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# A Green Wireless Powered Sensor Network: An Experimental Approach

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***Abstract*—This paper presents an experimental study of a green wireless powered communication network (WPCN), where sensors with wireless power transfer (WPT) capabilities are located at known positions and an energy transmitter (ETx) is employed to wirelessly power the uplink between the sensors and the access point (AP). By monitoring and measuring the charging time that the sensors require to power their operations, the ETx is turned on and off accordingly for a certain period of time in order to keep the packet transmission rate at a desired constant value. We consider a static and dynamic approach for the measurements and repeat the experiments for various packet rate constraints and different distances between the sensors and the ETx. Our results show that the power consumption of our smart ETx can achieve power savings of 80% compared to an ETx which operates continuously.**

***Index Terms*—Wireless power transfer, RF energy harvesting, wireless sensor networks, Powercast.**

## I. Introduction

Green wireless communication networks are designed in such a way as to provide as much energy efficiency as possible, compared to conventional wireless networks [1]. This is usually achieved by harvesting energy from natural resources (sun, wind, etc.) to power their operations and by implementing smart operation modes, e.g. the device "sleeps" when not in use. Recently, the concept of harvesting energy wirelessly from radio frequency (RF) signals has gained much attention [2]. A network with wireless powered communication capabilities, consists of a set of access points (APs) and/or energy transmitters (ETxs) which transmit RF signals and a set of RF harvesting enabled wireless devices. There are three fundamental architectures for wireless powered communication networks:

- Wireless power transfer (WPT): energy is transmitted from an ETx to the wireless devices over the downlink [3].
- Simultaneous wireless information and power transfer (SWIPT): energy and information are transmitted from an AP to the wireless devices over the downlink [4].
- Wireless powered communication networks (WPCN): energy is transmitted from a power beacon, i.e., an ETx, to the wireless devices over the downlink and information is transmitted from the wireless devices to the AP over the uplink [5].

Even though RF energy transmission provides less energy compared to other energy harvesting technologies such solar, air flow and body motion, it has several important advantages: it provides a constant energy flow without the use of cables and with the flexibility of controlling the ETx [6]. A basic system consists of power harvesters and ETxs. Power harvesters receive power from the RF energy source(s), and use it to complete their tasks. RF energy sources are divided into two categories [7]. Ambient sources which are not intended for RF energy transfer and include radio/TV stations and dedicated ones which are used to cover the energy demands of the network nodes. Ambient sources are free in the environment and thus do not require power expenses but cannot be controlled by the system and in most cases are unpredictable. Unlike ambient sources, dedicated RF energy sources are added into the system and designed to cover the power requirements of the system's devices. Usually dedicated ETxs can be controlled by the system with an extra cost as long they are on.

Due to the path-loss attenuations and obstacles in the environment, the ETx has to transmit with enough power to reach the receiver and only a portion of the transmitted power will be available for harvesting. For this reason most of the power harvesters operate in the range of μW, while the ETxs consume much more power [3]. Based on a case study in [8], the cost for providing the same amount of energy for state-of-the-art wireless power transfer nodes can be 60 times more compared to a conventional cable-based energy power supply. Due to this, RF energy transfer can be characterized as a power hungry technology. In [8], a smart wireless power transfer network was developed in order to minimize the power consumption of an RF energy transfer system. The authors tested two communication protocols, beaconing and probing, between the power harvester and the ETxs. Using these protocols, the ETxs exchanged messages with the power harvesters in order to transmit energy only when needed, thus reducing their operation time and power consumption up to 80%. Even though results in [8] showed that the power consumption can be reduced dramatically by controlling the ETx, the developed system required the harvesters to broadcast messages to the transmitters when power was needed which

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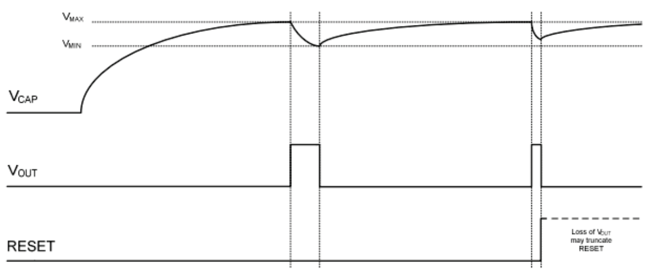



Fig. 1: The P2110-EVB evaluation board's timing diagram.

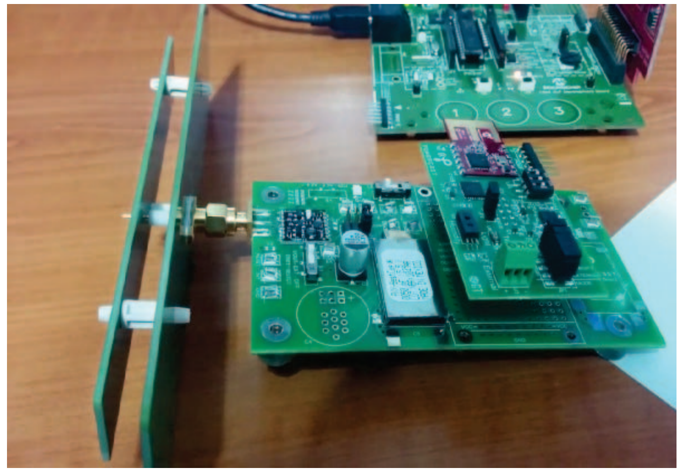


Fig. 2: The P2110-EVB evaluation board (bigger board) connected to a wireless sensor (smaller board) and to a directional antenna.

consumed extra power which the harvesters can use to extend their operating life.

In this paper, we study experimentally a WPCN which requires its WPT-enabled sensors to transmit data at a predefined rate. By considering this constraint, we focus on reducing the power consumption of the ETx by minimizing the unnecessary transmission time. Unlike to work in [8], the sensors are not required to send feedback to the ETx. We develop three algorithms which monitor the communication in the network through a processing unit and decide accordingly whether or not to switch of the transmitter. Our proposed algorithms accomplish a smart WPCN and our experimental results show that the power consumption can be reduced significantly.

The rest of paper is organized as follows: Section II introduces the developed system model, Section III describes the experiments undertaken and presents the derived results. Finally, Section IV summarizes the key findings and observations of the paper.

## II. System Model

In this section we present the considered system model. We first provide a description of the main components, then we provide the main setup we used and finally we present the developed algorithms.

### A. Components

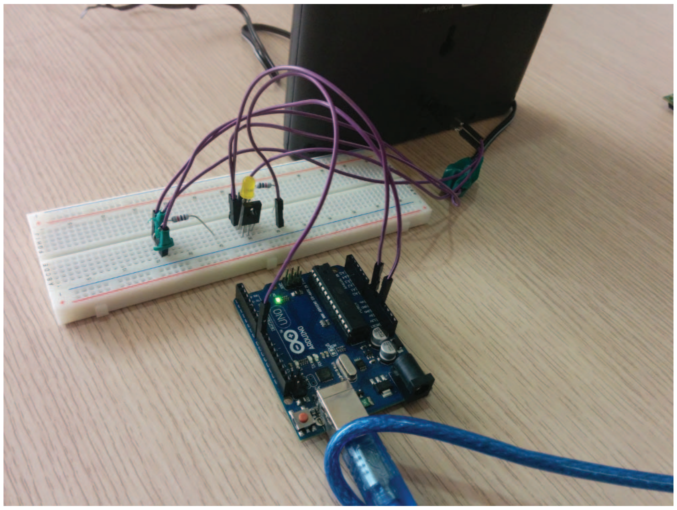
The configuration considered consists of four components: a power harvester, an energy transmitter, an access point and a processing unit.

*1) Power Harvester (ERx):* For the main power harvesting operations, we use the PowerCast P2110-EVB evaluation board [9]. The ERx employs a 6 dBi directional antenna and has an operation frequency range between $902–928$ MHz. The received RF energy at the antenna is converted to direct current and stored in a $50\,\mathrm{mF}$ capacitor. When the capacitor charges to a voltage $V_{\mathrm{CAP}} = V_{\mathrm{MAX}} = 1.25\,\mathrm{V}$, a boost converter produces a pulse voltage in the pin $V_{\mathrm{OUT}} = 3.3\,\mathrm{V}$. The pulse remains active until the capacitor discharges to $V_{\mathrm{MIN}} = 1.05\,\mathrm{V}$ or the input pin $\mathrm{RESET}$ is enabled. The $\mathrm{RESET}$ pin is connected to the wireless sensor device and is enabled as soon as a packet is transmitted. When $V_{\mathrm{CAP}} = V_{\mathrm{MIN}}$ or $\mathrm{RESET}$ is enabled, the board switches to harvesting mode [12]. A graphical representation of the voltage timing of the ERx is illustrated in Fig. 1.

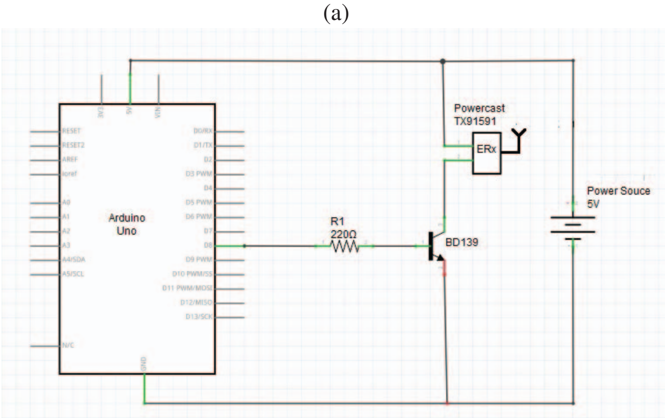
A wireless sensor device is connected to the evaluation board and is powered by the energy harvested by the ERx via the $V_{\mathrm{OUT}}$ pulse. The low power sensor establishes communication between the ERx and the AP at a frequency $2.4$ GHz and implementing the IEEE 802.15.4 standard [9]. The sensor transmits a packet to the evaluation board which contains the sensor's ID and together with some optional information that can be obtained by the sensor such as humidity, temperature and light. When a packet is transmitted, the sensor returns a $\mathrm{RESET}$ signal back to the ERx. Fig. 2 shows an ERx together with a wireless sensor. Our experimental study considers two power harvesters, without loss of generality.

*2) Energy Transmitter:* The ETx considered in our developed system model is the PowerCast TX91501-3W [9]. It operates at $915\,\mathrm{MHz}$ and transmits using the amplitude shift keying (ASK) modulation [6]. The transmitter is vertically polarized with a radiation pattern $60°$ high by $60°$ wide and transmits up to $3\,\mathrm{W}$ equivalent isotropically radiated power in direct sequence spread spectrum. The ETx's power supply is connected through a circuit that uses a bipolar junction transistor (BJT) as a switch. The BJT's base is connected with an Arduino Uno microcontroller board [10] through a digital pin that gives an output of $5$ or $0\,\mathrm{V}$, thus enabling or disabling the current flow in the BJT, i.e., turning the ETx on and off. The Arduino Uno board is controlled through the processing unit via serial communication by the AP. Fig. 3 shows the actual setup we've used as well as a schematic of the aforementioned circuit.

*3) Access Point:* The Microchip XLP 16-bit development board with a Microchip MRF24J40 PICtail daughter card [13] attached to it, is used as the AP of the system. Similarly to the wireless sensor, it operates at a frequency of 2.4 GHz and implements the 802.15.4 standard. The transmitted packets from the wireless sensors are received at the PICtail daughter card and decoded at the Microchip XLP. After that, the data is passed through serial communication to the processing unit.



(a)




(b)

Fig. 3: ETx controlling circuit: (a) hardware implementation, (b) circuit diagram

*4) Processing Unit:* For the sake of simplicity and higher level of control, the processing unit is chosen to be a personal computer that can support simultaneous communication with two serial connections: one for controlling the ETx through the Arduino Uno board and one for receiving data from the AP. The processing unit receives the data from the AP and uses them to extract the ERx's ID and other information if available. The processing unit then calculates the packet to packet (PTP) time which is defined as the time between two consecutive received packets at the processing unit. Then, based on the investigated scenario, the processing unit implements the appropriate algorithm (given in Section II-C) to decide whether or not to switch off the ETx. If the decision to switch it off is taken, the algorithm calculates the time period the ETx must be switched off in order to achieve the desired PTP time.

### B. System Setup

The system setup models a basic WPCN configuration where an ERx corresponds to a mobile device and the combination of the processing unit, the AP and the ETx corresponds to a central operations unit. The ERxs are placed

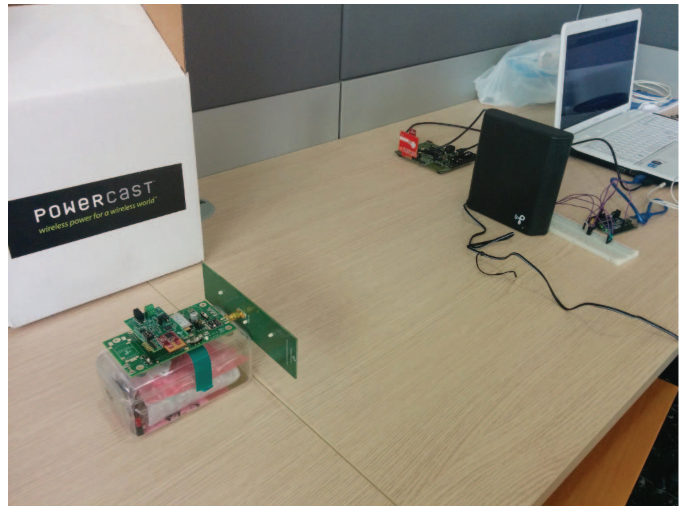



Fig. 4: Typical setup of the system.

at fixed locations and at a certain distance away from the ETx. Furthermore, the ERxs are placed in such a way so that they are in line of sight with the ETx and their antenna faces the main lobe of the ETx thus providing a near maximum harvesting performance. The ERxs are powered by the ETx and their packet transmission rate is monitored by the AP and the processing unit so that it falls below a predefined threshold value, e.g., at least one message every 20 seconds. The required packet rate is achieved with the use of an algorithm which alternates the on/off states of the ETx accordingly. As a result, the ETx's power consumption is reduce while the packet rate requirements are satisfied. The system setup with one ERx is shown in Fig. 4.

### C. Operation Algorithms

For determining the ETx's off time period, an algorithm was developed which run on the processing unit during the experiments. The algorithm was expanded to three variations where each one adapted to the needs of the considered experimental scenarios. All time durations were evaluated in seconds. Table I provides descriptions of the main functions and parameters used in the algorithms.

The first algorithm refers to a setup with a single ERx. A detailed description of the algorithm in pseudocode is given in Algorithm 1. Having one ERx in the system means that there is no need for ERx identification. The algorithm switches on the ETx until the ERx harvests enough energy to transmit a packet to the AP (line 5). Once a packet is received at the AP, the algorithm switches off the ETx and the time which the ETx was on is considered as the packet time (lines 5-10). The new ETx off time is then calculated by using the packet time, the old ETx off time and the desired PTP time (lines 11-22). The algorithm waits until the off time period passes, switches the ETx on and repeats the process (line 23).

For the scenarios where there are multiple ERxs in the system, two algorithms were developed, Algorithms 2 and 3. In this case, packets from all ERxs are taken into consideration

TABLE I: Functions and parameters of the algorithms. All time durations are in seconds.

| Function | Description |
|---|---|
| ETx(ON/OFF) | Turns the ETx on/off |
| getID(packet) | Returns ID of packet |
| getMax(T) | Returns index of maximum value in $T$ |
| **Parameter** | **Description** |
| packetRate | Target PTP time |
| packetTime | Time between ETx(ON) and packet received |
| ETxOffTime | ETx off time duration |

**Algorithm 1:** Calculate ETx off time for a single ERx.

```
1  Initialization;
2  packetRate = desired PTP time;
3  ETxOffTime = 0;
4  ETx(ON);
5  t_1 = current experimental time;
6  while the experiment is on do
7      if a packet is received then
8          ETx(OFF);
9          t_2 = current experimental time;
10         packetTime = t_2 − t_1;
11         if packetTime < packetRate then
12             ETxOffTime = ETxOffTime + packetRate −
                 packetTime;
13             if ETxOffTime > packetRate then
14                 ETxOffTime = packetRate;
15             end if
16         else
17             if packetTime − packetRate > ETxOffTime
                 then
18                 ETxOffTime = 0;
19             else
20                 ETxOffTime = ETxOffTime −
                     packetRate − packetTime;
21             end if
22         end if
23         wait ETxOffTime;
24         ETx(ON);
25         t_1 = current experimental time;
26     end if
27 end while
```

and are distinguished by the unique ID of the ERx which is contained in each packet. Algorithm 2 is implemented for the scenario where the processing unit has no knowledge of the ERxs' positions. When at least one packet from every ERx is received, the longest packet time amongst all ERxs is chosen as the system's PTP time (lines 11-18). Therefore, the desired PTP time of the system is satisfied as the packet rate of each ERx does not fall below the threshold. After that, the algorithm follows the same steps as Algorithm 1.

**Algorithm 2:** Calculate ETx off time for multiple ERxs (Dynamic).

```
1  Initialization;
2  packetRate = desired PTP time;
3  ETxOffTime = 0;
4  n = number of ERxs;
5  T = ∅;
6  ETx(ON);
7  t_1 = current experimental time;
8  while the experiment is on do
9      if a packet is received then
10         p = getID(packet);
11         if |T| < n then
12             if T[p] does not exist then
13                 t_2 = current experimental time;
14                 T[p] = t_2 − t_1;
15             end if
16             if |T| = n then
17                 s = getMax(T);
18             end if
19         else
20             if s = p then
21                 ETx(OFF);
22                 t_2 = current experimental time;
23                 packetTime = t_2 − t_1;
24                 begin
25                     execute lines 11–25 of Algorithm 1;
26                 end
27             end if
28         end if
29     end if
30 end while
```

The last algorithm considers the scenario where the positions of ERxs are known a-priori. In this case, we assume that the ERx which is positioned the furthest away from the ETx will also provide the longest packet time. Therefore, only that ERx is taken into consideration while all the others are ignored. Every time a message from that specific ERx is received, the packet time is calculated and the ETx off time is evaluated the same way as in Algorithm 1.

## III. Experimental Results

In this section we present our experimental results. The WPCN based on the system model in Section II is implemented and the power savings are evaluated through three different experiments. In the first experiment, the goal was to observe the packet rate for a single ERx based on its distance to the ETx. An estimation of the power savings for different distances and packet rates was extracted. In the second experiment, Algorithms 1 and 2 were used to evaluate the system's actual power savings under specific distances and packet rates. Finally, the third experiment provides a comparison between Algorithms 2 and 3. Note that all the

**Algorithm 3:** Calculate ETx off time for multiple ERxs (Static).

```
Initialization;
packetRate = desired PTP time;
ETxOffTime = 0;
s = furthest ERx's ID;
ETx(ON);
t_1 = current experimental time;
while the experiment is on do
    if a packet is received then
        p = getID(packet);
        if p = s then
            ETx(OFF);
            t_2 = current experimental time;
            packetTime = t_2 - t_1;
        end if
        begin
            execute lines 11–25 of Algorithm 1;
        end
    end if
end while
```

experiments were conducted using parameters which provided feasible results, i.e., the desired PTP time could be achieved.

### A. First Experiment: Single ERx

In order to observe the ERx packet rate based on the distance between the ETx and the ERx, a setup similar to Fig. 4 was used. For the case of accuracy, two ERx devices were placed next to each other at the same angle with respect to the main lobe of the ETx, and the PTP time was evaluated as the average between the measurements from the two ERxs. In the case of large deviations between the two ERx PTP times, the measurements were considered faulty and were repeated. Initially, both ERxs were placed at a distance of $60$ cm away from the ETx and after each measurement the ERxs were moved another $16.4$ cm further until a distance of $207.4$ cm was reached. The initial distance was chosen at $60$ cm because the PTP time at that distance was evaluated at around $0.5$ seconds which was considered ideal as a starting minimum point. The step distance of $16.4$ cm was chosen in order to match the wavelength of the transmitted signal given by the equation $\lambda = c/f_c$, where $f_c = 915$ MHz is the harvesting frequency band.

During the experiment, the ETx was constantly on and each measurement was completed after $55$ packets were received from each ERx. The data from the first $10$ packets from each sensor were ignored in order to give time for the sensors to reach a stable packet transmission rate. Then, the average PTP time was evaluated based on the remaining $45$ packets. The number of considered packets was chosen to be $55$ in order to keep the duration of the experiment short but accurate at the same time. Note that in this experiment, the ETx off time was estimated but the ETx remained on so that the average

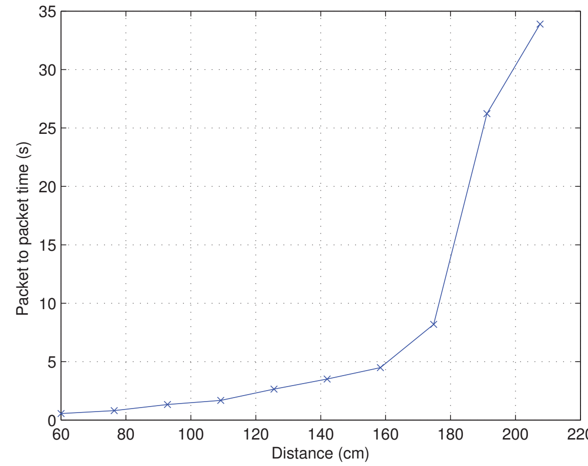



Fig. 5: PTP time versus the distance between the ETx and the ERx.

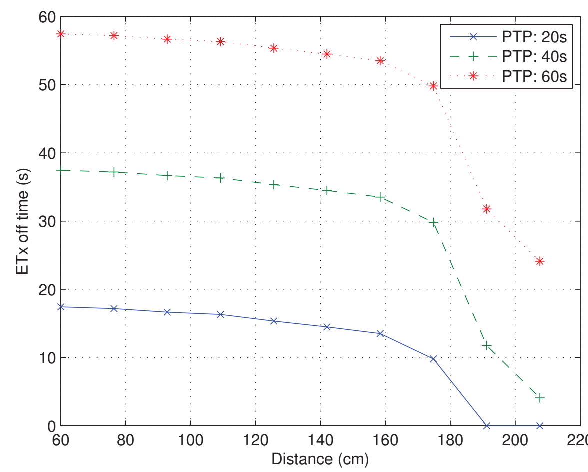



Fig. 6: ETx off time versus the distance between the ETx and the ERx.

PTP time would be evaluated. In Fig. 5, the average packet transmission rate versus the distance between the ETx and the ERx is illustrated, while Fig. 6 shows the estimated time that the ETx would remain off with respect to the distance for PTP time constraints $20$, $40$ and $60$ seconds. Finally, Fig. 7 depicts the percentage of time the ETx would be off during the operation of the experiment, again with respect to the distance for different PTP time constraints. The figures clearly show that as the distance between the ETx and the ERx increases, the PTP time and the ETx off time increases and decreases respectively. This is expected since according to the Friis transmission formula, a non-linear relationship exists between distance and received power [14]. Therefore, as the ERx was moved further away from the ETx, the energy harvesting rate decreased thus resulting in a higher packet transmission delay. Consequently, the ETx was required to operate for longer

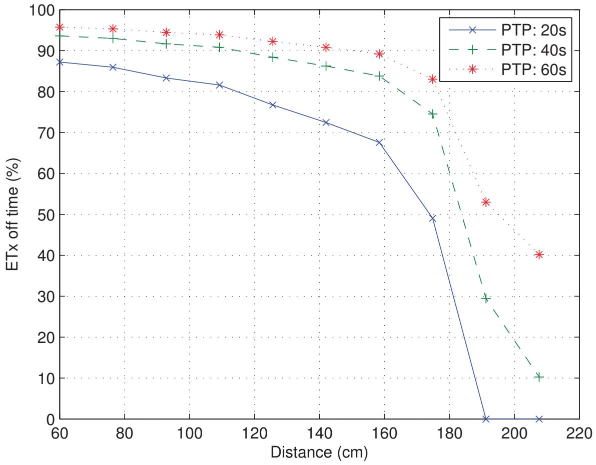



Fig. 7: Percentage of time the ETx was off versus the distance between the ETx and the ERx.

durations in order to satisfy the target PTP time constraint.

### B. Second Experiment: Single / Multiple ERx(s)

In the second experiment, a single ERx device was firstly placed at 120 cm away from the ETx. The desired PTP time was set to 20 seconds and the measurements were taken for one hour period using Algorithm 1. The results show that packets arrive at an average PTP time of 19.07 seconds and the average ETx off time was $11.726$ seconds or $58.63\%$ of the experimental time. In the second phase of the experiment, one more ERx was added to the system at the same distance away from the ETx and next to the first ERx. Then, the experiment was repeated using Algorithm 2. In this case, the results show an average PTP time of $19.09$ seconds and average ETx off time of $13.069$ seconds or $68,48\%$ of the experimental time. In the final phase of the experiment, the two ERx devices were placed at a distance of $100$ cm away from the ETx. Using Algorithm 2, the received packets arrived at an average of $18.83$ seconds and the average ETx off time was $15.28$ seconds or $80.1\%$ of the total experimental time. Note that this experiment's estimated ETx off time for a PTP time constaint of 20 seconds slightly disagrees with the off time estimated in Section III-A. Recall that in Section III-A the ETx off times were estimated but the ETx remained on. Therefore, the main reason for the difference between the two is the delay in the ETx's off to on transitions and the discharge of the ERx's capacitor while the ETx was switched off.

### C. Third Experiment: Multiple ERxs - Static vs Dynamic

In the final experiment, an ERx device was placed at a distance of 66 cm away from the ETx and another at a distance of 91 cm, both in line of sight with the ETx. Algorithm 2 and 3 were tested for one hour period and the recorded measurements are presented in Table II. According to the results, the ERx with the longest distance provides the highest PTP time. Thus, our assumption stated previously is validated.

TABLE II: Comparison between Algorithms 2 and 3.

| | PTP (secs) | ETx off time (secs) | ETx off (%) |
|---|---|---|---|
| Algorithm 2 | 19.095 | 14.53 | 76,76 |
| Algorithm 3 | 19.067 | 14.66 | 77,54 |

In the case where knowledge of the ERxs' positions exists, the PTP time of the furthest ERx is enough to satisfy the network thus avoiding the complexity of Algorithm 2.

## IV. Conclusion

In this paper, we investigated a method for reducing the power consumption of an ETx in a WPCN. We presented three algorithms for different scenarios which are evaluated experimentally. With the use of our proposed algorithms, sensors in a WPCN can achieve a target packet rate without the use of feedback or any other communication protocol. Our experimental results showed that the power consumption of the ETx can be reduced up to $80\%$. Future directions include extending our algorithms to adapt dynamically to transitions in the network such as change in the positions of the ERxs or addition/removal of an ERx. Moreover, an interesting pursuit is to consider the case where the ERxs are placed at any position around the ETx and the ETx is capable of directing its signals to specific ETxs with the use of an appropriate mechanism.

## References


[1] I. Ahmed, M. M. Butt, C. Psomas, A. Mohamed, I. Krikidis, and M. Guizani, "Survey on energy harvesting communications: Challenges and opportunities for radio resource allocation," *Elsevier J. Comput. Networks*, vol. 88, pp. 234–248, Sept. 2015.

[2] S. Bi, C. K. Ho and R. Zhang "Wireless powered communication: Opportunities and challenges," *IEEE Commun. Mag.*, vol. 53, pp. 117–125, Apr. 2015.

[3] H. J. Visser, and R. J. M. Vullers, "RF energy harvesting and transport for wireless sensor network applications: Principles and requirements," *Proc. IEEE*, vol. 101, pp. 1410-1423, Jun. 2013.

[4] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng, and R. Schober, "Simultaneous wireless information and power transfer in modern communication systems," *IEEE Commun. Mag.*, vol. 52, pp. 104–110, Nov. 2014.

[5] H. Ju and R. Zhang, "Throughput maximization in wireless powered communication networks," *IEEE Trans. Wireless Commun.*, vol. 13, pp. 418–428, Jan. 2014.

[6] A. M. Zungeru, L. M. Ang, S. R. S. Prabaharan, and K. P. Seng, "Radio frequency energy harvesting and management for wireless sensor networks," in *Green Mobile Devices and Networks: Energy Optimization and Scavenging Techniques*, H. Venkataraman and G.-M. Muntean, Eds. Boca Raton, FL: CRC Press, 2012, ch. 13, pp. 341–368

[7] X. Lu, P. Wang, D. Niyato, and Z. Han, "Resource allocation in wireless networks with RF energy harvesting and transfer," *IEEE Network*, 2015, to be published.

[8] Q. Liu, M. Golinski, P. Pawelczak, and M. Warnier, "Green Wireless Power Transfer Networks," [Online] Available: http://arxiv.org/abs/1504.00639.

[9] PowerCast Corporation, [Online] http://www.powercastco.com

[10] Arduino, [Online] https://www.arduino.cc

[11] XBee, [Online] http://www.digi.com/xbee/

[12] F. Eady, *"Riding an RF energy harvester"*, Nuts and Volts, The design cycle: advance techniques for design engineers, May 2011

[13] Microchip Technology Inc., [Online] http://www.microchip.com

[14] J. A. Shaw, "Radiometry and the Friis Transmission Equation," *Am. J. Physics*, vol. 81, pp. 33–37, 2013.