# WATTR: A Method for Self-Powered Wireless Sensing of Water Activity in the Home

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**ABSTRACT**
We present WATTR, a novel self-powered water activity sensor that utilizes residential water pressure impulses as both a *powering* and *sensing* source. Consisting of a power harvesting circuit, piezoelectric sensor, ultra-low-power 16-bit microcontroller, 16-bit analog-to-digital converter (ADC), and a 433 MHz wireless transmitter, WATTR is capable of sampling home water pressure at 33 Hz and transmitting over 3 m when *any* water fixture in the home is opened or closed. WATTR provides an alternative sensing solution to the power intensive Bluetooth-based sensor used in the HydroSense project by Froehlich et al. [2] for single-point whole-home water usage. We demonstrate WATTR as a viable self-powered sensor capable of monitoring and transmitting water usage data without the use of a battery. Unlike other water-based power harvesters, WATTR does not waste water to power itself. We discuss the design, implementation, and experimental verification of the WATTR device.

**Author Keywords**
Power Harvesting, Sensing, Water Conservation

**ACM Classification Keywords**
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

**General Terms**
Design, Experimentation, Measurement, Performance.

## INTRODUCTION

In recent years, we have seen an astonishing increase in the computational and storage capabilities of computing systems. Unfortunately, battery technology has not followed this same desirable trend. As a consequence, mobile devices and battery-powered wireless sensors are not often limited by their computational throughput but rather their energy efficiency. Power harvesting offers a promising alternative energy source. With power harvesting, self-powered sensors can convert ambient energy (e.g., in the form of solar, thermal, kinetic, or radio waves) into electrical energy. The problem then becomes designing a system capable of harvesting enough energy to power a sensor and transmit the sensor values.


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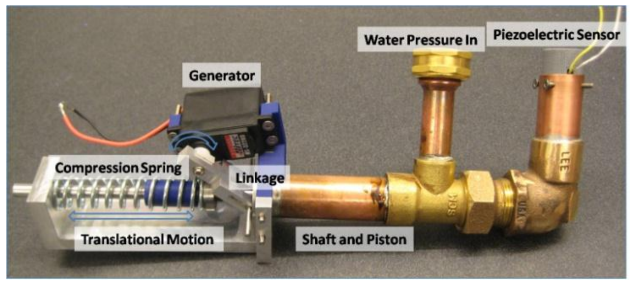


**Figure 1: WATTR mechanical harvester and sensor**

In this paper, we present WATTR, a self-powered wireless sensor node for collecting and transmitting water pressure transients in residential plumbing. The oscillating water pressure signals measured by this system are the same waves that power the on-board microcontroller, ADC, and wireless transmitter. WATTR's primary application is HydroSense [2], a pressure-based sensing solution for automatically detecting and classifying water usage down to the fixture level from a single installation point in the home. WATTR is a self-powered water pressure sensor for the HydroSense system, which completely eliminates the maintenance cost of constant battery replacement while maintaining quality of data required for activity recognition. WATTR is not an inline flow meter, and therefore does not waste any water to harvest power, nor does it require the cutting or modification of existing plumbing lines to be installed.

WATTR consists of a rotational power harvester (generator), piezoelectric pressure sensor, ultra-low-power 16-bit microcontroller, 16-bit ADC, and a 433 MHz wireless transmitter (see Figure 1). WATTR operates for pressure changes greater than 103 kPa[1], generates up to 15 mJ of energy, and can sample and transmit water pressure data for up to 8 seconds.

[1] 1 kPa = 0.145 psi (pounds per square inch)

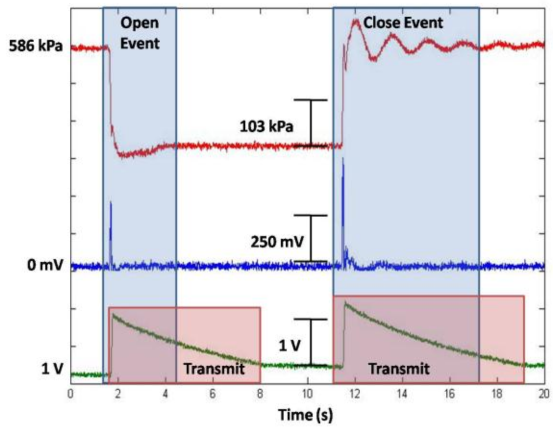


**Figure 2: A typical pressure wave showing the open and close events on a calibrated pressure sensor (red), and piezoelectric sensor (blue). Storage capacitor voltage during normal operation of the system (green)**

The application of WATTR to HydroSense represents the larger desire in ubiquitous computing (ubicomp) to make low-power, long-life sensors. The number of sensors installed in an environment will only increase as sensors continue to decrease in size and cost. Thus, it is crucial that these sensors be designed for low-maintenance—it is not practical to expect that a homeowner will frequently change batteries or run extension cords to support sensor deployments. The self-contained wireless unit provided by WATTR allows applications like HydroSense to function without power cables or batteries.

The research contributions of WATTR are threefold. First, we introduce the first power harvesting unit designed for residential water pressure transients. Second, we design optimized hardware and software for *long*-duration time-series sampling using the sensing stimulus as the power source. Finally, we investigate the feasibility of classifying water fixture usage based on the received data from WATTR in a single-home pilot experiment.

## RELATED WORK

In self-powered devices, energy is typically harvested from sources such as solar, ambient vibrations, or inductive coupling to RFID readers. The Wireless Sensing Platform (WISP) combines RFID-based self-powering techniques with continuous data collection of 0.25 Hz while the device is powered [6]. For long-term, low sample rates, the WISP is well tailored for the ubicomp community; however, for applications in which the RFID infrastructure is not in place, or those that require burst sampling, the WISP system falls short.

Several devices circumvent the problem of intermittent power by harvesting energy directly from the same stimulus that the device is designed to sense. For example, the MIT Pushbutton used energy generated from a single button-press to power a transmitter in order to send an identification message [4]. While this work showed that piezoelectric impulses could provide enough power for wireless transmission; however, the system was only powered for a very short duration (30 ms). We initially explored the use of piezoelectric power harvesting mechanisms similar to Pushbutton, but opted for a power source that could provide power for longer durations. Peppermill is a hand-cranked device which generates power while sensing the motion of the crank, and is used as a self-powered remote control [7]. The rotary style harvesting system used in Peppermill is similar to that used in WATTR, though we replace human stimulus with water pressure transients.

Power harvesting solutions that utilize water have previously been applied to commercial irrigation systems. Morais et al. used turbines in agricultural irrigation pipes to power wireless sensors that monitored water flow [3]. This system was unable to measure the *amount* of water flow, only the duration of water use. For home water sensing, inline turbine-based solutions require cutting a home's main inlet pipe or installing many distributed turbine sensors at the outlet of each fixture. The cost and labor associated with this type of installation can be prohibitive. Using abrupt changes in water pressure to harvest energy circumvents these issues because the pressure waves propagate throughout a home plumbing network and, as a result, can be detected and harvested from any water valve. Pressure-based sensing also allows for easy installation by unobtrusively screwing onto any faucet. Indeed, this iso-directional pressure wave propagation is, in part, what enables HydroSense's single-point sensing approach.

HydroSense works by sensing the transient pressure oscillations generated when a water valve is opened or closed to classify water usage down to the fixture level (e.g., kitchen sink, toilet, or dishwasher). Figure 2 shows pressure waves that are generated from the opening and closing of a faucet in a home. In order to classify the pressure wave, long-duration sampling of the waveform is needed. The initial HydroSense prototype used a Class 1 Bluetooth transmitter to send data sampling from a calibrated pressure sensor. WATTR enables the same time series classification as the initial HydroSense prototype, but uses a self-powered system and commodity pressure sensor.

## HARDWARE DESIGN

WATTR uses a mechanical mechanism to convert water pressure to rotational motion, which is converted to electricity by a generator. A rectifier, charge pump, and regulator are used to charge a storage capacitor, which serves as the power supply for the system. An ultra-low-power microcontroller samples a piezoelectric sensor at 33 Hz, and transmits the 16-bit data wirelessly using a 433 MHz transmitter.

### Mechanical Power Harvester

In initial iterations of the power harvesting unit, we attempted to use a piezoelectric striker as in the MIT Pushbutton [4]. These prototypes used motion of a piston to move a spring-loaded striker back and forth, crashing against a piezoelectric crystal at which point the voltage was harvested to a capacitor bank. However, this solution limited the ability to harvest energy because the piston had to move a set distance in response to water pressure changes before actuating the strike. Therefore, many pressure changes would not activate the striker and piezoelectric harvesting was ruled out.

Using designs for a pressure meter [1], the mechanical system for WATTR was modified to harvest energy from the pressure changes in a residential home. The device, shown in Figure 1, consists of a water inlet valve connected to a shaft and piston. Water enters the valve and pressurizes the piston against a calibrated compression spring. The compression spring has a spring rate of 3.23 N-m and creates a linear relationship between pressure and shaft position. The spring coefficient was optimized for residential water pressure ranging from 207 to 689 kPa and an inner pipe diameter of 20.32 mm, resulting in piston and shaft movements as large as 50.8 mm.

A small linkage converts translational motion to the rotation of a geared motor, which generates an unregulated ±8 V. We modified a Hitec HS-322 HD servo motor by removing the circuit board, position sensor, and rotation stopper. Although this motor is not optimally geared for maximum torque, its low-cost commodity nature makes it ideal for this application.

For rotational generators, the power output is an exponential function dependent on *total rotation* and *speed of rotation* [7]. For pressure transients, the total rotation is influenced by the pressure decrease or increase corresponding to a valve opening or closing, respectively. Furthermore, speed of rotation is influenced by the slope of the rising or falling pressure wave. WATTR is therefore most efficient for quick, high amplitude pressure waves, such as water-hammer, which is common in the home.

### Power Harvesting Circuit

A rectifier, charge pump, regulator, and storage capacitor are used to generate a stable long-lasting supply voltage, which is harvested from fast, low-amplitude voltage spikes. In particular, we use a bridge rectifier and the Texas Instruments TPS61200EVM, which includes the charge pump and linear regulator. The 3200 µF storage capacitor will charge as long as the input voltage is greater than 0.5 V, and the regulator ensures that the supply is limited to 3.3 V. Figure 2 shows the voltage measured on the storage capacitor during the normal operation of the system.

### Pressure Sensor

In most water pressure sensors, including the one found on the initial HydroSense prototype [2], water is separated from a piezoelectric element by a thin diaphragm. When water pressure increases, a small voltage change is induced. This voltage is amplified, and then sampled using an ADC. Unlike common pressure sensors, the WATTR sensor does not require amplification, which wastes energy in self-powered systems. The WATTR sensor uses a standard piezoelectric element found in the trigger mechanism of a

| | **Bathtub** open/close | **Lndry. Sink** open/close | **Bath. Sink** open/close |
|---|---|---|---|
| **Latency (s)** | 0.17 / 0.11 | 0.13 / 0.27 | 0.16 / 0.15 |
| **Duration (s)** | 5.5 / 6.2 | 7.7 / 8.2 | 1.4 / 3.3 |
| **∆ Press. (kPa)** | 191 / 248 | 299 / 353 | 108 / 148 |
| **Energy (mJ)** | 8.3 / 9.5 | 13.9 / 14.7 | 2.3 / 3.8 |

**Table 1: Sampling and transmission characteristics by fixture**

commodity push-button lighter. This piezoelectric transducer is placed in compression with the water pressure via a small piston and shaft, and the sensor can be unobtrusively installed on any faucet. Water pressure changes in the home exert a force on the piezoelectric crystal and result in a ±500 mV signal, which is rectified, and then directly sampled by the 16-bit ADC.

### Microcontroller, ADC, and Transmitter

We selected the MSP430F2013 16-bit microcontroller for its ultra-low-power modes, and its on-board 16-bit Sigma-Delta ADC. The microcontroller is programmed to sample and immediately transmit the piezoelectric sensor data at 33Hz. The Holy Stone MO-SAWR-AS434M 433 MHz amplitude-shift-keying (ASK) transmitter sends a 25-bit packet, including an 8-bit header, 16-bits of data, and 1 parity bit at a rate of 3.2 kbps. Between samples the microcontroller enters a 1.5 µW sleep state. During the sampling phase, the microcontroller consumes about 900 µW including the ADC, and the transmitter consumes about 36 mW while transmitting at 4 dBm with a supply voltage of 3 V.

## PERFORMANCE ANALYSIS

To investigate the reliability of WATTR when transmitting data, we installed the system in a single home under a bathroom sink fixture. First, we investigated which fixtures in the home generated enough harvested power to wirelessly transmit data. We found that 6 of 8 fixtures generated sufficient power, and the two failures were the kitchen sink and dishwasher, which produced the least pressure drop and were farthest from the sensor.

Second, we used the data from three fixtures, a sink, bathtub, and laundry machine, to qualitatively analyze the energy and sampling characteristics of the WATTR system. We conducted 10 trials at each fixture (30 open and 30 close events in total). Table 1 shows several characteristics of the WATTR system. *Latency*: the difference in time between the start of the pressure transient and the start of wireless transmission. *Duration*: the length of time that the transmitter continually samples and transmits pressure values. *∆ Pressure*: the average magnitude of the step change in pressure. *Avg. Energy*: the average energy harvested and stored on the capacitor, without a load.

From the data, it can be seen that enough energy is harvested to sample data for a few seconds. Although transient pressure waves may last longer, the beginning few seconds of the wave contains the most energy and is the most important feature for the HydroSense classification algorithm [2]. WATTR is therefore ideally suited for sampling the beginning of the waveform as the initial pressure drop quickly generates a voltage capable of powering the microcontroller. The WATTR power harvester can be repurposed for other low-power sensing applications as well. The system can generate up to 15 mJ of energy, which is enough to continuously power a 50 mW transmitter for 30 ms. In our application, we were able to power the system for much longer because the transmitter was duty cycled so that it woke up only when needed.

We also investigated characteristics of the transmitted packets at three different distances, 0.75, 1.5 and 3 m. For each distance, we performed 10 trials resulting 30 open and 30 close events for each distance (180 total events). Table 2 shows the percentage of packets that were sent but not received (packet loss), and the percentage of packets that were received but detected as corrupt based on the parity bit. These numbers only represent packet sent during the first 4 s after each valve event.

The high packet loss at 3 m is due to insufficient transmission power while the supply voltage drops. The data sent in the first few seconds after the valve event are sent at full power, but then the power is dramatically reduced due to the decaying supply voltage on the storage capacitor. The reduced output power correlates to the high packet loss at long distances.

To demonstrate WATTR's applicability to HydroSense, we investigated whether enough valid data is received and whether the data from the commodity piezoelectric sensor are stable enough to *classify* different water fixtures. We used the classification algorithm described in the original HydroSense work (nearest neighbor matched filtering). At each distance, we used the 60 collected events to form a library, and performed a leave one out cross validation, comparing the left out pressure transient to each of the remaining pressure transients in the library. The event with the highest matched filtering score was chosen as the fixture type and was also classified as an open or close (6 possible classes in the classification). We refer the reader to [2] for a more formal discussion of the classifier.

The classification resulted in 56/60 (93.33%) of the transients being classified correctly at 0.75 m, dropping to 66.67% at 3 m due to dropped packets.

## DISCUSSION

Mechanical systems [7] harvest far more energy than power harvesters that reply on ambient energy sources. Their limitation consists of size and proper mounting. The Peppermill project requires human input because forces necessary to charge heavily-gear rotary devices rarely exist naturally. WATTR replaces human input with water pressure transients, which has not previously been used for power-harvesting. For autonomous sensing, WATTR takes advantage of the large amount of mechanical power (up to 15 mJ) harvested to build the first self-powered sensor capable of long duration time-domain data collection.

| Distance (m) | Packet Loss (%) | Corrupted Packets (%) | Classification Accuracy (%) |
|---|---|---|---|
| **0.75** | 5.11 | 2.32 | 93.33 |
| **1.5** | 18.40 | 5.67 | 85.00 |
| **3** | 26.91 | 8.48 | 66.67 |

**Table 2: Transmission rates for WATTR by distance**

We demonstrate a self-powered wireless sensor by using WATTR for the HydroSense system. Despite the limitations of range and packet loss, the ability to classify with 93% accuracy suggests improvements to WATTR could make it a viable replacement for the sensor used in the initial HydroSense prototype.

Self-powered time-domain data collection can be elaborated outside of the water sensing space. Imagine a vibration-powered seismograph that collects time-domain data from earthquake events and then relays that information back to a base-station. Furthermore, many self-powered sensors are expected to operate autonomously for indefinite periods of time in inaccessible locations. WATTR demonstrates the ability to power a wireless device from its sensing stimulus on residential plumbing to show how specifically engineered harvesting devices can collect time-domain data with comparable results to standard sensing solutions.

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