Design and Implementation of Smart Flowmeter for Urban Water Metering

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***Abstract*—Mismanagement of water resources is one of the most pressing issues in developing countries like Pakistan. With the burgeoning population growth and migration to urban spaces for economic opportunities, freshwater resources are becoming highly stressed and polluted. In this paper, we present the design of a cost effective low power flowmeter with embedded intelligence and remote telemetry for urban residential water metering applications. The study provides fundamental architecture of water metering IoT node and necessary details of implementation. Results of the study are presented in terms of power consumption, accuracy and reliability of device in lab and in field setting. The proposed system could assist developing cities in estimating realistic water demand and creating sustainable socio-political urban water policies at the decision-making level.**

***Index Terms*—Systems Integration, Instrumentation, Smart metering, Urban water metering, Low power systems, ICT enabling smart cities, Sensors**

I. Introduction

The ability to meter the consumption of water plays a vital role in understanding and improving urban ecosystems as it enables stakeholders to study consumer patterns, assess requirements, and account for losses or theft [1]. The data required to make these assessments becomes important in developing countries like Pakistan which have highly stressed freshwater reserves. These water resources for megacities like Karachi are further strained by their ever-increasing migratory populations. Leakages and water thefts are common across the city leading to almost 35% combined non-revenue water (NRW) from physical and commercial losses [2].

The existing water system in Karachi provides no viable means of gathering quantitative data on domestic household water demand. The absence of this data has historically posed a challenge in studies attempting to develop an understanding of Karachi's water crisis through empirical analysis [3]. This highlights the strong need for developing a water metering solution to enable the study of water demand in Karachi. An automatic meter reading (AMR) system provides a solution to this challenge as it allows us to track data temporally and spatially. It is less prone to human error, and offers centralization for data integrity and consistency. Existing commercial solutions for AMR are costly and are ill-suited for long term, (near) real time monitoring purposes. Furthermore, they often require a continuous power source which is not ideal for a city like Karachi, as its localities suffer from frequent power outages. In addition, the available modes of communication in such solutions are often singular. These factors make them logistically unfeasible for deployment over a large-scale water network in Karachi. This demonstrates the need for a local solution development.

Through this paper, we present the electrical design of a smart water flow measurement device (referred to hereafter as a node) and the necessary IoT infrastructure for installation on household pipes. We begin by presenting our review of existing literature on the subject. This survey has been used to inspire the design choices and provide a benchmark for comparison. In following sections, we present the details of the developed system and its various subsystems which include the node architecture and the measurement methods deployed on the node. Thereafter, we provide the results and performance achieved by the developed system on household installations. In section VII, we provide future improvements and the conclusion of our work.

II. Literature Review

During literature review, many design challenges concerning the development of a smart water flow measurement system were identified. These can be characterized as: reducing the overall monetary cost of such systems, ensuring long-distance wireless communication, improving accuracy, and handling & organizing incoming data streams through smart networking architectures and algorithms. The work presented in [4] provides relevant framework for such challenges for open channel flows used for irrigation purposes. For piped flow, the use of velocity-type flow sensors for flow measurement were identified as a common choice in existing literature due to their ease of use, cost-effectiveness, and good accuracy [1] [5] [9]. Within this category, sensors utilizing the hall-effect to translate the flow rate to a digital signal are the most common

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[10] [6] due to their ease of integration with digital circuits. For instance, [7] modified a traditional velocity meter into a hall-effect by embedding a magnetic reed-switch pick-off and a tiny magnet. Similarly, [11] used a helical turbine coupled with a hall-effect sensor to measure the flow rate and transform turbulent water flow into laminar. On the other hand, [12] used the analog output voltage of a small 3-phase generator turbine to measure the flow rate.

The sensor calibration for systems involving hall-effect sensors was performed volumetrically. This involved conducting multiple experiments recording the time taken to drain a standard volume through the flow meter and adjusting a calibration constant until the calculated volume matched the known standard [6] [10] [11]. For a system involving a turbine as the means of flow measurement, the calibration was done similarly, but involved mapping the generated voltage to known flow rates by curve fitting [12].

To achieve long-distance transmission, the use of GSM technology (GPRS, CDMA,3G,4G) was a popular choice due to its wide access in urban spaces [5] [8] [9] [13]. For instance, [5] used it to create an urban water billing and metering system with an SMS-based networking architecture to send metering data, tampering alerts, and receive control signals to connect/disconnect the water supply. The system assumed continuous power and had an EEPROM backup during power failure. Its server-side architecture consisted of a GSM Receiver connected to a Linux operating system for data processing and management.

In more recent times, although relatively short in urban accessibility compared to GSM technology, WiFi has been extensively used in the development of smart IoT-enabled water flow measurement systems due to its ease of integration with microcontroller systems, access to the internet, and wide & cheap availability [11] [14] [15]. The WiFi chips from Espressif Systems were widely used to this end. An ESP32 and YF-S201 hall-effect flow sensor was used by [1] to record the water flow rate on different household connections, at intervals of 1 second. This was communicated to EmonCMS (cloud management system) using HTTP & the light-weight MQTT protocol. The system achieved an accuracy of 95% on flow rate measurement. Similarly, [10] used the NodeMCU-ESP8266 along with the YF-S201 hall sensor, performing continuous interval-based sampling and recording the data on the Heroku cloud service. They achieved a flow measurement accuracy of 99.36%. A node-gateway architecture was used by [6], using a NodeMCU and a Raspberry Pi that connected to the cloud.

Some more unconventional architectures for wireless data transmission explored technologies like Zigbee and LoRaWAN [8] [16] [17]. Some limitations posed by such technologies were their transmission distance. For example, the nodes in [9] were limited to a transmission distance of 100m using Zigbee technology and utilized mesh networking algorithms for routing across nodes to a GSM & WiFi transmission gateway. Similarly, [16] involved water flow measurement nodes and relays communicating to a concentrator-gateway within the same building block using LoRa. The data was then uploaded by the concentrator-gateway to the cloud using GPRS via a GSM module. A similar architecture was also presented by [17], which in addition also made use of the lightweight MQTT protocol for an urban stormwater monitoring system. Another paper [18] explored the use of RF nodes organized in a star topology, with a central Raspberry-Pi hub to measure flows in water distribution networks. The gathered data was uploaded to a Google Drive platform. The downside with such systems was their increased complexity and inter-dependency as a result of hardware centralization.

In many of the solutions explored, an external source of power was assumed for functionality [5] [9] [11] [15]. While in others, a battery is used as a back-up, as seen in [8] [12] [18]. A solar power harvesting circuit coupled with a battery management system was used in [17] to deploy sensors at remote locations along water streams.

III. System Overview

Fig.1 shows the overview of the complete data collection system comprising multiple nodes forming a star topology network as the data from all the nodes is centrally collected and analyzed. Each node consists of the flow sensor installed in the main water supply line and circuit board which performs signal conditioning and manages the data transmission. The node continuously monitors and samples the flow rates at a specified interval to calculate the water volume in liters. This data is stored on the meter in local storage till it transfers to a central server through either WiFi or GSM after which the stored data is relieved to the server.

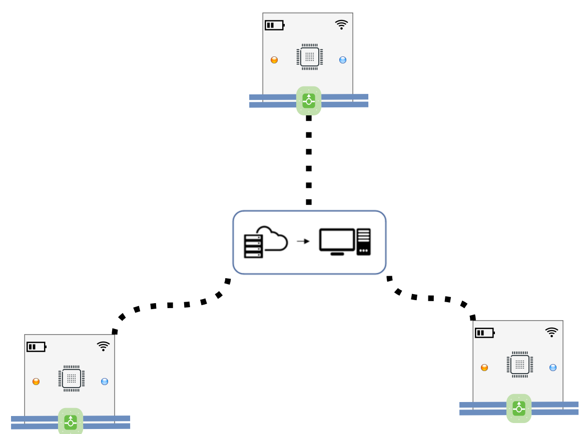

Fig. 1. System Overview

Each node is designed to operate in one of the two technologies of communication with the server, either by WiFi or GSM. The node is primarily designed to send data over WiFi using HTTP protocols. For places that do not offer WiFi connectivity, the node is configured to use the GSM modem for data transmission.

The data is collected on a centralized SQL-based server hosted on the Digital Ocean Cloud. Furthermore, a custom front-end dashboard is designed to show detailed information

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about the active and in-active nodes alongside data visualization features.

IV. Node Architecture

In following sub-sections, we categorically discuss the details of the components that form a node.

A. Power

The overall circuit is designed to operate on a 5V 2A DC power adapter, while a 3.7 V 1400 mAh Lithium-Ion battery provides backup in case the primary source of power fails. The node design fundamentally relies on off-the-shelf components to keep the design highly modular and low-cost.

To reduce the power consumption of the system, the node operates in light sleep mode. Table I presents a comparison of estimated and measured current consumption, and status of WiFi and CPU in the various operating modes respectively. Current consumption estimates are obtained from [19].

TABLE I
ESP32 Operational Modes

Parameters/Mode	Active	Light Sleep	Deep Sleep
Estimated	160-260mA	0.8mA	0.01mA
Measurements	155mA	12mA	8mA
WiFi	Working	Not Working	Not Working
CPU	Working	Working	Idle

Furthermore, the power side consists of a 3.3 V Low Drop-Out (LDO) regulator, battery protection, and charging-discharging module (based on TP-4056). In addition to charging the battery, the TP-4056 module also provides a constant output voltage of 4.2V DC, which is directly used for powering the GSM module, whereas the LDO regulator is used to powe-up the ESP32 and other electronics as shown in Fig. 2. The TP-4056 module helps ensure that the maximum discharge current limit is not exceeded, as otherwise the number of battery charge cycle is significantly reduced.

B. Processing

Data collection, processing, and transmission are handled by ESP32 system-on-chip microcontroller [19]. ESP32 performs the flow measurement by counting pulses from the flow sensor and timestamping each measurement with epoch time obtained from its built-in Real-time Clock (RTC). The system is configured to operate in two functional modes namely 'Active' and 'Light Sleep' mode. During the light sleep mode, the system continuously takes the samples of measurement and stores those into an onboard flash storage. After a set period of time, the system comes into 'Active Mode' and transmits all the data in flash to the server. The operational values of current consumption for each mode under lab practical setup are given in Table I. This approach of switching between two operational modes, helps in optimizing the battery life of system without compromising the accuracy of measurements.

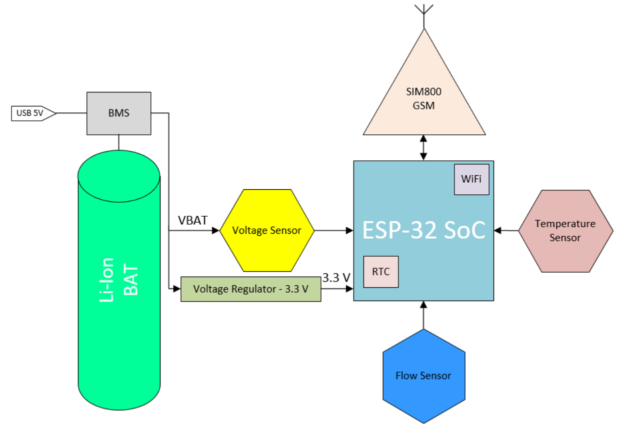

Fig. 2. Fundamental components of sensing node

C. Wireless Communication

The system is designed to communicate with a central server using either WiFi or GSM technologies. WiFi chip is available on-chip in ESP32 [19] whereas for GSM, SIM-800L module is incorporated in design as shown in Fig. 2. The system can be configured to communicate via either mode through hardware-level DIP switches by the user. During the deployment and operation of the flowmeter, only one communication method (i.e. WiFi/GSM) is active which is set at the time of installation based on the feasibility and availability of the network. The data readings are transmitted to the back-end server. The server performs data integrity checks and stores them in a database for further processing and integration with the user interface.

D. Sensing Elements

As shown in Fig.2, the system consists of a flow sensor, temperature sensor, and voltage sensor. The primary sensing element for measuring water flow rate is a paddle-wheel type flow sensor (model: G1-FS400A). Besides this, the circuit also includes a 10 kΩ NTC thermistor for housing temperature measurement, and a resistive network for battery voltage measurement. Housing temperature and battery voltage measurements are added for remote diagnostic and prognostic purposes.

V. Measurement Methods

This section describes the approaches taken for on-board time keeping and the algorithms used for processing and measuring the water flow. A discussion on battery voltage measurement and temperature measurement approaches is also presented.

A. Time Keeping

To reduce the cost and complexity of system, on-chip real-time clock (RTC) available in ESP32 [19] is utilized to keep track of time of measurement. The system synchronizes the RTC clock on each start-up using the Network Time Protocol (NTP) to attach the time label to each sample collected. The internal RTC provides time resolution in microseconds and is

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found to be extremely accurate for flow sampling in the order of seconds.

B. Flow Measurement

A robust approach towards the measurement of flow was incorporated in the design. During literature review, the measurement of flow rate, via counting the frequency generated by the flow sensor was generally found to be sampled either through polling or interrupt based methods. These approaches posses three limitations :

1) A loss of accuracy in the measurement. This is because each measurement only reflects the flow rate at the instant of sampling or across the duration during which the sample is recorded, which would be temporally finite as the microcontroller would need to handle other tasks periodically.
2) Interrupt-based approach causes sudden stops during wireless transmission which also results in transmission failure.
3) There would be a loss of data if the sampling interval needs to be increased. Increasing the sampling interval is a desirable feature as it would allow the microcontroller to conserve power by sleeping.

The proposed approach utilizes the frequency counting-based method using a hardware counter. A 16-bit hardware counter on ESP32 was configured to counter number of pulses generated by the flow sensor. Meanwhile, RTC provides a precise track of the time period for which the pulses were counted. The frequency was determined by utilizing the relationship defined in equation 1.

$$f = \frac{n}{T} \tag{1}$$

where f is the frequency in hertz (Hz), n is the count, and T is the time elapsed in seconds (s). Flow rate in pipe is calculated by equation 2

$$Q = \frac{f}{k} \tag{2}$$

where Q is the volumetric flow rate in liters per minute (L/min) and k is the calibration constant in pulses per liter, given in the datasheet of the sensor. The calibration constant was validated in the lab through experimentation. This approach addresses all three limitations identified here and is one of main contributions of the work.

C. Battery Voltage Measurement

To get an estimate of the State of Charge (SoC) of the battery, the voltage of the battery is measured on the node along with flow measurement. The maximum raw voltage that ESP32 ADC can measure is 2.45 V with 11 dB attenuation [19]. Since Li-ion battery ranges from 3.0 V to 4.2 V in normal operation, therefore, a voltage dividing resistors (VDR) network was utilized to step down the voltage by half as shown in Fig. 3. The resistors labeled r model the external resistors added to the board to make VDR while R models the input impedance of ESP32 ADC. Here the voltage read by ESP32 (V_{out}) can be modeled as:

$$Vout = \frac{V_{BAT}}{r/R + 2} \approx \frac{V_{BAT}}{2} \tag{3}$$

The approximation holds if internal resistance of ESP32 (i.e. R) is sufficiently larger than VDR resistors (r).

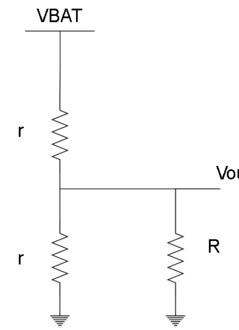

Fig. 3. Battery voltage sensor model

D. Temperature Measurement

For temperature measurement, a low-cost 10 kΩ negative temperature coefficient (NTC) thermistor is utilized in VDR configuration with sufficiently high resistance (56 kΩ) to reduce current draw and minimize self-heating. Steinhart–Hart equation is utilized in firmware to estimate the temperature from thermistor voltage drop.

VI. Results and Discussion

The proposed design of the smart water flowmeter was fabricated on a Printed Circuit Board (PCB) as shown in Fig. 4. It was designed to have all components on board, including the Li-ion battery, so that the design could be portable and easily fittable into widely available low-cost 4” x 4” or 4”x 6” IP-65 rated electronics enclosure boxes. Figure 5 shows flowmeter installation at one of the households participating in the study.

Fig. 4. Node Printed Circuit Board

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Fig. 5. Sample node installation in a household

A. Power Consumption

It was estimated and verified through practical experiments that the smart water meter node consumes less than 10 W of energy on average. Furthermore, the node was tested on a fully charged battery. Fig. 6 and 7 show the behavior of the battery terminal voltage over a period of time for the battery drain test. It is further evident from the figures that the average battery life of the system on GSM is 23 hrs whereas on WiFi it is 30 hrs.

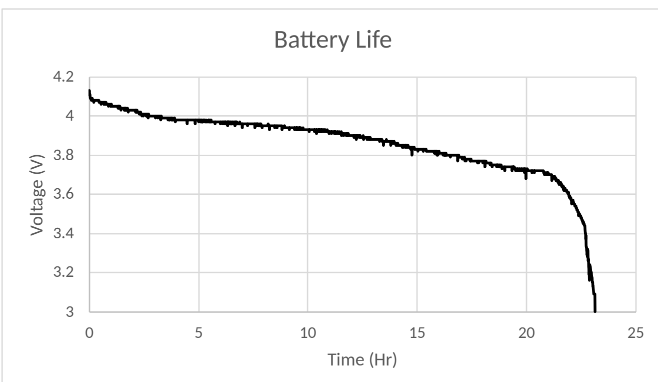

Fig. 6. Battery drain test results on GSM

B. Measurements Accuracy

To test the accuracy of the flow meter under different scenarios that are encountered in correspondence to different sites, various test cases were performed in a lab setup. Variations were made in the water pressure, the input flow rate (through controlling a valve opening), the operating voltage for the sensor, the sampling rate of flow measurements, as well as the sensor's physical alignment on the pipe section (i.e. horizontal, tilted, vertical, etc). Fig. 8 shows the histogram of percentage error for the 63 trials performed with 10 liters fixed volume of water at a flow constant of 4.2. The results demonstrate the repeatability of measurement with a standard deviation in error of 2.87%.

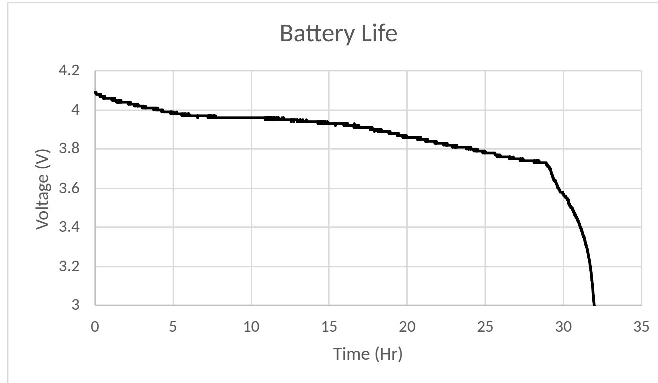

Fig. 7. Battery drain test results on Wifi

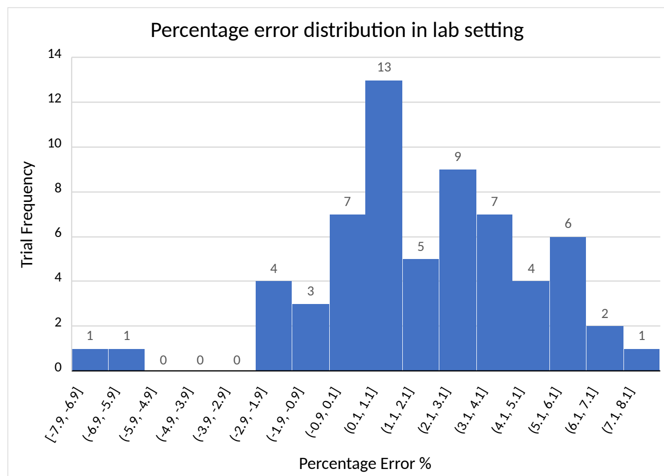

Fig. 8. Percentage error distribution over 63 trials for 10 L test

C. Device Reliability

The metrics for device reliability are based primarily on power consumption and memory availability. Fig. 9 shows the log of data collected over a duration of 24 hours. From top to bottom it shows the data of totalized flow, flow rate, temperature, sample time, and transmission history. Here, 'sample time' is the difference between the timestamps of two samples. It can be seen from the graph that the system operates without any glitches over the period of one day.

VII. Conclusion: Contributions and Future Scope

The proposed prototype is targeted to be the first indigenous residential water meter in Pakistan, having the onboard processing for determining water consumption in (near) real-time and can be utilized for purpose of leakage detection, water theft, and billing. The proposed device incorporates all the design customization of a low-cost and scalable prototype of

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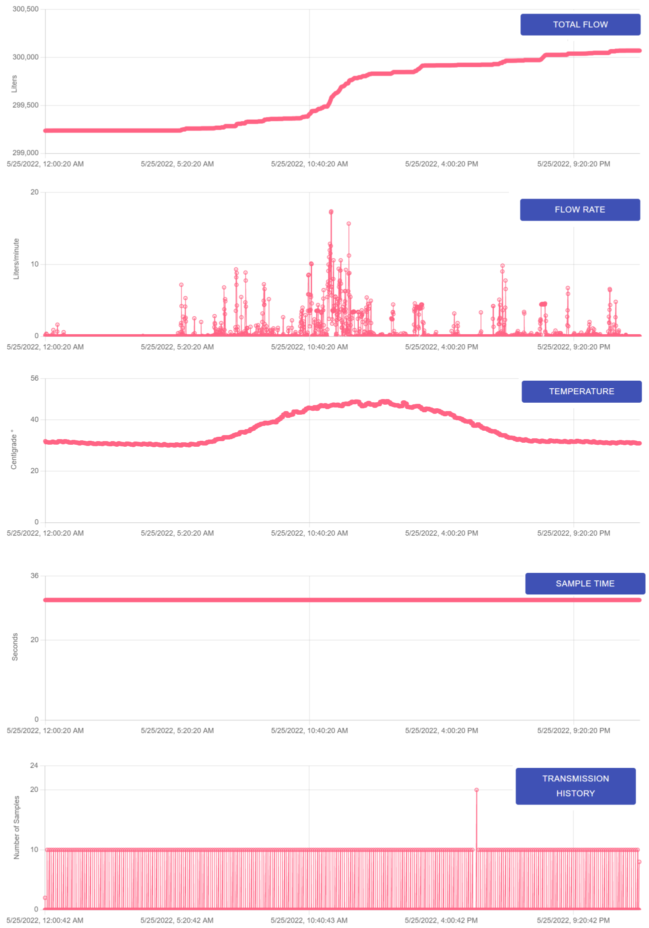

Fig. 9. System working over 24 hour duration

a water flowmeter for an urban water metering study. The flow meter designed is capable of measuring water volume for various test cases within a reliable accuracy window of the flow sensor used. Additionally, the meter can also operate stand-alone in the case of a power failure for roughly one day. Its scalable deployment can predict the city-wide water consumption profile to improve urban water management. Additionally, WiFi and GSM technology can assist metering in remote and isolated regions, and agrarian land in addition to dense urban cities, which is highly advantageous for an agricultural country like Pakistan. The instrument can further assist in estimating realistic water consumption demand for socio-economical sustainable land development to cater to the rapidly growing population. Nonetheless, the system is constrained by relying on external power lines which can be removed by considering renewable energy sources like solar and wind to make the system self-sustaining. Power consumption of the system can be further reduced by employing low-power radios or using the deep sleep mode of the microcontroller. For improving the accuracy of the system, novel low-power sensors can be explored to further extend this study.

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