Battery-Powered Wireless Sensor Network for Non-Invasive Monitoring of Water Usage Events in Premise Plumbing Systems

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***Abstract*—Collection of extensive field data on timestamped usage of various fixtures in residential and commercial buildings is necessary to derive the *p*-values, a probability factor of fixture use during peak hours for all fixture types. These values are critical to properly estimate instantaneous peak water demand when designing the premise plumbing systems of new buildings. This paper presents a wireless sensor network to address such requirement. The Zigbee-based sensor network includes a group of battery-powered, low-cost sensor modules, each with a size of 12×6.4×8.1 cm^3, for non-invasive, real-time detection of waterflow events. Two sensing modalities, acoustic and calorimetric, are integrated in the sensor module to provide accurate detection of waterflow under various noise and interference conditions in the field. The sensor module has fast response time for detection with a time resolution as small as 0.25 sec. Power efficient operation strategies result in a long battery lifetime >68 days, more than adequate for the target application. Field tests in a cafeteria restroom and test deployment of the wireless sensor network successfully verified its design and implementation.**

Keywords—non-invasive; real-time; wireless sensors; Zigbee; waterflow detection; 3D printing; acoustic; calorimetric; low cost

I. Introduction

Instantaneous peak water demand is the most important consideration when designing the premise plumbing system for a new building as it governs the size and cost of the water supply system including service line, meter size, heater capacity, pipe diameters, valves, fixtures, and so on [1]. With new efficient plumbing fixtures widely adopted, the traditional standard method to estimate peak water demand based on the Hunter's curve developed in 1940 has become outdated and resulted in significantly over-sized plumbing system in both residential and commercial buildings [2-4]. This can trigger potential water-energy problems such as higher construction cost and wasted energy/water from inefficient water heating, as well as public health concerns on the presence of opportunistic pathogens like legionella [5-6]. An improved method for this estimation has been developed; however, it requires a critical missing factor, *i.e.*, the probability, or the *p*-value, of fixture use during the peak hours for all fixture types in a building [1,7]. Estimation of the *p*-values for various fixture types requires collection of extensive field data on the fraction of time when each fixture is in use, *i.e.*, time-stamped binary (on/off) switching events.

Currently no devices with this capability are available. It is highly desirable for such device to be non-invasive and low-cost with ease of deployment so that it is amenable to larger scale deployment to provide better estimation accuracy of the *p*-values. Invasive waterflow sensors, while low-cost and widely available, require modification of existing plumbing and inline insertion of the sensors with waterpipes, making it challenging and costly to deploy.

This paper reports, for the first time, a low-cost solution based on distributed wireless sensor network and multiple non-invasive sensing modalities to address this pressing need (Fig. 1). Each miniature, battery-operated wireless sensor module in the network includes two sensing modalities, acoustic and calorimetric, to provide accurate and non-invasive detection of waterflow events in waterpipes that are connected to strategically selected fixtures in a building. Collected event data with timestamps over a target period, *e.g.* 1-2 months, can be used to extract *p*-values that are widely applicable depending on the categories of the building.

Commercially available non-invasive flow measurement technologies are typically based on ultrasonic sensors, which are sophisticated and expensive, unsuitable for binary event detections required in this application [8-9]. Very limited work

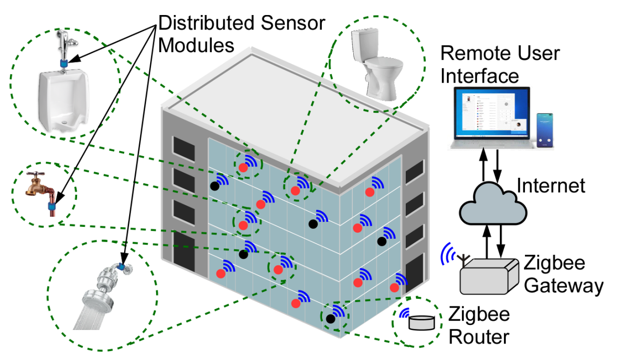

Fig. 1: Concept diagram of the wireless sensor network.

This work was supported primarily by the National Institute of Standards and Technology under Award Numbers 70NANB21H014 and 70NANB21H181 and by Ohio Water Resources Center.

has been done using acoustic sensors such as microphones for flow detection, while its feasibility has been demonstrated with moderate accuracy for agricultural sprayer nozzles and home monitoring [10-11]. The concept of calorimetric thermal flow sensors, either invasive or non-invasive, has been demonstrated for heating, ventilation, and air conditioning (HVAC) systems [12-18] and microfluidic devices [19-22] but has not been applied to monitoring of water delivery plumbing systems. We are reporting a calorimetric sensor designed and optimized for non-invasive flow detection on premise plumbing in an accompanying paper at this conference [23].

II. System Concept and Design

A. System overview

As illustrated in Fig. 1, the wireless sensor network system is based on the Zigbee protocol and consists of a group of miniature sensor modules, several Zigbee routers and a Zigbee gateway. The sensor module is battery powered for direct attachment to waterpipes without the need for any cable or external power sources and therefore can be distributed in a building under investigation at strategically selected sites for various types of plumbing fixtures. The Zigbee routers will be deployed to help expand the coverage range of the Zigbee network as necessary. The Zigbee gateway consists of a Zigbee coordinator and a Raspberry Pi unit. The coordinator interfaces with sensor modules and Zigbee routers with time synchronization among all units to ensure proper timestamp recording. The Raspberry Pi provides functions including system control as well as data collection and management, and interface with Internet for data storage/backup in the cloud and for remote interaction with end users through web applications.

The Zigbee coordinator uses Silicon Labs EFR32MG21 microcontroller unit (MCU) with embedded Zigbee function blocks and wireless transceivers for communication with sensor modules, and a UART interface to communicate with the Raspberry Pi. This MCU has ultra-low transmit and receive power, <1.4 µA current consumption in the deep sleep mode, high resolution analog-to-digital conversion (ADC) feature in a small size of 5×5×0.85 mm^3 [24].

Table I summarizes main system performance parameters.

B. Sensor module hardware

Figure 2 shows the hardware block diagram of the sensor module. It includes a non-invasive flow sensor unit with multiple sensing modalities, the same EFR32MG21 MCU with an embedded Zigbee transceiver, and a replaceable battery pack along with the power regulation circuit, all integrated inside a package with thermal and sound insulation.

The flow sensor unit combines two sensing modalities to enable robust waterflow detection. Sensing modality 1 (SM1) is acoustic measurement using a microphone. Sensing modality 2 (SM2) is calorimetric thermal detection using a miniature heater and temperature sensors; details are provided in [23]. SM1 is realized using a miniature high sensitivity MEMS microphone chip, PUI Audio PMM-3738-VM1010-R, which detects the waterflow events in real-time (with a 0.25 sec time

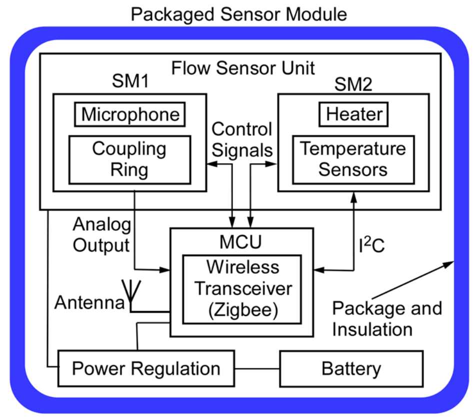

Fig. 2: Hardware block diagram of the sensor module.

resolution). The microphone has a key built-in feature: it can continuously monitor sound in the environment in the sleep mode with very low power consumption and send a triggering signal to wake up the MCU when the sound level exceeds a predefined threshold [25]. The MCU will then collect sound data from the microphone and process it using an algorithm to identify waterflow events. When a waterflow event is detected, the MCU turns on SM2; otherwise, the MCU and microphone return to the sleep mode. This allows the sensor module to stay in the sleep mode for most of the time and thus maximize the battery lifetime of the sensor module. As SM2 consumes higher power, it also helps save energy by only turning on SM2 when SM1 detects sound identified as waterflow; this allows using SM2 to cross check the accuracy of SM1 detection, particularly for those longer-duration waterflow events. The estimated lifetime of the sensor module is >68 days when a high-capacity battery pack of 10,000 mAh is used.

A flexible coupling ring is placed between the PCB and the waterpipe to form an acoustic chamber surrounding the microphone acoustic port to minimize noise from the environment and enhance sound coupling from the waterpipe.

C. System and sensor module software

The system software on the Raspberry Pi includes Python programs for system and data management as well as JavaScript programs for the web server and web applications for remote user interface and data processing. The system software also includes MCU programs for the Zigbee coordinator/routers for handling Zigbee communication.

TABLE I. System Performance Parameters

Parameter	***Value***
Sensor Module	
Sensor module size (fully assembled)	12×6.4×8.1 cm^3
Main PCB size (includes antenna)	36×46 mm^2
Time resolution for event detection	0.25 sec
Battery capacity	10,000 mAh
Lifetime (assume 70% battery capacity usable)	>68 days
Sensor Network	
Wireless protocol	Zigbee
Max. no. of units (theoretical / practical)	65,536 / >100s
Tested wireless comm. range (no obstacle)	>36 m
Tested wireless comm. range (with obstacle)	>25 m

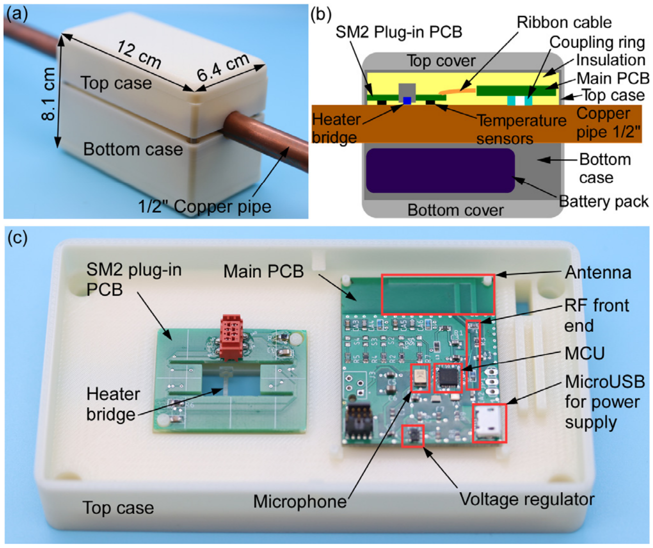

Fig. 3: (a) Photo of assembled sensor module mounted on 1/2" copper pipe; (b) cross-sectional illustration of packaged sensor module; (c) photo of top-down view of elements inside the top case of the sensor module.

The software for the sensor module includes firmware for local functions such as ADC, flash, and power management, as well as Zigbee communication functions; it also includes an algorithm for each sensing modality to process data and detect waterflow events. The SM1 algorithm allows a fast, real-time waterflow event detection. The algorithm filters the sound data to remove unnecessary noise/interferences and calculate a parameter named signal strength indicator (SSI). The SSI is compared to predefined thresholds to determine waterflow events. The algorithm was designed based on analysis of a large group of diversified types of noise and waterflow sounds as well as quantitative evaluations of various algorithm design choices to maximize the effectiveness in differentiation between waterflow sound and noise.

III. System Implementation

The implemented sensor module is shown in Fig. 3. The sensor module circuit is implemented on two custom-built printed circuit boards (PCB): a main PCB including MCU, microphone, antenna, heater driver circuit, and power regulator circuit; and a plug-in PCB for SM2 temperature sensors to prevent heat generated on the main PCB from affecting SM2 operation. The 3D printed package includes a top case and a bottom case. The PCBs along with the 3D-printed coupling ring and SM2 heater are installed in the top case of the sensor module. A 5V battery pack with 10,000 mAh capacity is integrated in the bottom case of the module. The top and bottom cases are joined together with bolts and nuts after mounting on the waterpipe for ease of deployment.

IV. Experimental Results

The wireless performance of the sensor module was tested by sending dummy data to the Zigbee gateway. The test results indicated that the wireless link had reliable transmissions for a range of >36 m without obstacle and >26 m with obstacle (*e.g.* a metal door). Full characterization of the wireless performance, including packet error rate (PER) and received signal strength indicator (RSSI), is underway.

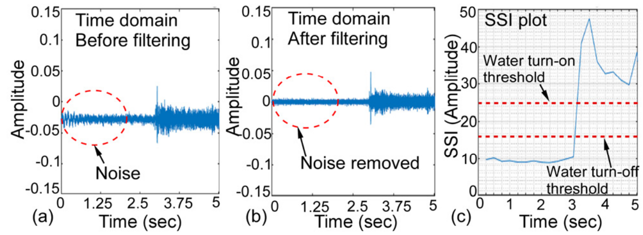

Fig. 4: Example SM1 results from field tests in a cafeteria restroom of on-campus residence building, showing one of the waterflow events captured during deployment and the effectiveness of algorithm in removing background noise (people talking in this case): (a) time domain before filtering, b) time domain after filtering, and c) calculated SSI.

TABLE II. Recorded Waterflow Events with Timestamps from Both Sensing Modalities in Overall System Tests

Events	Location	SM1 Timestamps (sec)		SM2 Timestamps Raw Data (sec)	
		On	Off	On	Off
1	1	0	103	1	103
2	1	200	303	202	303
3	1	400	502	401	503
4	1	600	702	603	702
5	1	800	903	802	903
6	1	1000	1103	1003	1103
7	1	1200	1303	1201	1303

Field tests were performed to verify the sensor module functionality in a cafeteria restroom of an on-campus residence building. Figure 4 plots the SM1 data of one of the captured water turn-on events, showing the effectiveness of the algorithm in removing background noise and in detecting waterflow events. As an example, a total of 275 water on-off cycles were detected during a 24-hr period.

A preliminary overall system test using the wireless sensor network was performed to verify its functionality. The Zigbee gateway was deployed with two sensor modules mounted on ½" copper pipes nearby regular water faucets. The distances between the sensor modules and the Zigbee gateway were 3 m and 18 m, respectively. Both sensing modalities in the sensor module were tested concurrently for waterflow detection. The data was wirelessly recorded into the Zigbee gateway and downloaded through the user interface on the web application. A subset of the recorded waterflow events with timestamps are listed as examples in Table II. A delay of 0-3 sec was observed between the event timestamps generated by SM1 and SM2, which is as expected and considered acceptable. The wireless sensor network system was successfully verified for its operation and functions for the intended application.

V. Conclusion

A wireless sensor network with distributed battery-powered, low-cost sensor modules for non-invasive waterflow event detection has been successfully designed, implemented, and experimentally verified. It will be deployed in the field to collect realistic water usage data for *p*-value estimations.

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