi-passive RFID tags. Three different power source types are available at the moment: power reservoirs, power distribution methods and power scavenging sources.

Among the power reservoir technologies investigated over the last years [5], rechargeable lithium thin film batteries seem to be the most suitable solution to be embedded in organic substrates due to their small thickness (less than 100 um). Such batteries have rechargeable capabilities which overcome short lifetime limitations, thus making them extremely useful for the drive of the sensors in active and semi-passive RFID tags. Whereas the active tags solely utilize the battery to power the sensor and the IC, the semi-passive need a power distribution method (i.e. electromagnetic power transmission) to operate the IC, thus allowing the sensor to use the battery as an independent power source.

The main advantage of the reservoir source is that it eliminates the need for the label to collect energy from the reader, permitting the transmission of relatively large amounts of data over long distances (>100 ft.) while improving its signal-to-noise ratio. On the other hand, electromagnetic power transmission used with a battery allows for a reduced battery consumption and an increased node's lifetime.

Among the power scavenging sources, thin film solar arrays play a major advantage in outdoor applications with difficult access and impossibility of using wires (i.e. industrial chemical WSN's). In the conference we will present comparative results from three multistage-scavenging architectures for the power scavenging in UHF and Cellular bands utilizing as the integrated testbed the module of the Fig.3 with the generic architecture of Fig.5.

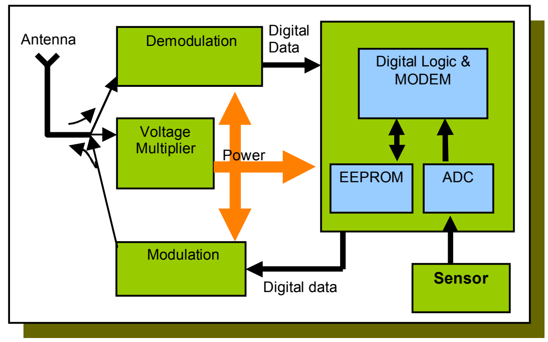

Fig. 5. *Block diagram of RFID tag.*

3. SCAVENGED SOURCES - EMC EXPERIMENTS

As for the locations of experiment, different places are chosen considering the typical places where typical business persons spend their lives in Tokyo. For the commuting by train, the selected places to measure field strength were JR Yamanote line, Oedo line, and major stations (Shinjuku and Ikebukuro). As an office environment, a university laboratory was selected where many PCs, printers, wireless LAN, and cell phones are in use. Hongo 3 chome area and Ueno park were selected as city streets and an open space area, respectively. Most of the major communication and broadcasting systems are serviced in this UHF frequency band between 75 MHz to 3.0 GHz, including TV, FM Radio, mobile phone and WiFi [4].

The detailed results show that the 76-770MHz radio and television broadcasting field strength depends strongly on the relative location between the measuring point and broadcasting antennas (as these are rather infrequent). Both distance and line of sight should be considered. The mobile communication frequencies, on the other hand, depend mainly on the crowd congestion in a given environment, as it is the number of active mobile phone equipment that directly influences the radiation level. Equipment operating in 800MHz range emits significantly stronger signal than others. The observed radiation in 800MHz is therefore relatively strong. The wireless LAN range of 2.4GHz is generally much lower than those of mobile equipment.

Assuming a typical daily life of office worker in Tokyo, the maximum energy obtained from energy harvesting is given in Figure 10.

The following formulas [5] were used during calculations:

$$P(t) \approx 31.15 \frac{G_h}{f_m^2} |I(t)|^2 \quad \text{Eq. (1)}$$

$$E = \int P(t)dt \quad \text{Eq. (2)}$$

where: E - gained energy, P - effective power, G_h - receiver antenna relative gain(We use 5dB in this estimation), f_m - frequency, $I(t)$ - measured field intensity at time t.

Bear in mind the model of life includes only 13 hours of daytime (as the radiation power inside living places was not measured). According to the graph, the 800MHz frequency band is the best choice for investigated purposes, and the obtained energy level equals to approximately 6.38J, which is more than sufficient to power an RFID circuit board for the whole 24h of continuous operation (assuming 50µW power consumption). Some measurements were also conducted concerning 800MHz and 1.9GHz mobile equipment. The field power measured 30cm from devices was 21.9mW and 4.1µW, respectively. Assuming average 384s phone calls and 162kB of data transfer daily (according to 2005 ARPU statistics), the 800MHz equipment can produce as much as 9.42J per day.

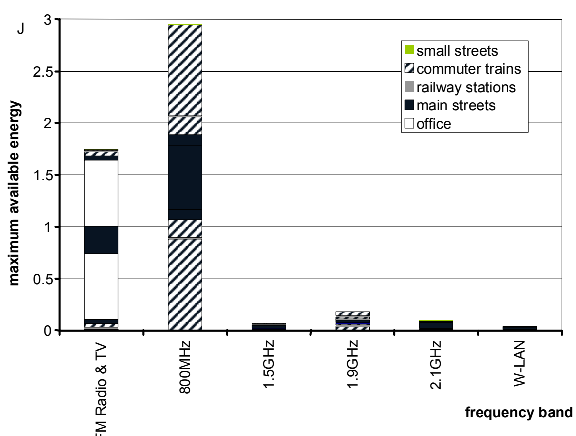

Figure 10. Maximum energy available during a typical day of Tokyo resident

Hence, the power specification for µW Computing device is 109µW for always-on services.

time	activity	location	duration
7:00	walking towards commuter train	small streets	10 min
7:10	waiting for a train	railway station	5 min
7:15	commuting	commuter train	30 min
7:45	waiting for a train	railway station	5 min
7:50	commuting	commuter train	1 hour
8:50	walking towards office	main street	10 min
9:00	working	office	4 hours
13:00	lunch brake	main street	1 hour
14:00	working	office	4 hours
18:00	walking towards commuter train	main street	10 min
18:10	waiting for a train	railway station	5 min
18:15	commuting	commuter train	1 hour
19:15	waiting for a train	railway station	5 min
19:20	commuting	commuter train	30 min
19:50	walking home	small streets	10 min

Figure 11 A Typical Daily Life of Worker in Tokyo

4. CONCLUSION

An overview of novel scavenging approaches for almost autonomous ICT applications will be discussed and evaluated in terms of efficiency, integrability, cost and applicability in rugged environments. Various frequencies of potential scavenged power will be tested and different electronic scavenging configurations will be presented and becnchmarked in comparison to commonly used approaches in low-cost paper-based inkjet-printed RF modules with 3D “cubic” antenna scavengers. Their performance will be evaluated in metal-rich multipath indoor environments, as well as in multi-users outdoor and indoor rural and urban topologies.

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