
Zahoor Ahmad, Abubakr Muhammad

Department of Electrical Engineering, SBA School of Science & Engineering
Lahore University of Management Sciences (LUMS), Pakistan
zahoor.ahmad@lums.edu.pk, abubakr@lums.edu.pk

Abstract—Motivated by the critical need to monitor and control the world’s largest irrigation and river networks, such as those in the Indus river basin, we have developed a smart water meter to gauge open channel flows. While developing this design, we have overcome challenges related to power consumption, precision, calibration, field conditions, data communication and cost. We report successful field deployments with the hope that large scale deployment of such WSN inspired canal flow meters will ensure equity of water distribution, manage water scarcity and thereby increase agricultural productivity.

Index Terms—telemetry; hydrometry; ultrasonic ranging; GPRS;

I. INTRODUCTION

Many river systems and irrigation networks around the world require unprecedented levels of automation and usage of decision support systems to enhance system health and ensure high efficiencies of water delivery [12]. Frequent and pervasive measurement of open channel flows is one basic requirement for such automation. In many developing countries, where the need for such large-scale deployment is the highest, the desire for infrastructure modernization conflicts with economic constraints on both deployment and maintenance. Therefore, there is a need to develop extremely low-cost, low-maintenance and scalable open channel flow measurement systems. In [11], the authors give an overview of such a system being developed and deployed for irrigation networks in Pakistan. The work is part of a wider research initiative, to determine the feasibility of a fully automated, smart water grid for Pakistan covering other aspects of estimation, control, optimization and decision making [6], [9]. The initiative is strongly linked with issues related to participatory irrigation management, enforcement of water rights and accountability. In other related works [10], [13], the need for such measurement technologies have been amply stressed by researchers in academia and industry. Our current initiative focuses on automating the hourly-to-daily measurement of water discharges for canals with typical flow rates in the range of tens to a few hundreds cubic feet per second (cfs) [11].

In this paper, we give full details of the electronics designed for a wireless sensor network (WSN) technology inspired flow gauge, most suitable for installation on branch canals and distributaries at irrigation canal networks in a developing world scenario. We report issues related to design, performance and calibration of the WSN node. We discuss steps to achieve extremely low-power battery powered design providing a practical compromise between two extremes: A direct AC mains powered system which is infeasible at remote locations and a solar-powered system which is difficult to secure physically and adds significantly to the cost. Our design guarantees a long-life completely battery powered system only requiring low-cost annual battery replacement. Secondly, we successfully demonstrated usage of maintenance-free ultrasound based sensing instead of conventional mechanical floats or pressure transducers. We have selected extremely accurate, weather proof and narrow beam sensors to overcome installation difficulties within a stilling well. We have taken care to compensate for changes in speed of sound in weather exposed conditions. Thirdly, the unit is field deployable in that we have packaged, tested and calibrated the sensor for all extreme conditions. Our confidence in the choice of ultrasonic ranging as the prime sensing modality is shared by other researchers in recent works [14], [15].

II. HARDWARE ARCHITECTURE

The block diagram in Fig. 1 shows the main components of the hardware. The ground connection is common for all blocks. The microcontroller, PIC18F26K20 works as a master component, controlling the state of most other modules. MB7380 is the main sensor for sampling water level. As the sensors consume no more than 2mA of current, we turn them on/off via microcontroller pins. Real time clock (RTC) is run by a separate 3.3V cell. The main battery is directly connected to the GPRS module, but we turn it on/off using PWRKEY pin of SIM900D. The MCU has three wire connection with the GPRS module i.e. asynchronous transmit/receive and PWRKEY pin. Each TTL data line is pulled up to 2.9V through a 10k resistor.

The sensor is packaged in an IP67 weather proof casing [2]. The sensor is suspended at the top of a concrete stilling well, constructed in close proximity of the canal. Water level
inside the stilling well is sampled every 10-15 minutes and readings are transmitted in bulk every hour using GPRS. A back-end software server collects the data converts the level into discharge. Some photographs of the developed meter have been given in Fig. 2. For system level details and description of civil infrastructure, please see [11].

A. Ultra Sonic Sensor

The Maxbotix MB7380 Ultra Sonic Sensor [3] is a cost-effective solution for applications where precision range-finding, low voltage operation, low-cost and IP67 weather resistance rating is needed. The manufacturer claims 10mm accuracy for a target distance of 1 meter (1% of range). To correct power related noise issues we added a 100uF capacitor to the sensor between the V+ and GND pins. If the temperature or applied voltage changes during sensor operation, the sensor applies necessary compensations. For best accuracy, we have also used an optional external temperature sensor MB7955 for compensation. MB7380 sensor has a calibrated beam pattern. Refer to Fig. 3, the beam fits inside the stilling well dimensions so that there are no spurious reflections from concrete walls.

B. Microcontroller

Microchip’s PIC18F26K20 flash microcontroller [4] with extreme low power (XLP) is used with 1.8V to 3.6V operating range. It has 64 kbytes of linear program memory addressing, 1024 bytes of EEPROM data and up to 3936 bytes of linear data memory addressing. Each data sample is time stamped which makes it 8 bytes long. We save the most recent 110 records in non-volatile EEPROM and the remaining 400 records in the volatile SRAM, thus enabling storage for many days in case of communication blackouts. The EEPROM memory write/erase endurance of PIC18F26K20 is limited to 10k cycles, due to silicon issues [5]. Hence, while programming, we avoid using frequent erase/write cycles. The choice of this MCU is due to its high memory (programming memory, EEPROM and SRAM) and its Fixed Voltage Reference (FVR) module. The FVR reference is a stable fixed voltage reference, independent of VDD, with a nominal output voltage of 1.2V. We cannot measure the voltage using analog to digital converter (ADC) module in the absence of some reference voltage. If we use battery voltage (3.6V) as a reference voltage, with the passage of time this voltage will drop and ADC will always show a fixed value. This reference can be enabled by setting the FVREN bit of the CVRCON2 register to 1. The FVR voltage reference can be routed to the ADC input channel. Refer to Fig. 4 for the microcontroller program flow chart for the main routine. The actual program is much more complicated than the flow chart. In the flow chart, S and T denote sampling time and transmission time respectively in minutes. As WSN turns on, MCU reads all EEPROM locations (110 records) and send them in the first transaction. In normal transactions, the message is limited to 50 records. In case of continued GPRS transaction failure, it sends all the data it has on volatile RAM (400 records) when connected. The circuit has a 5 pin In Circuit Serial Programming (ICSP) connector. We use PICKIT 3 for its ease of programming even in the field.

C. GPRS/GSM Module

SIM900D is an ultra-compact and reliable wireless module-SIM900D. This is a complete Quad-band GSM/GPRS module [8] in a SMT type and designed with a very powerful single-chip processor integrating AMR926EJ-S core, which makes it cost-effective and small in dimensions. The module is integrated with the TCP/IP protocol. SIM900d has GPRS data transfer rate of 42.8 kbps. RF output power is around 33dBm and RF receive sensitivity is around -107dBm. Refer to Fig. 5 for SIM card interface with SIM900D. The module automatically detects whether to provide 1.8V or 3.0V to the SIM card. SIM card is powered from internal 3.0V regulator inside the module. The 22R resistors shown are placed in series to protect SIM I/O port. The GSM part of WSN is protected against electro static discharge (ESD) with SMF05C, a 5 line transient voltage suppressor array, having a peak power dissipation of 100W (8 x 20 µS waveform) [7]. It has ESD rating of class 3B (exceeding 8 kV) per human body model and Class C (exceeding 400 V) per machine model. Human
body interaction with the circuitry is possible during SIM replacement.

**D. Battery and Power Considerations**

It was envisioned that the meter should work uninterrupted for at least one year with an annual battery replacement and general maintenance. To enable such low power application, we selected Microchip’s PIC18F26K20 with sleep currents below 100 nA, watch-dog timer down to 1 μA and run-currents down to 100 μA/MHz at 2.9V. We cannot use less than 4 MHz crystals, because then we will not be able to receive the sensor asynchronous TTL data at 9600 baud rate efficiently nor will we be able to read sensor’s pulse width output. Also, with 10 bit ADC resolution in the MCU, the resolution will always be less than 1mm. Hence we used 4MHz crystal with asynchronous TTL input from the sensor. We are powering the circuitry with 3.6V, 14,000mAH Lithium Thionyl Chloride batteries [1]. Fig. 6 shows typical discharge characteristics at various current levels. We cannot run it with normal Lithium ion cells with lower surge currents.

GSM/GPRS transactions consume most of the battery power. We turn the GSM module off after every transaction which takes 30uA at shutdown mode and is spending 98% of its time in this mode. Also the sensors are turned on only at sampling time. The current consumed by ultrasonic and temperature sensors are negligible as compared to current consumed by the GPRS module or microcontroller.

**E. Real Time Clock**

For RTC implementation, Dallas DS1302 was selected for its ease of availability and reliability interfaced to the MCU via three wire SPI interface. It consumes less than 500nA in battery backup and is operated with separate 3.3V 40mAh cell. The RTC cell backup time=40mAh/500nA=80,000 hours=9 years.

**F. Integration and Installation**

During assembly, anti-static wrist straps are used to prevent electrostatic discharge (ESD), by safely grounding the technician working with electronic equipment. The external antenna is mounted at the highest point inside the Stilling well and away from metal brackets designed to suspend the instrument. Being operated from 3.6V battery, we are quite close to the minimum voltage ratings of SIM900D i.e., 3.1V during burst. The copper traces from battery to the GSM module are 3.2 mm wide on top layer as well as on bottom layer in the PCB design to reduce the voltage drop in situations, where the circuit consumes high currents like 1-2A.

**G. Handling Current Demand Spikes**

Care has been taken in the selection of polymer capacitors to counter the presence of high Equivalent Series Resistance (ESR) in electrolyte capacitors. When supplying spike currents to the GPRS module (typically 1.5A for 575μsec), ESR becomes important and even dominant for poor choices. Failure to supply this current results in frequent failures of the GPRS module to register itself with the network. For successful GPRS transaction, our battery should be capable of providing enough current to maintain this current without dropping the voltage below 3.1V at the peak. We connect two parallel 1200μF ultra low ESR capacitors (typical ESR of 12 milliohms) across the battery terminals to provide sufficient current to continuous current spikes of around 1.5A.
To see this effect, refer to Fig 7. Typical ESR values for electrolytic capacitors are greater than 120 milliohms. The battery internal resistance is approximated from Fig. 6 as 0.45 Ohm. For a current spike of 1.5A, we have RL=3.6/1.5= 2.4. Thus at high currents RL becomes comparable to battery internal resistance or ESR and we get a voltage reduction. When the battery discharges to a certain level the power supply cannot supply sufficient currents to GPRS module in case of a single 1200uF capacitor. So we placed two ultra low ESR polymer capacitor 4SVP1200M (Made by SANYO) to ER34615M battery. High capacitance across the battery also ensures its full discharge.

![Fig. 7: Power module for WSN.](image)

III. PERFORMANCE

A. Power Consumption

Refer to Fig. 8 and Fig. 9 below for current vs. time plots for the WNS’s current consumption. As mentioned above, the main power consumer of the system is the GPRS communication module. Its power consumption increases even further during poor signal reception.

The readings are taken by measuring voltage across a 0.5 ohm precision resistor placed in series with the WSN circuitry connected to the main battery. The instrument used is a Rigol DS1052E 50 MHz, 1GSa/sec digital oscilloscope. We used different time scale for current vs. time plots to explain the nature of current spikes associated with GPRS transaction. Refer to Fig. 8 for current consumption during registration with the network. We have several spikes during registration with the network, GPRS connectivity, connecting to the server and data transmission. The GSM signal quality as calculated by SIM900D was CSQ= 18 or \(-113 + 2 \times 18 = -77\) dBm. In both Fig. 8 and Fig. 9, a major grid on vertical axis=200mA whereas a major grid on horizontal axis= 20ms. Fig. 9 shows current spikes during sending the data to the server.

Refer to Fig. 10 for a current spike of 1.45A scaled in time for another transaction with CSQ=12 (\(-89dBm\)) and horizontal grid size of 2ms. The GSM/GPRS frame of 4.615ms time is divided into 8 equal time slots of 577µs each. As the GSM/GPRS module transmits one time slot of 577 µs in a 4.615ms period, and receives or remains idle for the rest, this shows that it is a GSM/GPRS class 8. Each bit being 3.69231 µs long, only 114 data bits (total 156 bits) can be transmitted in 577 µs. Refer Fig. 11 for manufacturer specifications to the nature of these transmission bursts. The presence of capacitors makes these spikes like shown in Fig. 10.

The GSM module transmits strongly in case of low reception to communicate control messages with the network. Refer to Fig. 12 for comparison between current vs. time plots for -73dBm and -93dBm signal levels. The later plot with -93dBm signal level has higher current spikes than with a signal level of -73dBm. Refer to Table I for more results. The major grid on horizontal axis represents 50 ms of time. As GSM/GPRS signals attenuate in metal casings, so we are using GPRS antenna external to the box for strong signals.

We also tested the WSN with Uni-Trend UT60A digital millimeter in the lab for several hours, with a 1 minute sampling interval of water level and 5 minutes of GPRS transmission interval. The average received signal strength in the lab was around -69dBm. We had a total of 37 GPRS tries and all of them successfully uploaded data to the server. We sampled the current every 0.5 second. The result for four GPRS transactions of the test is shown in the Fig. 13. To find the total charge consumed from the battery, we find the

![Fig. 8: Current vs. time plots during network registration at -77dBm.](image)

![Fig. 9: Current vs. time plots during data transmission at -77 dBm.](image)
TABLE I: Current consumption during transmission at different received signal strengths

<table>
<thead>
<tr>
<th>No.</th>
<th>Signal Quality (CSQ)</th>
<th>Signal Strength</th>
<th>No. of bursts</th>
<th>Avg. max. current</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27</td>
<td>-59 dBm</td>
<td>270</td>
<td>600mA</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>-73 dBm</td>
<td>520</td>
<td>900mA</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>-77 dBm</td>
<td>140</td>
<td>100mA</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>-93 dBm</td>
<td>268</td>
<td>1450mA</td>
</tr>
</tbody>
</table>

Fig. 10: Current vs. time plots during network registration at -89dBm.

Fig. 11: Voltage drop during transmission burst according to manufacturer specifications.

area under the curve for three hours (37 transactions) by

\[ q(T) = \int_0^T i(t) \, dt \approx \sum_{n=0}^{10800} i(n) \Delta t = 131.3 \text{Coulomb}, \]

which is 0.26 percent of the total charge available for single battery (14*60*60 C=50400 C). Note that the small (but not negligible) current values during sleep mode are currents consumed during sampling when the sensors are active.

B. Measurement

To experimentally validate the sensor performance, a version of the sensor was deployed outdoor under some controlled conditions. Refer to Fig. 14 for a test spanning 4 days and 8 hours. A sealed well with a constant water level was sampled every minute and transmitted every 10 minutes. During the experiment, temperature varied between 17–45°C. A maximum variation of 15mm was observed in the water level from the true value. Note that the true water level decreased slightly during the four days because of evaporation. This decrease was factored while calculating the variation. The graph shows a correlation between temperature and water level. However, this variation was acceptable for our application and less than that experienced in original designs where temperature compensation was not used.

Several versions of the smart water meter have also been tested and deployed in the field. Refer to Fig. 15 where measurements from one deployment have been reproduced. The hydro-graph shows 48 days of continuous discharge and temperature data recorded by a unit installed at the head of Mubarik (1L) Distributary off Hakra Branch Canal in Haroonabad, Punjab. The nominal discharge of the canal is 81 cfs. The data was recorded with 10 minutes sampling interval and one hour transmission interval with a total of 6410 samples. The sensors did not directly measure flow but rather water level inside a stilling well. The water depth \(d\) (in feet) was converted into flow \(Q\) (in cfs) at the server using the hydraulic flow formula,

\[ Q(t) = k(d(t) - s)^n, \]

where \(t\) is the time-stamp provided by the sensor’s RTC, \(s\) is the correction for dead level and \(k, n\) are hydraulic constants. For Mubarik distributary, these constants were determined by \(k = 10.78, n = 1.67, s = 0.43\, ft\).
The average received signal strength at the well was $-90$ dBm, which is a very weak signal due to the well's remote location. This resulted in frequent retries in transmission. However, the sensor continued to pump continuous uninterrupted data for most of the period. There are four long instances of missing data (e.g. for 23 hours on 12/07/2013). Upon investigation, it was determined that the cause of the outages was related to server or software problems and never with the sensor electronics or GPRS based communication. This prompted us to increase the length of local storage of measurements up to several days in later deployments.

There are only two truly erroneous measurements (i.e. 20 minutes of corrupt data) in the hydro-graph on 16/06/2013. Upon investigation it was discovered that it rained heavily at the site at that time, as confirmed by the drop in temperature at exactly the time of corrupted readings. We conjecture that the error must have been due to accumulation of moisture / droplets on the sensor element. This is being investigated further.

IV. CONCLUSIONS

The results of various tests and experiments show that the designed hardware is low-power and field-ready for a wide-scale deployment in irrigation canal networks. Regarding the accuracy, we show that it achieves a practically acceptable limit in the field and is therefore, a feasible replacement of the current manual system. Power requirements, packaging, installation and system integration issues have been addressed and resolved.

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