NFC Hybrid Harvester for Battery-free Agricultural Sensor Nodes

Spyridon Nektarios Daskalakis, George Goussetis, Apostolos Georgiadis,
School of Engineering & Physical Sciences, Heriot-Watt University, Edinburgh, UK
{sd70@hw.ac.uk, g.goussetis@hw.ac.uk, apostolos.georgiadis@ieee.org}

***Abstract*—This paper presents an efficient, low-complexity, low-cost hybrid power harvester for supplying agricultural battery-free sensor nodes. The design is a solar/electromagnetic (EM) energy harvester that uses energy from solar radiation and NFC (Near Field Communication) technology at the same time. The design consists of an NFC coil antenna, a full wave rectifier operating at 13.56 MHz, a solar cell and a capacitor for energy storage. The NFC coil antenna is connected to the rectifier circuit that provides the rectification of the incoming EM signals and the collection of dc energy coming from the solar cell. The harvester was connected to a commercial dc-dc converter and the open circuit voltage was increased from 80 mV to 4.6 V, charging a 1000 μF capacitor. The harvester was fabricated on FR-4 substrate in order to reduce the overall cost of the future sensor node. The stored energy could supply a sensor in a wireless network, with average power consumption 60 μW.**

***Index Terms*—Boost converters, energy harvesting, Internet-of-Things(IoT), NFC (Near Field Communication), rectifier, wireless power transfer.**

I. INTRODUCTION

Near-field communication (NFC) is famous wireless communication technology within the set of radio frequency identification (RFID) systems that allows communication between two devices separated by a few centimeters [1]. The recent inclusion of NFC readers into smartphones has enabled a resurgence in near-field RFID technology with applications focused on human-computer interaction, smart homes, payments and healthcare. An NFC device can operate at the frequency of 13.56 MHz as reader or tag and has three different modes in the communication [2]. The "reader/writer" mode, uses a NFC reader or smartphone to read/write information that are pre-stored in an NFC tag. The "peer-to-peer" mode can be applied in information sharing between two NFC devices. With "card emulation" many integrated circuit (IC) cards such as credit cards could be replaced by smartphones for access control, transportation or payments. This technology is also widespread for development of low-cost sensors, since it provides an easy way to get the data from them, simply approaching the reader to the tag without need of pairing the two devices [3]. The most significant advantage of NFC, is that devices can work in a battery-less mode by harvesting energy from magnetic field induction between reader and tag antenna [4], [5].

In [3], a battery-less NFC tag is presented and it is able to sense soil moisture, temperature and relative humidity parameters. The tag uses NFC energy harvesting capability thus the magnetic field generated by a commercial smartphone, is stable enough to power the microcontroller, the sensors and the other components of the tag. In [5], the authors present a programmable, sensing and computationally enhanced platform (NFC-WISP) for RFID enabled sensing and user interface applications. It is fully powered and read by commercially available RFID readers and includes temperature/acceleration sensors, LEDs and an active bistable matrix E-ink display.

Today, there is a necessity for precision agriculture techniques in agriculture sector in order to minimize the production risk. By deploying low cost and battery-free sensors and monitoring the microclimate conditions (temperature, soil moisture, etc.) the producers could stop make decisions based only on their own practical experience and optimize their daily tasks. Our lab project discusses the implementation of a low-cost and low-power wireless sensor network for agricultural applications [6], [7]. Each sensor node could have a super capacitor instead of battery thus the idea is to create a low maintenance batteryless system. Each sensor node will include environmental sensors of humidity, temperature, atmospheric pressure and it will be able to send data wirelessly to a low-cost base station via Bluetooth Low energy (BLE) or backscatter technology. The deployment of the network will be outdoors and a small solar panel will provide energy autonomy to each sensor node for two days. In order to maximize the energy autonomy, every node is kept in sleep mode for most of the time. When an event occurs, the device wakes, takes the data from its sensors and a short message is "advertised" to a nearby base station.

The sensor node includes also integrated NFC technology for interaction with the farmer's smartphone. The farmer could securely read device's identification (ID) number or upload configuration parameters without moving the node from its installed position. The NFC can be also used for powering the sensor in parallel with solar panel offering a additional wireless power transfer capability. For example, in a extreme cloudy weather scenario (dark for more than four days), the farmer could activate each sensor using his smartphone. Trying to find a solution for the above extreme situation, this work is an attempt to develop a power harvester for our sensor node using circuits necessary to combine the output of a solar cell and an NFC electromagnetic harvester [8]. The circuit includes an NFC antenna, an NFC rectifier, the solar panel and a commercial boost converter working all together in order to charge a super capacitor. The proposed circuit is capable to harvest solar ambient energy and electromagnetic (EM) radiation at NFC frequencies, providing a certain amount of

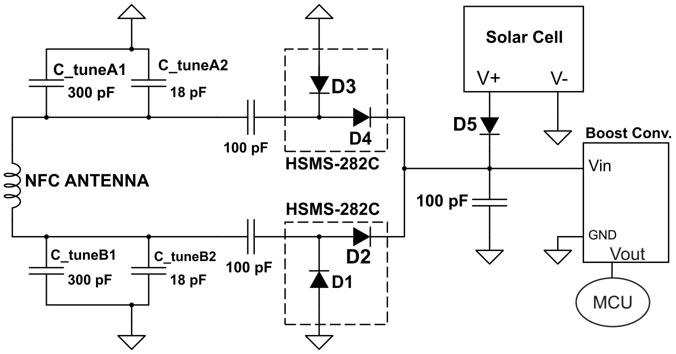

Fig. 1. Schematic of the proposed dc combining circuit for power harvesting. The boost converter is supplied by the solar panel and the NFC rectifier.

power to the boost converter (Fig. 1).

The work is summarized as follows: in Section II, the analysis of the NFC antenna and the rectifier is presented. It is also described how the NFC antenna can be tuned. Section III describes the boost converter part and in Section IV, experimental results are presented. The work is concluded in Section V.

II. Hybrid Power Harvester

A typical NFC communication system consists of two devices, an active and a passive device. The active device has a power source and induces a magnetic field with a coil inductor antenna. When the passive device is placed in this magnetic field, the varying magnetic field will induce current (power) in the passive device. The induced power in the passive device is used to retrieve and transmit data back to the active device. An active device can also be called a poller and a passive device can also be called a listener or a tag. In our work, as a tag we amuse the power harvester module connected with the future designed sensor node. The sensor nodes will be based on the nRF52832 system on a chip (SoC) which supports BLE and NFC technology for communication. Fig. 1 shows the block diagram of the hybrid inductively coupled power transmission system which consists of a magnetic inductive coil antenna, a rectifier, a solar cell and a dc-dc boost converter.

The NFC antenna is a coil inductor, and together with capacitors to ground (C_{tuneA1}, C_{tuneA2}, C_{tuneB1} and C_{tuneB2}), they form a parallel resonant LC tank. The inductive coil captures the RF signal and the coupled energy is then passed to a resonance tuning circuit to generate AC voltage. High transmission frequency as 13.56 MHz adopted by NFC specification means smaller matching and filtering capacitors in the antenna matching circuit. A maximized power transfer takes place when the active antenna of the smartphone and the passive antenna of the tag have the same resonance frequency. Since the active device operates at 13.56 MHz, the passive antenna should also resonate at the same frequency. In addition to the resonance frequency, the antenna's physical size and shape also matters. In our work, a reference design from Nordic Semiconductor was selected as NFC antenna thus it follows the resent standards of commercial NFC tags [9]. The goal of the tuning is to find the optimal value of the parallel capacitors, $C_{\text{tuneA1,2}}$, $C_{\text{tuneB1,2}}$ so that the resonance frequency of the LC circuit be at 13.56 MHz.

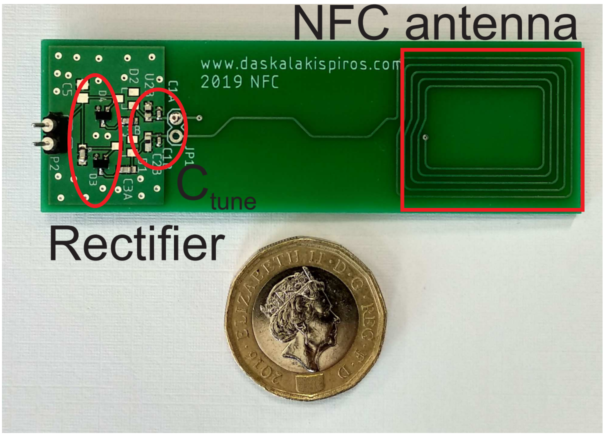

Fig. 2. The fabricated rectifier and NFC antenna on the same printed circuit board. The NFC coils is connected to the rectifier through four tuning capacitors.

The unregulated AC input voltage is converted by a full wave rectifier to a dc voltage first, and then managed by a dc-dc boost converter in order to charge a 1000 μF super capacitor. For the rectifier, the Avago HSMS-282C zero-bias Schottky diodes were used for their high-detection sensitivity at microwave frequencies. The rectifier is based on an differential design with four diodes. In our case, this acts as a full wave rectifier and gives an improved output compared to the single ended or half wave counter part, as there is always a conductive path in the circuit for both positive and negative half cycle of the input signal [10]. For the solar panel, a Polycrystalline silicon board 45×45 mm (0.25 W, 5 V) was selected and is was connected at the output of the rectifier through an extra Schottky diode (Fig. 1). The output of the solar cell and the rectifier, are joined together, adding the currents from each part and finally, feeding a 100 pF capacitor. The NFC antenna with the rectifier and the matching network was fabricated on low cost FR-4 substrate as depicted in Fig. 2.

The resonance frequency of the tag can be calculated using the formula:

$$F_0 = \frac{1}{2\pi\sqrt{L_c(C_{\text{IC}} + C_{\text{p}} + C_{\text{tune}})}}. \qquad (1)$$

Where L_c is the antenna inductance of the tag, C_{IC} is the internal IC capacitance or in our case the capacitance of the tag circuit, C_{p} is the layout parasitic capacitance, C_{tune} is the summation of the capacitance used to adjust the resonance frequency to the operation frequency of 13.56 MHz. The C_{tuneA1} must have the same value with C_{tuneB1} and C_{tuneA2} must have the same value with C_{tuneB2}, respectively. The internal capacitance C_{IC} was measured at approximately 4 pF, and L_c was measured with a Vector Network Analyzer (VNA) at 918 nH. A practical procedure to adjust the tuning capacitance can be performed with a VNA or using above equation. In our

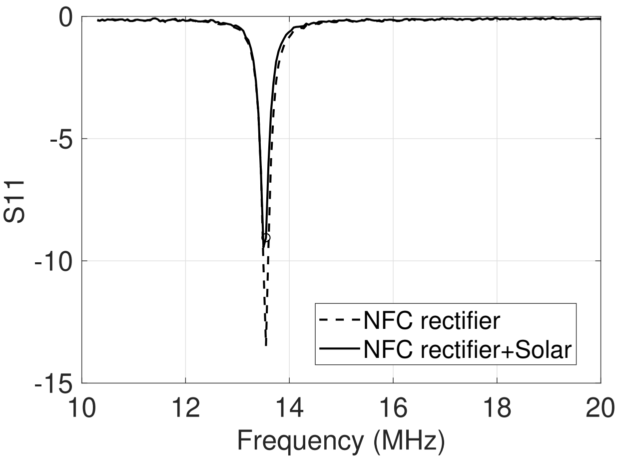

Fig. 3. The return loss in the test coil antenna over a frequency span of 10–15 MHz. The hybrid harvester resonates at 13.56 MHz.

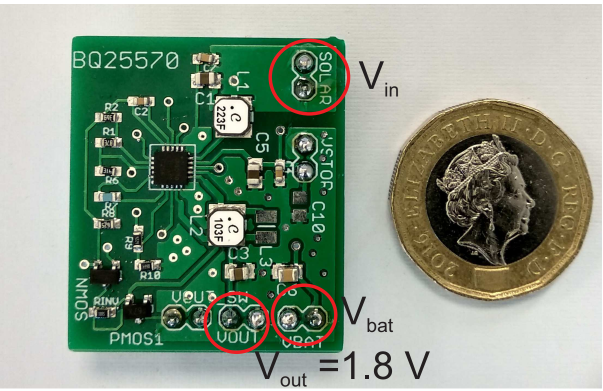

Fig. 4. The fabricated board with the dc-dc converter. Texas Instrument BQ25504 was chosen including maximum power point tracking (MPPT) operation.

case, the return loss of the coil antenna was measured with the VNA over a frequency span of 10–15 MHz to find the optimal value of the parallel capacitors. The frequency that results in a dip is the resonance frequency of the NFC tag antenna. In order to make the circuit resonate on a frequency close to 13.56 MHz, the values of C_{tuneA1} and C_{tuneA2} were found at 300 pF and 18 pF, respectively For the VNA measurement, a same NFC antenna was connected to port 1 and the S_{11} parameters are measured with the tag connected with the boost converter circuit that is described below. The distance between the test antenna and the tag antenna was large enough (1 cm) to avoid the coupling between them. The measured S_{11} parameters of the test antenna are presented in Fig. 3. It can be observed that the NFC harvester resonates at 13.56 MHz after tuning. The harvester was measured with and without the solar panel connected at its output.

III. BOOST CONVERTER

The Texas Instrument BQ25570 IC was chosen as our power management unit with a boost charger, and a nanopower buck converter at the output [11]. The converter includes maximum power point tracking (MPPT) with minimum cold start voltage and typical input power of 330 mV and 10 μW, respectively. The BQ25570 was connected at the output of the rectifier in order to boost the output voltage of the charge pump and store the dc power in a 1000 μF super capacitor. Once the power received by the rectifier, is sufficient to turn-on the power management IC, it begins accumulating charge in the capacitor. When the voltage accumulated in the capacitor (V_{bat}) exceeds 2.5 V, the power management IC releases the power to output in order to supply the future sensor node. The output voltage (V_{out}) of the power management IC can be determined by external resistors from 1.5 V to 5 V. In this application, the output voltage is set to be 1.8 V because our future sensor node requires a minimum supply voltage of 1.7 V. Once a sufficient voltage is obtained, the sensor node starts operating in active mode, utilizing the energy stored in the capacitor. As the capacitor discharges, the output voltage remains 1.8 V until the stored voltage decreases to 1.9 V. Then the power management IC disconnects the sensor node and sensors from the capacitor to recharge the voltage of the supercapcitor to 2.5 V again. The period of the operating/recharging duty cycle is determined by the output power level of the charge pump, the efficiency of the power management IC, and the capacitance of the energy tank. The boost converter is depicted in Fig. 4 and was fabricated in separate printed circuit board (PCB) for debug purposes.

IV. EXPERIMENTAL RESULTS

The power harvesting performance of our circuit were tested using a signal generator and a Huawei P8 lite smartphone that includes NFC communication. The Huawei smartphone allows for a more real world testing scenario but offered limited control over the NFC communication. The "NFC Research Lab" Android application was used to activate the NFC. In this case, was observed that the smartphone continuously scanned for tags using multiple NFC protocols at output power level of approximately 3 dBm. The output power of the smartphone was measured using a same antenna with our design and a spectrum analyser. The "Max hold" reading of the smartphone NFC signal is shown in Fig. 5.

A LED with current consumption at approximately 20 mA, was connected at the V_{out} pin of the boost converter emulating the load of our sensor node. When the capacitor's voltage reached an upper limit V_{high} = 2.5 V, the capacitor was connected with the LED, causing it to flash. When the capacitor decreasing voltage reached a lower limit of V_{low} = 1.9 V, the LED was disconnected from it in order to start a new charging cycle. The operation of the boost converter can be observed in Fig. 6. The V_{BAT} signals (ping waveform) were measured using an oscilloscope and in parallel was measured the original NFC signal from the smartphone. A second NFC antenna was connected with the oscilloscope for the last measurement. The antenna was placed next to our tag antenna in order to capture the same signal from the smartphone.

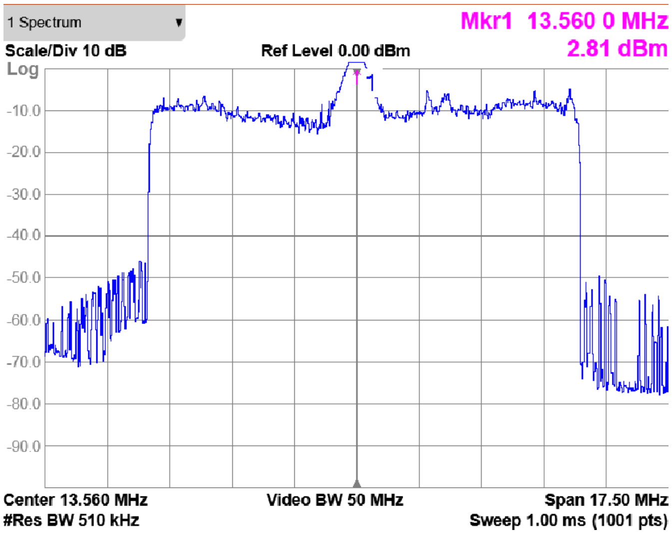

Fig. 5. Measured output NFC power of a Huawei smartphone. The "Max hold" reading was used in the spectrum analyser.

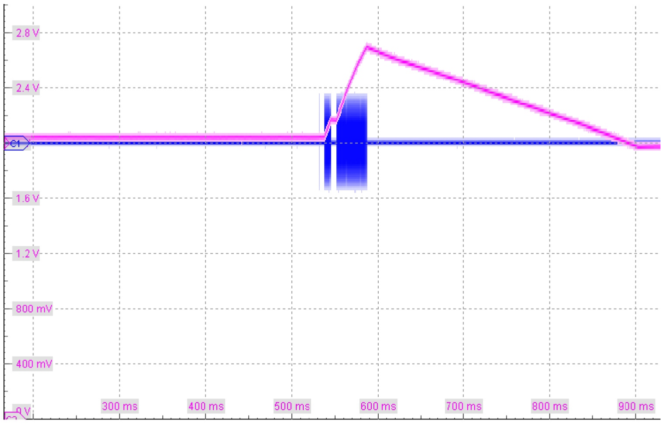

Fig. 6. Oscilloscope measurement of boost converter output and NFC frequency signal. Voltage across 1000 μF capacitor (V_{BAT}) is represented as the ping waveform. The blue waveform is the NFC signal received from the oscilloscope.

V. CONCLUSION

In this work a hybrid harvester for battery-less sensor nodes was designed and fabricated. The design uses NFC frequencies and a solar cell in order to provide energy to a commercial boost converter. The circuit was designed using a full-wave rectifier and an NFC antenna, on a low-cost, FR-4 substrate. Future work should be focused on simulations, measurements and the efficiency calculation of the harvesting system.

ACKNOWLEDGMENT

The authors would like to acknowledge and thank Lloyd's Register Foundation (LRF) and the International Consortium in Nanotechnology (ICON). The authors would like to thank also Panagiotis Petridis for his help in various steps throughout this work.

REFERENCES

[1] V. Coskun, B. Ozdenizci, and K. Ok, "A survey on near field communication (NFC) technology," *Springer Wireless personal communications*, vol. 71, no. 3, pp. 2259–2294, Aug. 2013.

[2] L.-C. Lin, K.-Y. Chen, W.-H. Yang, R.-Y. Huang, K.-H. Chen, Y.-H. Lin, S.-R. Lin, and T.-Y. Tsai, "A digital reverse current self-calibration technique in 90% high efficiency rectified power supply for near field communication through magnetic field induction," in *Proc. IEEE Int. Symp. on Circuits and Systems (ISCAS)*, Baltimore, MD, USA, May 2017, pp. 1–4.

[3] M. Boada, A. Lazaro, R. Villarino, and D. Girbau, "Battery-less soil moisture measurement system based on a NFC device with energy harvesting capability," *IEEE Sensors J.*, vol. 18, no. 13, pp. 5541–5549, May. 2018.

[4] J. I. Cairó, J. Bonache, F. Paredes, and F. Martín, "Reconfigurable system for wireless power transfer (WPT) and near field communications (NFC)," *IEEE J. of Radio Frequency Identification*, vol. 1, no. 4, pp. 253–259, Dec. 2017.

[5] Y. Zhao, J. R. Smith, and A. Sample, "NFC-WISP: A sensing and computationally enhanced near-field RFID platform," in *Proc. IEEE Int. Conf. on RFID*, San Diego, CA, USA, Jun. 2015, pp. 174–181.

[6] S. N. Daskalakis, S. D. Assimonis, E. Kampianakis, and A. Bletsas, "Soil moisture scatter radio networking with low power," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 7, pp. 2338–2346, Jun. 2016.

[7] S. N. Daskalakis, G. Goussetis, S. D. Assimonis, M. M. Tentzeris, and A. Georgiadis, "A uW backscatter-morse-leaf sensor for low-power agricultural wireless sensor networks," *IEEE Sensors J.*, vol. 18, no. 19, pp. 7889–7898, Oct. 2018.

[8] K. Niotaki, A. Collado, A. Georgiadis, S. Kim, and M. M. Tentzeris, "Solar/Electromagnetic energy harvesting and wireless power transmission," *Proc. IEEE*, vol. 102, no. 11, pp. 1712–1722, Nov. 2014.

[9] *nRF52832 NFC Antenna Tuning, White Paper*, Nordic Semiconductor, Inc., 2018. [Online]. Available: https://infocenter.nordicsemi.com/pdf/nwp_026.pdf

[10] B. Tiwari, P. G. Bahubalindruni, A. Santa, J. Martins, P. Mittal, J. Goes, R. Martins, E. Fortunato, and P. Barquinha, "Oxide TFT rectifiers on flexible substrates operating at NFC frequency range," *IEEE J. of the Electron Devices Society*, vol. 7, pp. 329–334, Feb. 2019.

[11] *BQ25570 Ultra Low Power Harvester Power Management IC with Boost Charger, and Nanopower Buck Converter, product manual*, Texas Instruments, 2019. [Online]. Available: http://www.ti.com/lit/ds/symlink/bq25570.pdf