# Demo Abstract: Software-defined Wireless Charging of Internet of Things using Distributed Beamforming


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## ABSTRACT

Smart homes will compose of multiple sensors that will sense, compute and transmit information to a central cloud, all of which are energy consuming tasks. We propose to demonstrate a software-defined solution for wirelessly charging these sensors using RF energy, thereby extending their lifetimes. In our demo, the actions of more than one energy transmitter (ET) are synchronized in phase and frequency in real time using periodic feedback from the target sensor, but without any common clock reference. The controller selects the optimal subset of ETs to satisfy the energy request from a given sensor, which cooperatively beamform RF energy towards that sensor. Our software-defined framework, implemented in Python, allows the central controller to automatically discover the installed sensors, obtain energy needs, and schedule charging tasks in an asynchronous and non-blocking manner that allows the network to scale. The demonstration includes advancements in design and fabrication of RF energy harvesting circuits that interface with the TI EZ430 sensors, implementation of a software-defined control and data plane, as well as a real-time distributed beamforming algorithm on USRP radios that results in a battery-free network of sensors.


## 1. INTRODUCTION

Battery-operated sensors and Internet of Things (IoT) are enhancing the quality of human experience and safety- related measures when deployed in homes, transportation and manufacturing floors. The operational state of such sensors is heavily dependent on the continuous supply of energy. Periodic battery replacement becomes a costly maintenance task in these scenarios, apart from introducing undesirable downtimes. We address this problem by using contactless and on-demand RF-charging [2], and further improve the scalability of powering a network of sensors through an automated software-defined control plane. This demo presents an implementation showing the various steps of the network operation, including device discovery, selection of energy transmitters (ETs), and coordinated digital beamforming so that the energy is transferred to the sensors efficiently without increasing the interference to neighboring devices significantly.

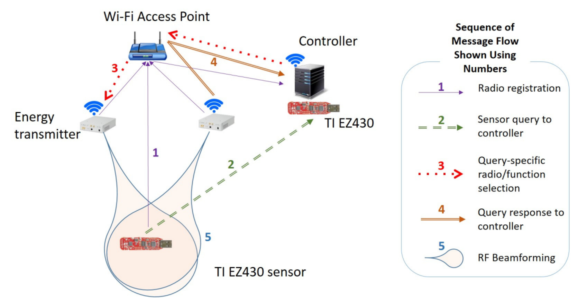


**Figure 1: Software-defined Wireless Charging of IoTs Architecture**

An overview of the demonstration network is shown in Figure 1. It is composed of multiple ETs, each of which is a universal software radio peripheral (USRP) N210 device. A number of TI EZ430 sensors integrated with our custom-designed passive energy harvesting board are deployed in the same space. In addition, there is a controller node that runs the ET/sensor registration and task scheduling algorithms. All network components connect to a WiFi network through an access point. The sensor provides direct 1-bit feedback broadcasts, which is used by the ETs to continuously tune the phase and frequency of their continuous wave RF emissions. Furthermore, the controller can selectively activate ETs (or power them down) for energy transfer or assign a wholly different task like reporting back received signal strength values from the local environment. A novel feature of our control plane design is that it is built upon Python's Twisted framework that allows scaling the network to very large number of sensors through the asynchronous and non-blocking message flow between the various devices. This design choice helps the control plane to achieve uninterrupted query resolution and makes the operation robust in failure scenarios.

## 2. SYSTEM DESIGN AND IMPLEMENTATION

### 2.1 Software-defined Control Plane

The Python-based control plane uses the Twisted framework, which uses a single event loop to cycle through tasks



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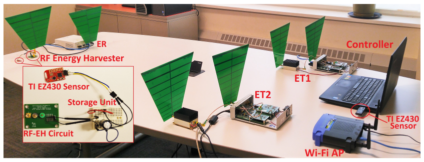


**Figure 2: Setup for software-defined wireless charging of IoTs**

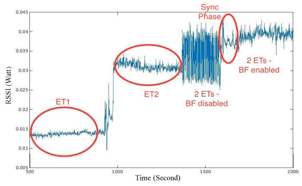


**Figure 3: Received energy comparison according to number of ETs and usage of Beamforming scheme**

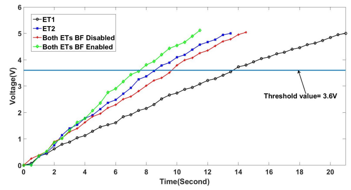


**Figure 4: Charging time comparison according to number of ETs and usage of Beamforming scheme**

in small time units instead of branching and threading. The controller accepts registration beacons emitted by sensors and ETs, as they enter in the network over WiFi. Each beacon contains not only the unique device ID, but also a description of the functions supported by the discovered device in a pre-determined JavaScript Object Notation (JSON) format. This is especially useful for the ETs, and future proofs the system design, i.e., as newer and enhanced capabilities get incorporated into ETs, we only need to extend the JSON definitions. We modified the UHD driver for the USRP devices to automatically transmit these beacons, if the device is not already registered. Twisted runs two reactor loops at both ends of the ET/sensor-controller connection, allowing each device to accept higher level directives as and when they arrive, while also allowing the controller to receive energy requests from sensors, and also forward user- configuration requests to any of the network devices. The controller then executes remote procedural calls, wherein it invokes specific functions in the ETs (such as tuning the center frequency and starting the beamforming algorithm) based on the incoming energy requests.

## 2.2 Beamforming Algorithm

The demo begins with a sensor sending a request for energy (see Figure 2) to the controller, which assigns two USRP N210 radios to perform the ET role. The ETs organize themselves into a virtual antenna array and focus their trans- mission energy in the direction of the sensor, such that the emitted waveforms add up constructively at the target sensor. The energy harvesting circuit converts the incident RF energy into DC voltage stored in the capacitor. The sensor estimates the received signal strength (RSS) of the net incoming signal and broadcasts a single bit to all the ETs to indicate whether this value is higher or lower than that measured in the previous time slot. If the RSS is higher, the ETs update this information and perturb their phase setting using the last setting as the baseline. If the RSS is lower, the ETs revert their phase selection to that of the previous time slot, before beginning the subsequent round of phase perturbation. This randomized ascent procedure is repeated until the ETs converge to phase coherence [1]. This significantly improves the energy efficiency: an N-node beamforming virtual array transmitting at fixed power can attain RSS in the order of $N^2$ . From our experiments, we found that with 2 ETs, the RSS at the sensor, at a distance of 1.3 meters from the ETs was 0.019W. The RSS changed to 0.04W with 3 ETs. For demo purposes, we set a third USRP radio near the sensor as an energy receiver to confirm the RSS readings at the sensor.

## 2.3 Energy Harvesting Circuit

The RF energy harvesting circuit contains four components: antenna, impedance matching network sub-circuit, 4-stage diode-based Dickson voltage rectifier, and $3300\mu F$ capacitor for energy storage, as seen in Figure 2. We use 6 dBi directional PCB-printed antenna whose response lies within the energy reception frequency. The impedance matching network sub-circuit maximize the energy transfer and minimizes power reflection between the antenna and voltage rectifier. For efficient DC conversion, we design a 4-stage diode-based Dickson voltage rectifier by choosing the schottky diode that operates with quick activation time and lower forwarding voltage drop [3]. The $3300\mu F$ capacitor stores energy from the voltage rectifier, and provides energy to the TI EZ430 sensor. As shown in Figure 4, the conversion efficiency depends upon the accurate phase matching of the ETs and the circuit design. Once the voltage across the capacitor reaches 3.6V, the sensors disconnect from the charging phase and resume their normal operation.

# 3. RESULTS AND CONCLUSIONS

Our experiments with two ETs and one TI EZ430 sensor show that all ETs synchronize their phase during beamforming over time (see Figure 3). Upon synchronization, we observe that a the sensor node begins to gain back the energy lost during network communication (see Figure 4) owing to the constructive addition of the incoming RF signals. This charging approach extends the lifetime of sensor devices by replenishing the charge in the battery and can ideally lead to eliminating batteries completely in IoT deployments.

# 4. ACKNOWLEDGMENTS

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