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Title: WIRELESS ENERGY TRANSMISSION TO SUPPLEMENT ENERGY HARVESTERS IN SENSOR NETWORK APPLICATIONS

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Wireless Energy Transmission to Supplement Energy Harvesters in Sensor Network Applications

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ABSTRACT

In this paper we present a method for coupling wireless energy transmission with traditional energy harvesting techniques in order to power sensor nodes for structural health monitoring applications. The goal of this study is to develop a system that can be permanently embedded within civil structures without the need for on-board power sources. Wireless energy transmission is included to supplement energy harvesting techniques that rely on ambient or environmental, energy sources. This approach combines several transducer types that harvest ambient energy with wireless transmission sources, providing a robust solution that does not rely on a single energy source. Experimental results from laboratory and field experiments are presented to address duty cycle limitations of conventional energy harvesting techniques, and the advantages gained by incorporating a wireless energy transmission subsystem. Methods of increasing the efficiency, energy storage medium, target applications and the integrated use of energy harvesting sources with wireless energy transmission will be discussed.

Keywords: Wireless Energy Transmission, Energy Harvesting, Embedded Sensing

1. INTRODUCTION

1.1 Wireless Sensor Networks

The trend toward wireless sensing networks offers many advantages in numerous engineering applications. In the present work we consider sensor nodes designed specifically for structural health monitoring (SHM). The purpose of the SHM sensor node is to improve the safety and reliability of aerospace, civil, and mechanical infrastructure by detecting damage before it reaches a critical state. The SHM process can be implemented using hardware and software components designed to provide cost-effective condition-based maintenance schedules [1], augmenting or replacing traditional time-based inspection methods. One promising method for [illegible]lementing SHM techniques is through the use of active material sensors and actuators. Such active-sensors are very e[illegible]nt in assessing the health of localized areas of a structure; however for large-scale systems it may be necessary to incorporate hundreds or even thousands of individual sensors. The cost of implementing such a vast network of sensors using traditional wired systems can be very high due to the installation and maintenance costs associated with the wiring itself. This has lead to the recent shift toward wireless sensor nodes designed specifically for structural health monitoring [2, 3].

The ability to communicate wirelessly allows the sensor node to be installed in locations that would otherwise be difficult or impossible for traditional wired systems. The flexibility that comes with a wireless sensor node makes it more amenable for integration within civil, aerospace, or industrial structures, as they can be either integrated into the design of future systems or used to retrofit existing structures without the need for significant modifications. However, this desired flexibility also comes with the necessary design considerations regarding the need for a reliable and sustainable method for powering the sensor node. Most commercially available and R&D prototype nodes rely on conventional battery technologies, requiring the periodic recharge or replacement of the power supply. One option meant to address this issue is the integration of energy harvesting strategies that could extend the life of, or ultimately replace, the battery embedded within the wireless sensor node. In this approach the node is designed to scavenge ambient energy from the host structure or its surrounding environment, convert it into a form (typically electrical) that can be stored or

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used directly to power the desired instrumentation [4-6]. In SHM applications the most common forms of available energy include thermal gradients and mechanical vibrations; however other potential sources include solar, wind and acoustic energy in some applications. While extensive research has focused on the development of an effective energy harvester, the amount of scavenged energy often falls below the levels need for powering sensing, on-board processing and telemetry subcomponents of the standard wireless sensor node, and this is especially true for nodes with active sensing capabilities. To address these issues our team has worked to develop a sensor node with the explicit intent that it be able to operate using either harvested energy or energy received from directed RF energy transmission.

One approach to improving the sensor nodes' performance is to develop a hybrid, or multi-source energy harvesting solution [7], where energy is extracted from a combination of different sources (e.g. thermal, mechanical, chemical). The energy from each of these different sources is then conditioned and used to charge a common storage medium. Such an approach could be used to augment batteries that are installed in the sensor node, or they could be coupled with a directed RF energy system that could periodically bring energy near the sensor node, allowing the node to harvest this microwave energy and use it to supplement the energy harvesting system.

In this paper we present several studies performed to 1) characterize the potential of conventional energy harvesting methods, and to 2) implement a hybrid energy solution whereby the energy harvested from the environment is supplemented by energy transmitted using an RF source. The harvested ambient and received RF energy is then used to operate a recently developed low power sensor node [8]. The sensor node under consideration is capable of measuring and recording the electrical impedance of piezoelectric transducers, providing information about the structural health of a system through the coupled electromechanical properties of the piezoelectric. This sensor node combines several different components, including a microcontroller for onboard computing, telemetry for wireless data transmission, multiplexers for managing up to seven piezoelectric transducers per node, energy harvesting and storage mediums, and wireless triggering circuits into one package that offers a comprehensive, self-contained active-sensor node for SHM applications.

1.2 Energy Harvesting Overview

Of the common energy harvesting methods, the three most common methods under investigation for their feasibility in powering a WSN are: ambient vibration harvesting with piezoelectric materials, thermal energy harvesting with thermoelectric materials, and solar energy harvesting with photovoltaic cells. This study focused primarily on energy harvesting from ambient vibrations using piezoelectric materials. However, researchers have obtained good results by combining independent ambient energy harvesting techniques, utilizing thermoelectric materials exhibiting a high Seebeck coefficient (such as bismuth telluride), as well as conventional photovoltaic solar cells [9].

Piezoelectric materials belong to the family of materials whose molecular structure consists of electric dipoles. Under the piezoelectric effect, when a mechanical strain is present in the material a potential difference is created across the dipoles. Piezoelectric materials can operate in either a bending or a stack configuration. In the stack configuration large forces can be obtained but only with very small associated deflections. In the bending configuration, relatively larger deflections can be tolerated, which makes that configuration better suited for energy harvesting purposes. Tests have shown that piezoelectric-based energy harvesters are capable of producing approximately 800 μW/cm3 when mounted to machines that vibrate in the kHz range [6].

1.3 Wireless Energy Transmission

One alternative to traditional energy harvesting systems is the use of RF energy transmission to remotely power the WID3 sensor node. While this method can be used to harvest ambient RF energy in urban areas, our focus has been on the use of directed RF energy to remotely power the sensor node. In this paradigm the WID3 is outfit with a tuned receiving antenna designed to collect a specific bandwidth of energy that is being transmitted by a mobile agent used to power and interrogate sensor nodes mounted on civil infrastructure.

In the current paradigm for SHM sensor networks, sensors and sensor nodes are installed in discrete locations throughout a host structure to measure, process and transmit relevant data to a central station where it is post-processed and decisions are made regarding the health of the structure. One key component of this design is the nodes must be powered, either through a network of wires, or through localized sources that are mounted with, or near, the sensor node. The use of a wired network has been shown to be inefficient due to installation and maintenance costs associated with the wiring, while the use of localized batteries leads to recharge / replacement issues that would need to be considered when placing sensor nodes. To alleviate this issue a new method has been recently proposed by the authors which integrates the transmission of microwave energy wirelessly with remote interrogation platforms to assess damage within structural systems [10]. This mobile platform would be designed to serve as the RF energy source, as well as a relay- or base-station that could receive and process data from the sensor network, alleviating the need for hopping protocols in data transmission and the power limitations associated with large-scale wireless sensor networks.

Originally considered for alleviating the wiring harness in space structures, or micro-aerial vehicles, or providing extremely low power for those typically used in RFID tags in the 1-100 μW range, the application of a RF wireless energy transmission system for powering electronics used in distributed sensing networks has not been studied substantially in the past. In particular, the application of this technology for SHM sensor nodes to alleviate the challenges associated with power supply issues has only recently begun to appear in the literature. Therefore, the authors recently proposed a new and efficient SHM sensing network whereby the electric power and interrogation commands are wirelessly provided by a mobile host [10-12]. This approach involves using a mobile platform to generate an RF signal near receiving antennas that are connected to the sensor nodes embedded on or within the structure. The sensors measure the desired response at critical areas on the structure and transmit the signal back to the mobile host via RF communications. The 'wireless' communications capability draws power from the RF energy transmitted by the mobile host, using it to power both the sensing circuit and the transmission of data back to the host. This research extends the traditional sensing network to the next level, as mobile hosts (such as UGV or UAV) will be used to interrogate known critical infrastructure based on GPS navigation, deliver required power, and conduct an inspection of the structure without human intervention. The mobile host will be used to search for sensors on the structure and gather critical data needed to perform the structural health evaluation. This integrated technology will be directly applicable to rapid structural condition assessment of buildings and bridges after an earthquake or other significant event. Also, this technology may be adapted and applied to damage detection in a variety of other civilian and defense-related structures such as pipelines, naval vessels, aircraft, hazardous waste disposal containers, and other locations where it is dangerous for humans to access. It should be emphasized that this technology can be hybrid in that the sensor node is still equipped with energy harvesting devices and the mobile host would provide supplemental energy if the harvester is damaged or unable to provide enough power to operate the sensor nodes. Even if the energy harvesting device provides sufficient power, the mobile host can wirelessly trigger the sensor nodes, collect information and/or provide computational resources, significantly relaxing the power and computation demand at the sensor node level.

2. WIRELESS SENSOR NODE

2.1 Background and Overview

The wireless impedance device (WID) was originally developed based on capabilities demonstrated in previous studies of the impedance-based structural health monitoring method [13]. The impedance method uses high-frequency vibrations to monitor for changes in structural impedance that would indicate damage. The impedance method can be implemented with relatively low power compared to other active-sensing SHM techniques such as Lamb wave-based methods. The impedance method also has applications in sensor self-diagnostics to determine the operational status of piezoelectric active-sensors used in SHM [14].

Three generations of the WID have been developed and field-tested by our research team [15-17]. The WID2 was developed to address some of the limitations of the previous version, which could monitor only a single sensor, had limited triggering capabilities, and used telemetry components with high power demands. The WID3 has further extended capabilities with advanced communications, increased triggering options, local data storage, and multiple powering options including a variety of energy harvesting sources. The WID3 can self-configure into a network with neighboring sensor nodes at fixed time intervals or in the presence of a 'mobile-agent' that interrogates the sensor network.

In addition to improving the capabilities of the previous WID versions, the WID3 has been designed to function as part of a modular hardware platform that incorporates other sensing modalities on separate boards, including time-domain measurements. By combining modules, resources such as telemetry, processing, data storage, and respective measurement capabilities of each module can be shared, resulting in a highly functional sensor node. This integrated sensor node combines both actuation and sensing capabilities in a single package with the ability to implement multiple SHM techniques for the rapid health assessment of civil, aerospace and mechanical infrastructure.

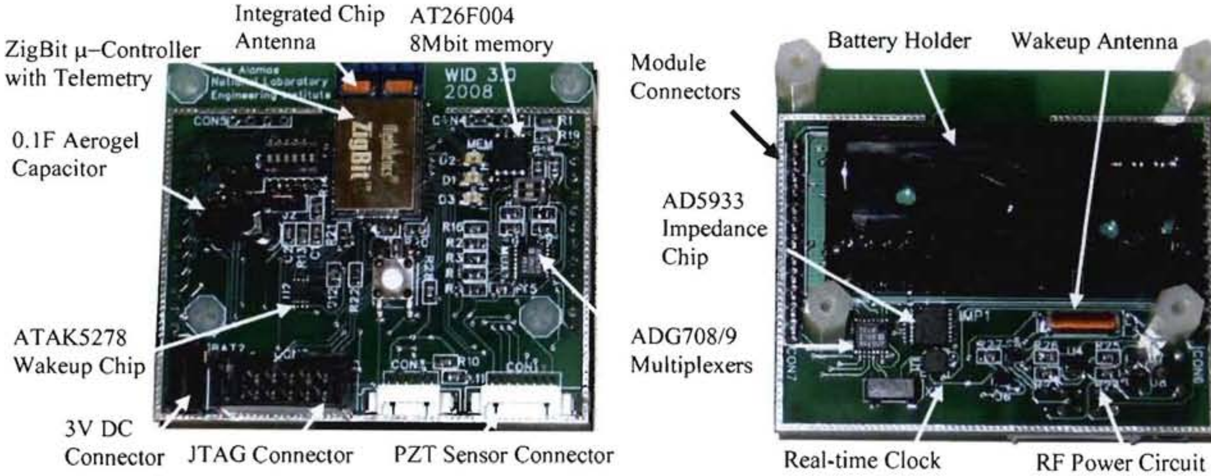

Fig. 1. Major components of the WID3

2.2 WID3 hardware and capabilities

The major hardware components of the WID3 are shown in **Error! Reference source not found.**. The WID3 uses a ZigBit module which integrates an Atmel ATmega1281v microcontroller (µCu) with an Atmel AT86RF230 radio in a single integrated circuit (IC). The µCu is part of Atmel's 8-bit AVR line, and it contains 128kB of flash memory for algorithm and code storage. It also contains 8kB of SRAM for program execution. The AT86RF230 is an 802.15.4 compliant radio, and it uses an open media access control (MAC) table distributed by ZigBit. The availability of the MAC table facilitates programming for robust data transmission. The AT86RF230 has very low energy requirements and requires few external components, making it particularly attractive for an SHM device.

The key measurement component the WID3 is the AD5933, an IC for impedance measurement. This IC has the ability to measure electrical impedance up to 100 kHz. The AD5933 can only measure a single channel, but the WID3 is equipped with two low-power and low-resistance multiplexers, which are indicated in **Error! Reference source not found.**. Each multiplexer has eight total inputs, providing for four impedance measurement ranges and the ability to measure seven sensors. One of the sensor ports is dedicated to a calibration cycle, reducing the number of sensor channels from eight to seven.

There are two main options for data storage on the WID3: internal EEPROM on the ATmega1281v, and a flash memory module, the Atmel AT26F004. The data storage available in these locations is 8kB and 512kB, respectively. The WID3 has very low maximum power consumption in spite of the active nature of its measurements. Operating at 3V, the WID3 takes 16 seconds to measure four sensors with 100 points and four averages per point. With data reduction, only a few seconds would be required to transmit the data, or a few microseconds to store the data locally. The current draw can also be reduced to approximately 0.01mA with proper use of sleep modes. With these steps, the WID3 could take, analyze, record and send one measurement per day for over 5 years on two conventional AA lithium batteries. At this extremely low power level, the WID3 could also be powered by a wide range of energy harvesting methods.

The WID3 has multiple powering options, all of which can be utilized to communicate to the WID3 the desired behavior on powering and/or awakening. From a zero-power state, the WID3 can be initialized by powering it either through a concurrently mounted energy harvester or by directly beaming RF energy. By simultaneously utilizing the WID3's included low frequency wake-up chip, the Atmel ATA5283, the WID3 can be instructed to transmit its stored measurements to an inspector's computer system located with the RF power source. This wake-up method would be used by a mobile-agent for recording on-demand measurements. From a low-power sleep state maintained by an energy harvester or a small rechargeable battery, the low frequency trigger or the WID3's internal timer can be utilized to collect on-demand or scheduled measurements, respectively. With these solutions available, the WID could run in low duty cycle operation with additional on-demand measurements indefinitely with only a small local power storage capability.

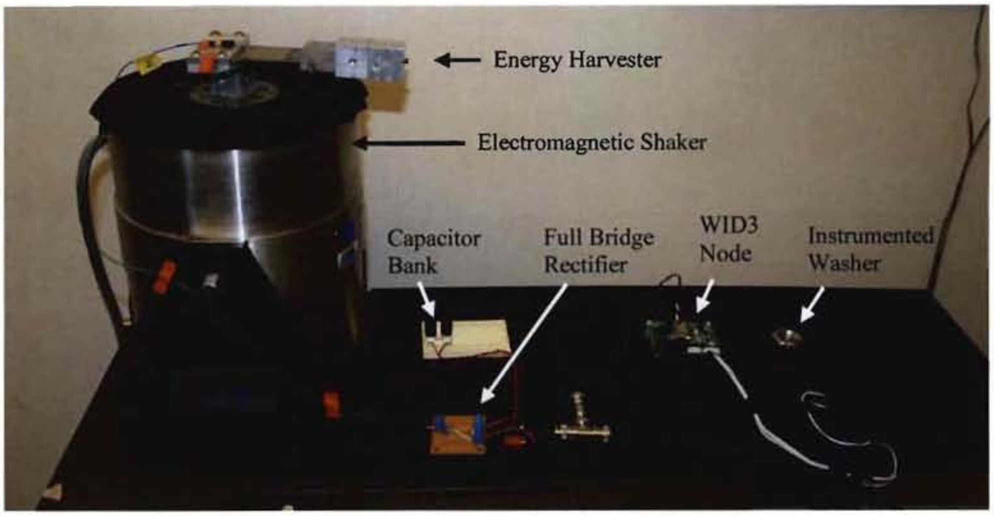

Fig. 2. Cantilevered beam with piezoceramic patches mounted in a bimorph configuration, subjected to base excitations.

3. EXPERIMENTAL RESULTS

3.1 Energy Harvesting

Energy harvesting test setup: PSI-5A4E lead zirconate titanate (PZT) piezoceramics from Piezo Systems, Inc. were used as the electromechanical transducers in this study. In the energy harvesting experiment, PZTs (3.6cm x 3.6cm x 0.27mm) where mounted in a bimorph configuration on a thin spring steel substrate (3.8cm x 86.5cm x 0.5mm) cantilevered from a clamping fixture that provided a base excitation (see **Error! Reference source not found.**). Aluminum blocks (2.5cm x 2.5cm x 2.5cm) were added as a tip mass to reduce the natural frequency of the test sample, increasing the transverse displacement of the cantilevered beam (and thereby the strain in the PZT), while maintaining a higher frequency to maintain efficient energy conversion. In previous studies, such a test fixture was tuned to match the fundamental frequency observed in the vibration response of the Omega Bridge, located in Los Alamos, NM [18]. A more detailed description of the energy harvester, including its analytical model and experimental verification has previously been presented by the authors [18]. Researchers have also worked to develop broadband vibrational energy harvesters [9].

The energy harvester used in this investigation was first characterized with a 0-1000Hz chirp excitation, provided by a Vibration Test Systems model VG-100-6 electromagnetic shaker. The first three natural frequencies of the energy harvester were measured to be 11.8Hz, 119.5Hz, and 775Hz (see Fig. 3). From the measured response it was decided

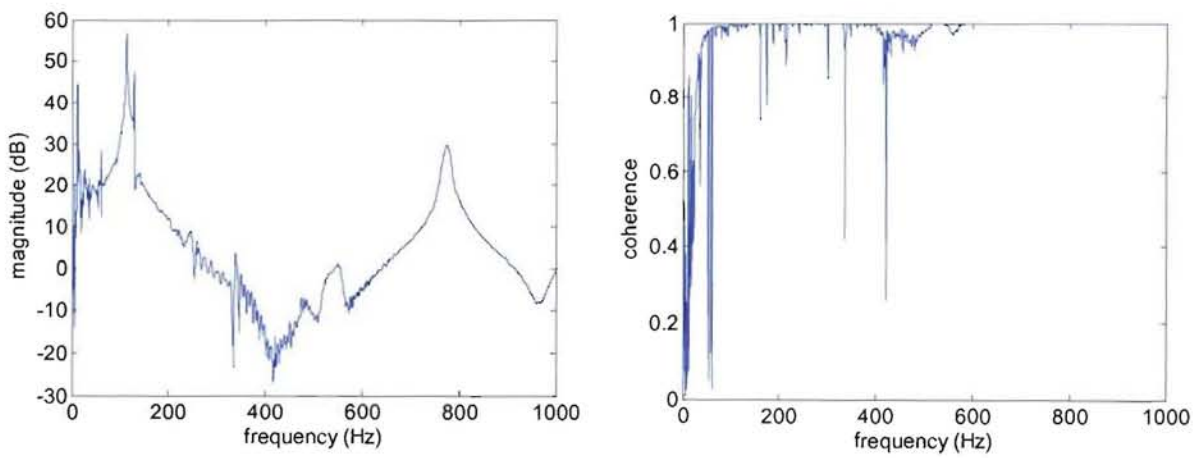

Fig. 3. Frequency response (left) and coherence (right) measurements of the cantilevered energy harvester.

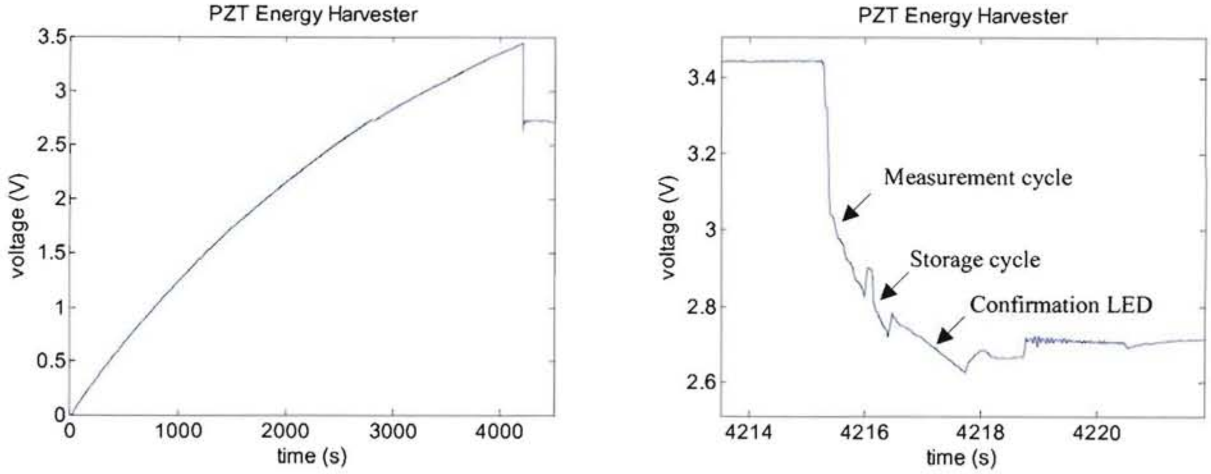

Fig. 4. PZT energy harvesting results: PZT charging profile (left) and close-up of WID3 measurement profile (right).

that the harvester should be excited at its second natural frequency (119.5 Hz) for the harvesting studies. Using a sinusoidal excitation generates an alternating output voltage from the PZT bimorph that was conditioned through a full bridge rectifier and used to charge a 0.1F capacitor bank that connected to the WID3 sensor node as shown in Fig. 2.

The voltage stored within the 0.1F capacitor bank was monitored to characterize the charging capabilities of the PZT energy harvester. From the response presented in Fig. 4 it is seen that the energy harvester requires approximately 70 minutes to obtain the 3.5V needed to trigger the power conditioning circuit on the WID3. In this experiment the WID3 is programmed to monitor the electrical impedance of an instrumented washer when the energy harvester produces the required 3.5V needed to trigger the power conditioning circuit. The power drawn during WID3 operation is illustrated in detail in Fig. 4 (right). As seen in the figure, most of the power is used to power up the micro-controller and to measure the status of the instrumented washer. Following the measurement cycle some energy was replenished by the harvester before the data was written to the WID3 flash memory during the storage cycle. Once data was written to memory, an LED was illuminated to confirm the successful operation. As the stored voltage drops to 2.7V, the power conditioning circuit removes power from the micro-controller, allowing the energy harvester to once again begin charging the 0.1F capacitor bank.

3.2 Wireless Energy Transmission

RF Energy transmission test setup: In previous iterations, researchers in the authors' group used commercially available transmitting and receiving antennas [15]. While commercially available parabolic grid antennas are still useful for transmission, custom microstrip patch antenna arrays designed by our group in both 2.4GHz and 5.8GHz frequency bands significantly outperform commercially available designs on a per receiving area basis [18, 19]. A more detailed description of the individual patch antenna arrays can be found in the references [18, 19].

For a single microstrip patch antenna such as the one shown in Fig. 5, the gain associated with an individual antenna is relatively low (1-2%) at 1-meter spacing [19]. However, the overall performance can be greatly enhanced as large arrays of the microstrip patch antennas can be fabricated with relative ease. The array configuration greatly enhances the receiving antenna's performance as it can harvest much more of the incident wave generated by the source antenna. Additionally, each individual microstrip patch can be connected in combinations of series and parallel circuits in order to select the voltage level output from the array. Each element in this array is coupled with its own rectifying circuit, such that the output of each element is a rectified version of the microwave transmission. The result of integrating the rectifier with the antenna design is commonly referred to as a 'rectenna' [20]. For the rectenna shown in Fig. 5, the patch antennas are connected in groups of four (each in series), with these groups subsequently connected in parallel to increase the available current. In this configuration, laboratory tests have shown that the thirty-two element antenna array is capable of charging a 0.1 F capacitor to 3.5 V in 35 seconds when located 0.75 m from a source antenna emitting 910mW of power in the 5.8 GHz range.

When used to power the WID3 sensor node, the capacitor is quickly charged to the threshold voltage of 3.5V, at which point current is allowed to flow into the WID3. The charging profile observed when powering the WID3 with the RF

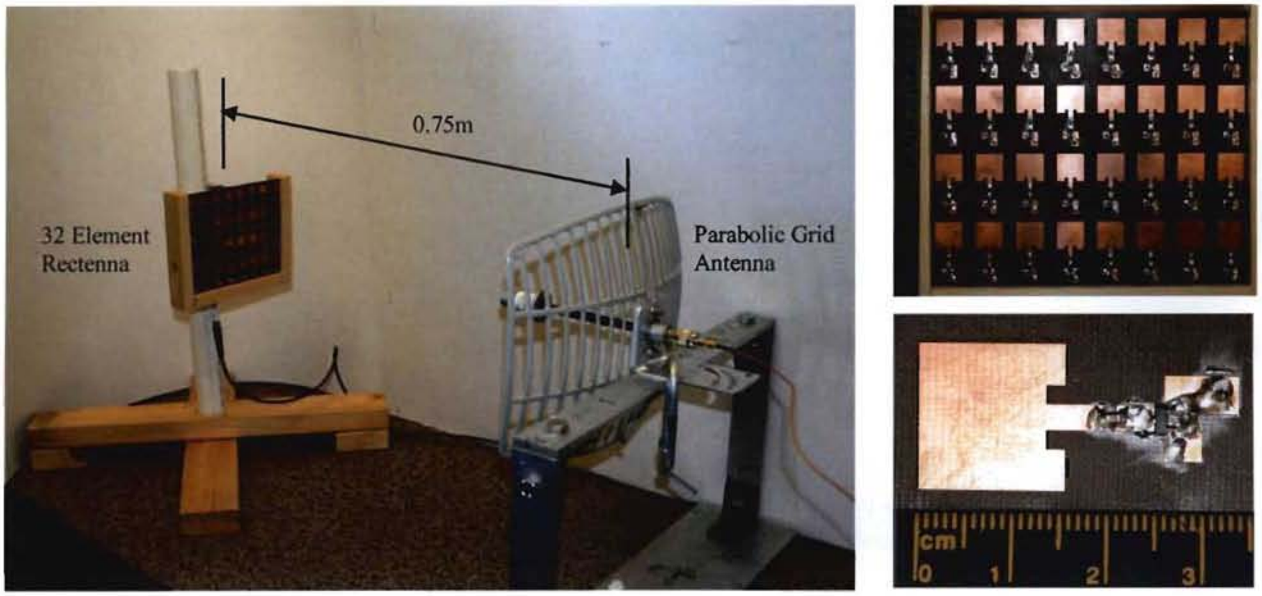

Fig. 5. 5.8 GHz energy transmission test setup (left), with the 32 element rectenna array used in this study (top right) and close-up of single receiving patch (lower right).

source is shown in Fig. 6. Shortly following the 40 second mark in Fig. 6 (left), the WID3 begins drawing power to take an impedance measurement and subsequently store the measured data in onboard flash memory. Using the RF source, three repeated measurements were taken in quick succession, with the charge / discharge cycles clearly shown in Fig. 6 (left). In this manner, on-demand measurements can be taken as desired using transmitted RF energy without the need for a dedicated on-board power supply. As expected, the close-up of the WID3 measurement profile using RF energy, shown in Fig. 6 (right) almost identically matches that for the energy harvester method, visible in Fig. 4 (right).

3.3 Combined Harvesting and RF Transmission Experimental Results

Following the successful demonstration of both energy harvesting and energy transmission techniques, the two systems were combined to provide a hybrid power system. In deployed mode, the PZT energy harvester may only provide sufficient energy for extremely low duty-cycle operation, depending on the available ambient energy sources and the extent of the measurements desired. In the case that an off-cycle measurement is desired, RF energy can be brought to the node to provide instant (by comparison to the PZT harvester) power for additional measurements, processing and

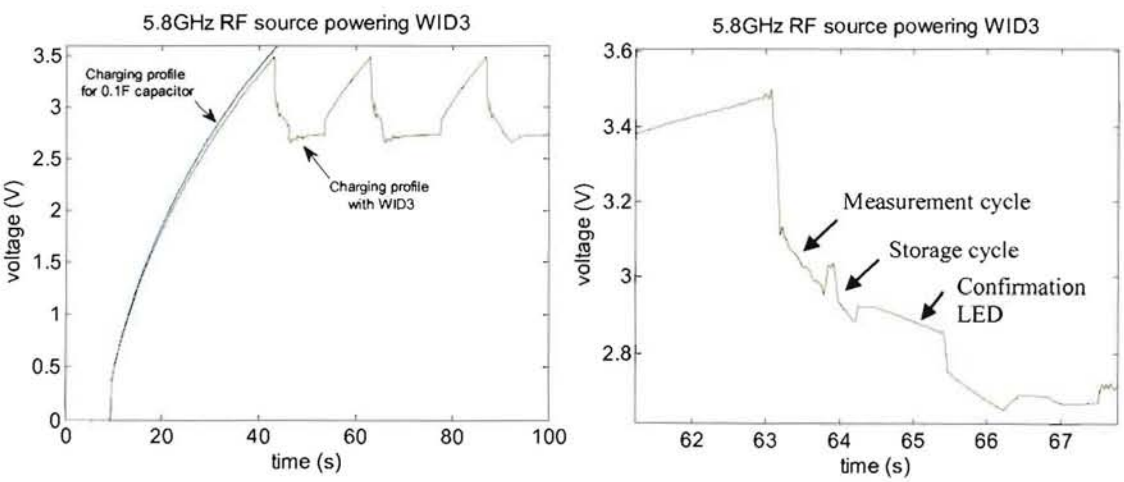

Fig. 6. 5.8 GHz RF source powering WID3 with multiple measurement cycles (left) and close-up of WID3 measurement profile (right)

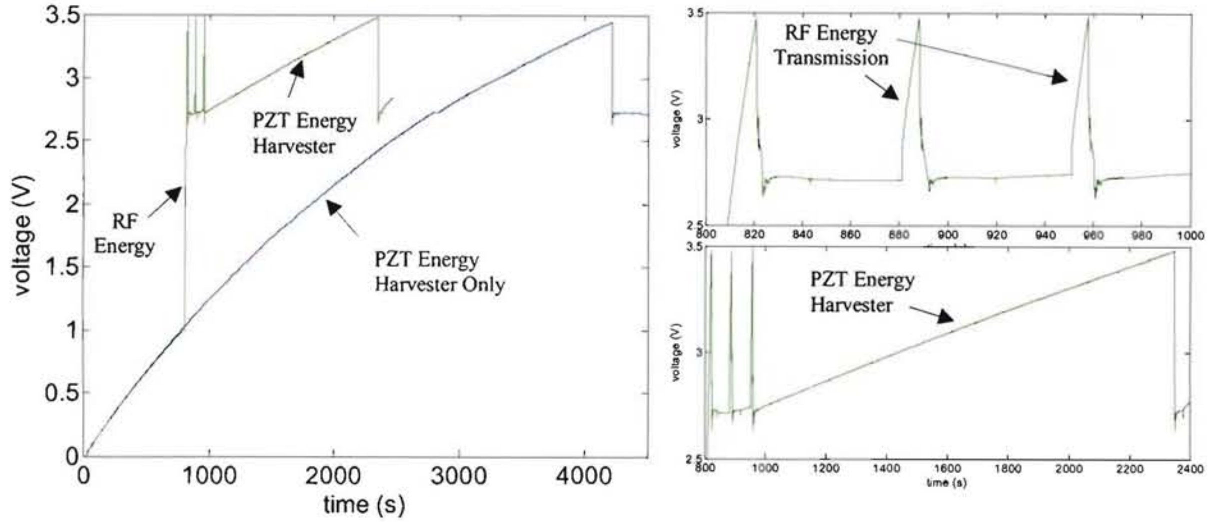

Fig. 7. Hybrid PZT charging profile with 5.8 GHz supplemental energy transmission (green) overlaying energy harvester charging profile alone (blue)

communication. Fig. 7 (left) shows the capacitor's voltage response when charged by the PZT (in blue), indicating a charging time of just over 4200 seconds, or slightly more than an hour. Shown on the same plot in green is the combined harvester and RF transmission power trace, wherein the RF source was brought to the node as the capacitor reached approximately 1 Volt using the PZT energy harvester. In very short order (<30 seconds) the WID3 was powered, and then it cycled through three measurement cycles before returning to the PZT harvester charge rate. A close-up of the three measurement cycles is shown in Fig. 7 (top right), and a close-up of the power circuit's return to the PZT harvester charge rate is shown in Fig. 7 (bottom right). Note that after performing the on-demand measurements, the PZT harvester needs only to charge the capacitor from 2.7 Volts, because the power conditioning circuitry on the WID3 maintains a 2.7V pre-charge on the capacitor following a measurement or communication operation.

4. SUMMARY AND FUTURE WORK

In many applications there is enough ambient energy from kinematic or thermal sources to power low level operations on wireless sensor nodes given a low enough duty cycle. This is especially true for systems were asynchronous measurements can be used across the network and local nodes can operate basically as stand-alone devices. The main difficulty in this approach is the need to extract data from the individual nodes, requiring more power intensive transmission operations that may be too taxing for the energy harvesting system. Therefore, in this study a hybrid energy harvesting / energy transmission approach was examined as a possible alternative in which power is supplied for normal measurement operations by a piezoelectric energy harvester, then augmented by a RF energy transmission system for on-demand measurements and data extraction. The energy harvester developed in this study was used to power a WID3 sensor node previously developed by the authors, providing a measurement duty cycle of 70 minutes when the storage capacitor is completely drained, and a duty cycle of 25 minutes when the WID3 power conditioning circuit disconnects power at 2.7V. For on-demand measurements a 5.8GHz RF transmission system was used to power the sensor node, requiring ~ 30 seconds to charge the storage capacitor from 0V to 3.5V; and 9.5 seconds to charge the system from 2.7V to 3.5V during subsequent operating cycles. Laboratory tests demonstrated energy harvesting and transmission approaches could be combined to provide a hybrid power system that relies on ambient energy to power standard measurement operations, and that RF energy could be used to provide supplemental power for on-demand measurements and data transmission operations. The next state of this study will be to optimize the power conditioning circuitry that combines the power sources, and integrate these within the WID3 sensor node itself. Future demonstrations of this technology are intended to be on civil and energy infrastructure through tests at the Alamosa Canyon Bridge in southern New Mexico, and on a suite of small- to mid-scale wind turbine blades under investigation in condition and structural health monitoring studies.

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