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A Reliable Algorithm for Efficient Water Delivery and Smart Metering in Water-Scarce Regions

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Abstract: Smart water meters play a significant part in the interactive control of water supply networks required for smart cities. Opposed to completely mechanical water meters, electro-mechanical water meters or fully electronic water meters can capture real-time data via an automated meter reading process, making them more appropriate for smart city applications. However, the depletion of fresh water supplies as a result of climate change, as well as the rising demand associated with population increase, are some growing concern in many regions globally. Monitoring water distribution and delivery is a critical strategy for increasing distribution efficiency. This paper presents a wireless transceiver unit that can be integrated with existing electronic water meters. The unit utilises a reliable communication algorithm for real-time data exchange. Metering data is transmitted using cutting-edge narrow-band Internet of Things technology that operates using low power whilst covering a wide range with effective penetration.

Key words: Smart meters, Internet-of-Things, water meter, communication algorithm, LoRa.

Introduction

The smart city term was introduced as an urban development concept to incorporate cutting-edge advancements in the fields of information and communication technology (ICT) and the Internet-of-Things (IoT) in a secure manner for municipal management and development (Deakin, 2014). Compared to traditional cities, a smart city uses real-time data and provides an interactive platform for citizens to administer the city's resources with increased efficiency (Difallah et al., 2013; Li and Peter, 2019). Water supply network management and automation is a major concern for smart cities since water supply networks consist of huge underground pipes that require decades to implement and route and are not easily accessible (Mizuki et al., 2012). Furthermore, water losses in supply systems due to deterioration of infrastructure, inefficient billing systems, inaccurate metering, and unauthorised usage may reach 50% on a global scale (Pimenta and Paulo, 2021). Hence, smart water delivery is one of the most pressing issues influencing water distribution efficiency globally. Such problems intensify when trying to incorporate such advancements in water-scarce regions such as the Middle East and North Africa (MENA) region. Almost nine out of ten youngsters in the MENA region live in areas with high water stress. Such a situation has significant impacts on their physical and mental health, nutrition, cognitive development, and future livelihoods. According to recent reports, the MENA area is the world's most water-scarce region. Eleven of the world's 17 most water-stressed countries are in the MENA area (Borgomeo et al., 2021). To overcome

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this issue, rooftop tanks are commonly used to store water. Furthermore, the water supply is intermittent by pumping water to specific regions through a scheduled timetable (Hussein, 2018). Hence, the utilisation of the water delivery system is extremely low and inefficient.

Water utility providers have traditionally deployed water meters, mainly mechanical, which are low-cost and reliable but are incapable of real-time or water usage monitoring. As a result, monitoring is performed by having frequent visits to the water meter installation site to manually obtain data, whereas billing is estimates based on prior use profiles. This procedure has high operational expenses, consumes heavy time, and is highly susceptible to errors (Marais et al., 2016). Electronic circuit components have gradually been added into mechanical water meters during the last two decades to give autonomous functionality and minimise operational expenses. These are known as electro-mechanical water meters (Hauber-Davidson, 2006; Lee et al., 2008; Li and Peter, 2019), and their measuring principle remains mechanical. Recently, fully electronic water meters based on novel measuring methods such as electromagnetic, fluidic, and ultrasonic meters (Li and Peter, 2019; Paulsen et al., 2001) have been developed. The upsides and downsides of the three main types of water meters are shown in Table 1.

Despite the significant advancements in the smart metering sector, a lot of untapped potential is yet to be explored. This paper proposes a reliable communication algorithm based on LoRa technology for improved water delivery and metering in water-scarce regions that use scheduled water delivery schemes. The hierarchical order of this article is as follows – Section: **Micro Hydro Generator** introduces the micro Hydro-Generator and its application; Section: **LoRa Module** discusses the LoRa technology and its characteristics. The design methodology and the system's overall structure are presented in the Section: **Design Methodology**. Section: **Conclusion** explains the paper and elaborates on the findings.

Micro Hydro Generator

The collection of real-time data from sensors will necessitate the use of electrical energy. However, with the presence of pressurised water running in pipes, energy harvesting becomes a viable solution. Several designs were proposed for self-powered meters. As studied by Tasic et al. (2012), a self-powered measuring sensor is presented. However, due to its design, its use is largely restricted to tiny pipes and indoor applications. A direct current (DC) motor was used to generate electricity by Hauber-Davidson (2006). However, using a DC motor as a generator has a significant flaw in that it requires a hole in the pipe to link the blades connecting the DC motor, restricting the system's reliability. In a study by Cho et al. (2017), a smart meter driven by electromagnetic and piezoelectric energy harvesters was presented. The design, however, necessitates the adjustment of huge water pipes which are usually hardly accessible. Furthermore, the design fails if tiny water pipes were used since it is highly dependable on water flow. Therefore, if the water quality is poor, the system's performance will suffer. Mezzera et al. (2018) suggested a platform for monitoring several water quality indicators with energy harvesting, including pressure, temperature, pH, conductivity, flow rate, and micrometric deposit thickness. The suggested platform has the potential to deliver exceptional sensor resolution at the expense of expensive hardware components and high current consumption. Recently, micro-hydro water turbine generators (WTGs) became a popular solution for energy harvesting in water pipes since they serve as a flow sensor and a power generator simultaneously. Figure 1 illustrates a typical micro-hydro generator and its internal structure.

The rotor and the stator are the main elements in the generator and are hermetically separated. The rotor's core is a magnetic rod, around which the magnetic field is in equilibrium. Allowing the rod to float in its bearing, enables a frictionless rotor motion during water flow

Table 1: Comparison of three types of water meters

Meter Type	*Advantages*	*Disadvantages*
Fully mechanical	Low cost, extremely simple design	Low accuracy at low flow rates, accumulative measurements only, no real-time information delivery
Electro-mechanical	Ability to provide real-time information	Low stability, hard to interface, requires extra isolation and protection for the electronic components
Fully electronic	Highly accurate, Ability to interface with microcontrollers, Ability to provide real-time information	Requires extra isolation and protection for the electronic components, and requires an external power supply.

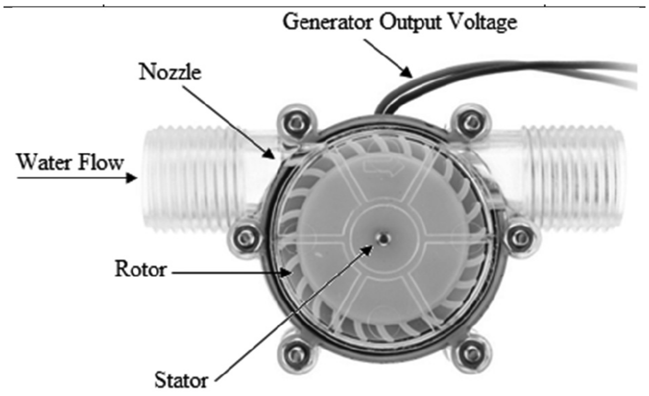

Figure 1: Micro-hydro water turbine generator.

resulting in a boost in the turbine's energy efficiency. The water pressure controlling the turbine's rotational velocity is directly proportional to the voltage produced by the generator. Such micro generators have the ability to produce a maximum of 80 V or 12 V of regulated voltage with a maximum of 220 mA output current at low water pressures. Figure 2 shows the relation between the output voltage of the generator versus the water pressure while equation 1 illustrates the generated power by the turbine.

$$Power = \mu \times s \times g \times h \times Q \quad (1)$$

where:
η: Turbine efficiency (typically 0.5 for micro turbines)
ρ: Water density 997~1000 kg/m^3
g: Gravitational acceleration 9.8 m/s^2
h: Sum of the pressure head and the velocity head
Q: Flow rate in m^3/s.

Typically, water suppliers pump water for household use with a pressure of 0.2~0.35 mpa (29~50 psi). This is equivalent to a pressure head (h) of 35 m. Furthermore, a nozzle with a smaller diameter compared to the water inlet is located at the input of the rotor chamber. This will concentrate the water flow causing an increase in the water pressure which relates to higher output voltages.

Having a voltage regulator at the output of the generator ensures a stable DC voltage signal that can be used to charge a battery. Due to their high energy density, low cost, and long life cycle, lithium-ion batteries have become the primary power source for portable electronic devices (Liu et al., 2018). A 12v regulator is used at the output stage to provide the required voltage to charge a 2200 mAh Lithium-Ion battery and to draw the maximum rated current from the generator (220 mA). However, since rechargeable batteries experience impedance variations with different

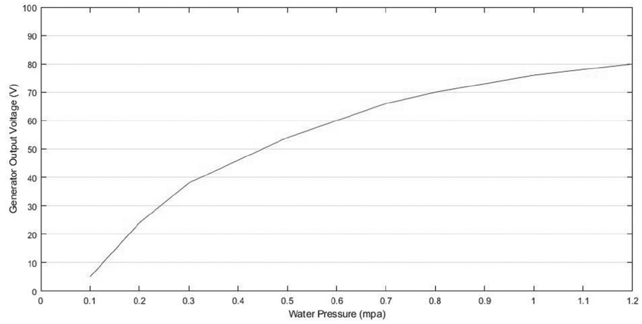

Figure 2: Output voltage of micro-generators versus water pressure.

levels of charging, the amount of current drawn by the battery also varies. A battery charging management module should be present to control the charging process of the battery.

To resolve the issue of water shortage, governments and utility providers in water scarce regions usually schedule water distribution on a weekly basis. Hence, water supply is typically intermittent with a distribution rate of 20-36 hours per week per geographical area (Denny et al., 2008). Such a scheme diminishes the water network's reliability, performance, and usability. However, using the micro-hydro generator, the lithium-ion battery in the proposed system will only require 5 hours of water flow to be fully recharged from 50% of its initial charge capacity.

LoRa Module

The majority of existing smart meters transmit data using Bluetooth technology (Li and Peter, 2019; Mizuki et al., 2012). However, the Bluetooth module draws nearly 0.5 mA of current in standby mode, about 8.5 mA in active mode and requires about 35 mA in pairing mode (Li and Peter, 2019). To reduce the power consumption, designers lower the baud rate at which data is transmitted or limit the number of devices to be paired with the meter which will lower the speed and reliability of the system. Furthermore, the longest distance over which Bluetooth may transfer data is restricted to 10 meters per hop, limiting the system's scalability (Haartsen and Mattisson, 2000). Similar to Bluetooth, Wi-Fi uses radio waves to deliver high-speed data wirelessly across short distances measuring up to 45 meters per hop (Li et al., 2019). Due to the enhanced range and data transmission rate, Wi-Fi consumes more power compared to Bluetooth. As a result, micro-hydro generators might not be able to provide the needed power in water scarce regions. In recent years, new transceiver technologies have been developed allowing for power-efficient communication across extremely long distances (LoRa, 2022). LoRa is a novel transceiver technology that is targeted towards IoT applications where hundreds of devices are employed to collect sensor readings across a wide geographical area (Bor et al., 2016; LoRa, 2022; Marar, 2022). Consuming very low power, LoRa is intended for applications in which end-devices are battery-powered or have a limited energy supply. With its data rate reaching up to 50 Kbps, whenever channel aggregation is used, LoRa technology is extremely useful for end-devices not needing to transmit more than a few bytes at a time (Augustin et al., 2016; Haxhibeqiri et al., 2018). The initiation of data traffic can be done either by the end-device or by an external entity wishing to communicate with a specific end-device (Augustin et al., 2016). Low-power wide-area networks (LPWAN) improve the scalability and the communication range of systems, making them an ideal architecture for the smart metering platform. The open source LoRaWAN protocol works on top of the LoRa physical layer offering the medium access control (MAC) mechanism allowing numerous devices and network gateway(s) to communicate with one another (Marar, 2022; Seneviratne, 2019). Figure 3 illustrates the format of the LoRa frames.

Starting at the physical layer (PHY), the LoRa frame begins with an 8-bytes Preamble that is used for synchronization purposes and defining the modulation scheme. Following the Preamble is a 20-bit PHY Header and Header CRC. The Header contains information including the length of Payload and whether the 16-bit Payload CRC is available in the frame. Receivers can reject and discard packets with incorrect headers using the Header CRC. The header is optional, therefore, it can be disabled in cases such as when the payload length, coding rate, and CRC presence are known ahead of time. Following the physical layer is the MAC layer at which the processed packet includes a MAC Header, a MAC Payload, and a Message Integrity Code (MIC). The MAC Header specifies the protocol version and whether the message in the MAC Payload is a management or a data frame. In addition, the header specifies whether the frame is transmitted using an up-link or a down-link, and if data must be acknowledged. Using a Network Session Key (Nwk_SKey), the MAC Header and MAC Payload are used to calculate the MIC value. The MIC value ensures the integrity and security of the message by authenticating the destination node. Afterwards, the MAC Payload that includes a Frame Header, a Frame Port, and a Frame Payload is handled by the application layer. The Frame Header includes a 4-byte Device Address. The first byte identifies the network, and the remaining 3 bytes are assigned to hosts within the network. A 1-byte Frame Control handles the control information including the gateway's up-link transmission data rate and whether the message contains an acknowledgment for receiving the previous message. A Frame Header also includes a 2-byte frame counter for sequence numbering and a Frame Options field used to request the alteration of data rate or transmission power. Besides the Frame Header, a 1-byte Frame Port is specified based on the type of application. The Frame Payload contains the data transmitted wirelessly and is encrypted with an Application Session Key (App_SKey) that uses an AES128 encryption algorithm (Nicholas et al., 2015). Having 3 bytes for host addressing within a network, a single network may contain more than 16 million end users. This proves the reliability and extreme ease of scalability of networks using the LoRa technology (Bernier et al., 2020; Marar, 2022). Furthermore, the availability of the Network Session Key and the Application Session Key ensures the integrity and security of data transmission. Integrating the LoRa module within the electronic water meter enables the transmission of water flow and consumption readings to gateways 5 kilometers away in urban areas and about 15 kilometers in rural areas whilst consuming only 4.2 mA with an RF output power of +22 dBm (Sanchez-Iborra et al., 2018). Such low power enables the LoRa module to continuously transmit data for more than 10 days using a 2200 mAh battery before the battery reaches half its charge. The proposed design will further minimise the power consumption by utilising the sleep mode and interrupt signals to elevate the performance in water scarce regions with intermittent water supply.

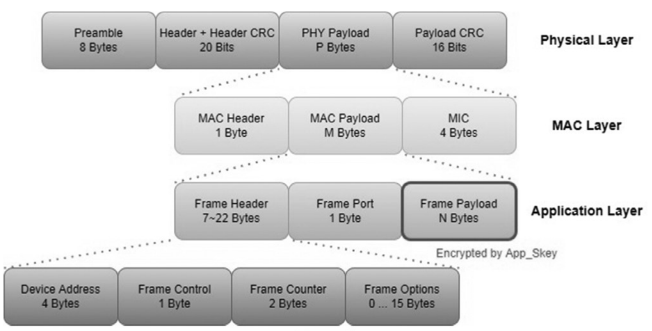

Figure 3: LoRa frame format.

Design Methodology

The block diagram of the proposed system is presented in Figure 4. Once water flows through the micro-hydro generator, an output voltage with a maximum of 80 volts can be generated depending on the water pressure. The output voltage is connected to a step-down circuit that reduces the voltage level to be compatible with the microcontroller. This voltage is used to measure the availability of water and its flow rate. In addition, the generator's output voltage is also connected to a voltage regulator to ensure an efficient and stable operation of the charge management chip. The Lithium-Ion battery will be charged and deliver power to the system through a power management module. A LoRa module will wirelessly communicate with a gateway to deliver the operational data.

Microcontroller

Equipped with an on-chip analog-to-digital converter (ADC). several low-power microcontrollers are available for the implementation of such a system. Having a maximum output voltage of 80V, a step-down circuit should be present to interface the voltage signal with the microcontroller. Able to calculate the water pressure from the generator's output voltage, frequent readings are collected and saved in the microcontroller. Estimates indicate that in water-scarce regions in developing nations in Asia, Africa and Latin America, the daily available freshwater per capita may be as low as 20-60 liters (Falkenmark et al., 2014). People in developed nations in Europe, Asia, and the North consume about 10-100 times more water per capita compared to those in developing countries (Falkenmark et al., 2014). Hence, rooftop tanks are the primary means of water storage. With the availability of pressurised water in pipes, a zero water flow, measured by the controller, indicates that the rooftop tanks are completely filled. Consequently, the microcontroller will close the water input valve, allowing water pressure to be distributed to other users. Having an intermittent water supply with a distribution rate of 20-36 hours per week per geographical area, a microcontroller will operate in sleep mode to minimise power consumption. A wake-up signal broadcasted by the utility provider can restart the process for the intended geographical area. The micro-hydro generator's output voltage is also fed to a voltage regulator to maintain a stable constant output voltage regardless of input voltage or load variations. The fixed DC output voltage is then fed to the charge management chip to control the charging process of the battery.

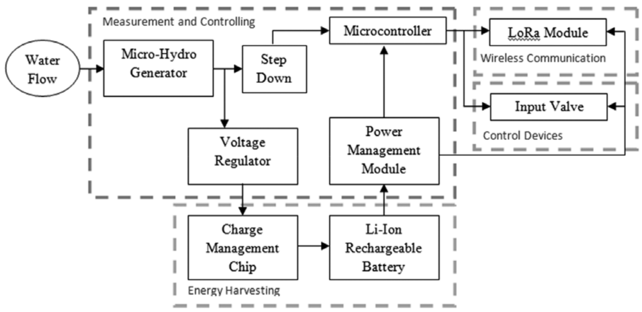

Figure 4: Block diagram of proposed system.

Charge Management Chip

In contrast to several other battery types, the charging process of lithium-ion batteries includes four stages: a trickle charge stage, a pre-charge stage, a constant-current charge stage, and a constant-voltage charge stage. The battery management chip has to control several aspects and parameters during the charging process including the input voltage and current, the system power, battery charging voltage and current, and battery temperature among others. For instance, the charge management chip will regularly alter the battery charging current based on the battery temperature to prevent thermal hazards (Xiao et al., 2012). A narrow output voltage direct-current (NVDC) power management is a recent architecture that is commonly used for Li-Ion battery charging management. The architecture allows instant charging of the batteries despite having a low input voltage; furthermore, it alters the charging voltage based on the battery's voltage to minimise the voltage stress on the system's components. In addition, the NVDC architecture allows the instant use of the battery's power when the generated charging power drops beyond a certain level (Li and Michael, 2011). This ensures an uninterruptable operation of the proposed system. Despite the complex process of charging and power delivery of lithium-ion batteries, their high energy density, low cost, and long life cycle make them an ideal means of energy storage in the proposed system.

Power Management Module

In the absence of water flow, the system must rely on the battery charge to power the different modules. To minimise the power consumption, the microcontroller and the LoRa communication module can operate at voltages as low as 2.7 V while the input valve requires a 5 V signal. To provide the system with different levels of voltage, a configurable power management module should be available. The power module is also used to monitor the remaining power in the battery and provide notification messages.

LoRa Module

As illustrated in Figure 3, the LoRa frame header includes a 4-byte Device Address in which one byte is used for network identification and the remaining 3 bytes are used for host assignment within the network. Using this structure, and based on the scheduled timetable for water delivery, geographical areas based on timeslots can be grouped in a single network. With more than 16 million users per network, the proposed system can effectively accommodate all the users in water-scarce developing countries. Such a structure provides high reliability and can be highly scalable in rural areas.

Proposed Algorithm

The proposed algorithm is divided into two segments to administer the scheduling process of water delivery to end users by the utility provider. Figure 5 illustrates the diagram of the proposed algorithm for end users.

The process starts by broadcasting a wake-up message from the utility provider to a specific network. The wake-up message acts as an external interrupt notifying end users of the start of the scheduled timeslot for water pumping. Once activated, the microcontroller will acknowledge the reception of the broadcast message and will synchronise with the utility using a predefined Nwk_SKey and App_SKey. Afterwards, the processor will enable the step-down converter and the power management module. The power module will provide various voltage levels to all components as needed while the step-down converter will send a voltage, relative to the water flow, to the microcontroller's ADC. Afterwards, the controller will open the input valve to allow water flow. A set of configurable variables are available to increase the system's reliability including V_{gen}, V_{min}, T and T_{max}. V_{gen} represents the actual voltage generated by the micro-hydro generator while V_{min} represents the minimum voltage required by the charge management chip to charge the battery. If V_{gen} is less than V_{min}, this means that the water flow is too low to generate the minimal charging voltage. Hence, the microcontroller will have an incremental delay to check the water flow. If the time delay exceeds a pre-defined maximum delay of T_{max}, the microcontroller will send a "No_Flow" notification via the LoRa module to the utility provider and re-enter the sleep mode after disabling the system's peripherals. Such a feature can be used to aid in the monitoring and identification of water delivery network failures. Equation 2 represents the function of the incremental delay.

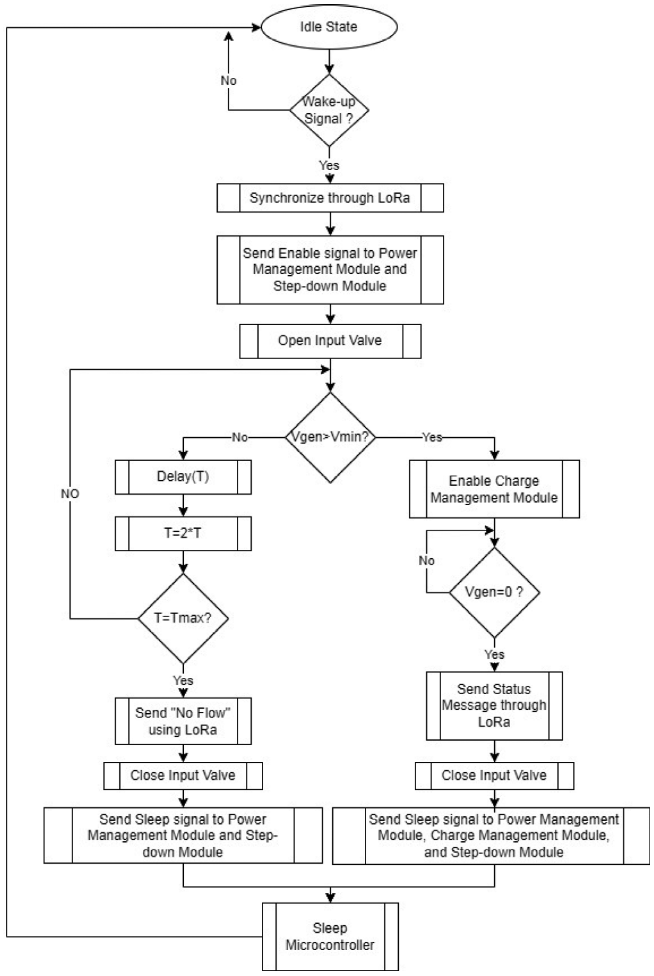

Figure 5: Algorithm for end users.

$$T = T \times 2_N \tag{2}$$

where N is the number of iterations performed by the microcontroller

If V_{gen} is larger than V_{min}, the process of charging the battery starts by enabling the charge management module. Multiple causes can lead to the termination of the charging process. This includes the battery reaching its maximum charge. In such a case, the charge management module will automatically disconnect the battery, preventing over charging. Other cases include having $V_{gen} = 0$. Such a scenario might happen due to having no water flow, or due to having the rooftop tanks completely filled. A "Flow_Stopped" status message will be sent to the utility via the LoRa module and the system will re-enter sleep mode after disabling the system's peripherals. In the case of having the tanks full, closing the input valve will help the network by allowing water pressure to be distributed to other users. It should be noted that prior to entering the sleep mode, the microcontroller will check the battery's charge through the charge management module. If the battery's charge is below a pre-defined value, the controller will send a "No_Charge" alert message. Such a message will help the utility provider identify regions with low flow or limited pumping timeslots.

The second segment of the proposed algorithm to administer the scheduling process of water delivery is utilized by the service provider. Figure 6 presents the flow diagram of the proposed algorithm for the provider.

The service provider starts by enabling the water pumping process to a specific network (N). Afterwards, a broadcast message will be sent to all users within that network and the synchronization process starts. The algorithm will keep track of the number of hosts sending the status message "Flow_Stopped". A predefined variable, Host_Max, indicates the minimum required number of users having completely filled tanks before switching to a new network. For instance, assuming a network N has 100 users. Host_Max can be set to 95. This means if 95% of users have completely filled tanks, then the utility provider can switch the flow to network N+1. Such an algorithm will improve the reliability and water delivery for users. Having a distribution rate of 20-36 hours per week per geographical area, rooftop tanks will be usually filled before the end of the timeslot. Hence, under normal conditions, there is a period during which water is being pressurised for a specific geographical area without being used. The proposed algorithm effectively enhances the water delivery process by tracking the number of users with filled tanks and taking action accordingly. Furthermore, a parallel process will keep track of the time to make sure the distribution of water per network does not exceed the 20-36 hours limit. To test and implement the algorithm, the ATmega328PB microcontroller was used. Since the current increases linearly with the clock speed, the running clock frequency was reduced to 1MHz to minimise the power consumption of the system. Figure 7 shows the implementation of the proposed system.

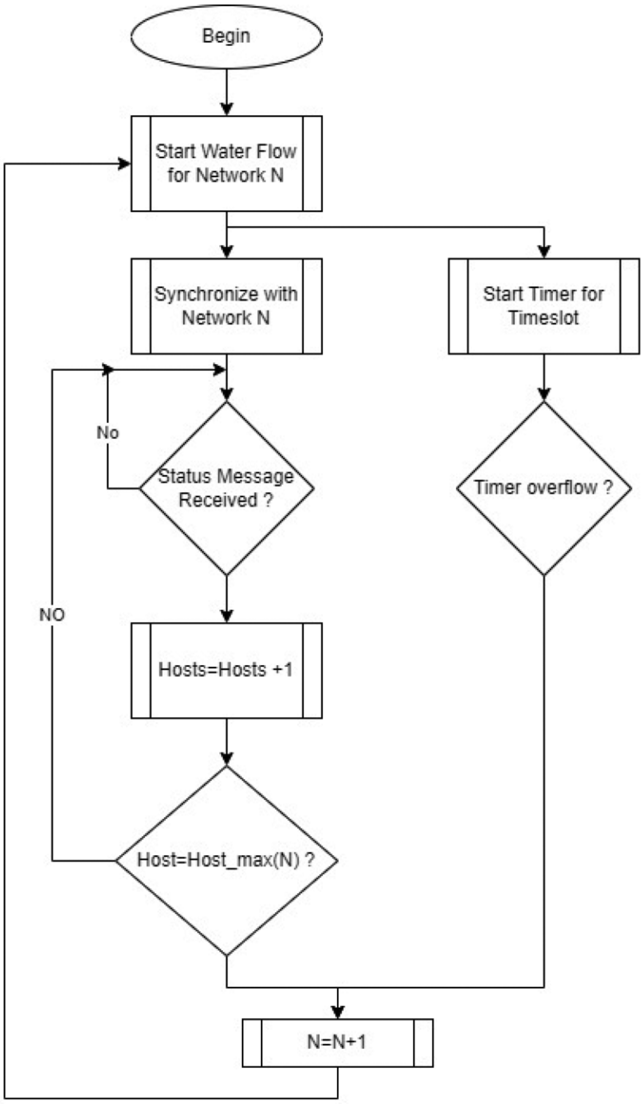

Figure 6: Algorithm for utility provider.

A 10 W–80 V water turbine generator with an inlet/outlet diameter of 12.7 mm was used for the testing of the system. To simulate the residential water supply in water scarce countries, a water tank and a water pump are employed. The pump's maximum water flow rate is set to 1000 L/h, which is around the maximum residential water flow rate in such countries. With a pumping rate of 25 hours once a week, the Lithium-Ion battery was able to maintain a minimum of 67% of its full charge capacity at the end of each water distribution

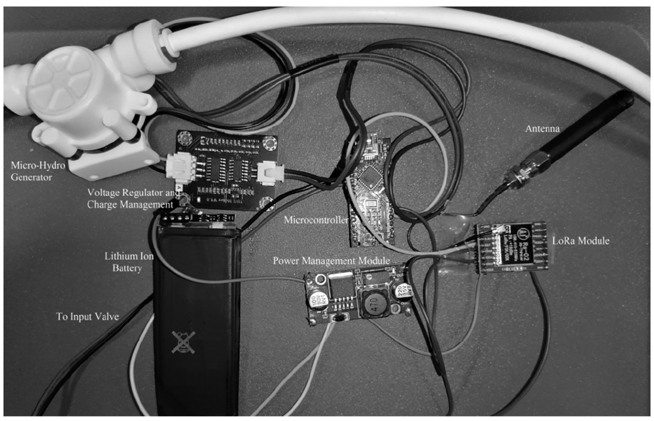

Figure 7: Proposed system implementation and testing.

cycle. The digital water meter consumed an average current of 50 µA while the LoRa module consumed 15 mA at peak times.

Conclusion

A self-powered smart water meter is proposed and implemented using a micro-turbine generator interfaced with a LoRa transmitter, providing a reliable, low-cost solution for water delivery in water-scarce regions. The LoRa module is able to transmit data over long distances while consuming minimal power. A set of configurable variables will maximise the utilisation of the water delivery network by having the ability to deliver water to multiple geographical areas without the need to wait until the end of the weekly allocated timeslot. Since rooftop tanks are the main means of water storage in water-scarce regions, the filling process might end prior to the end of the time slot. Therefore, using this algorithm, the water network's reliability, utilisation, and scalability are improved. The system utilises a low-power microcontroller powered by a battery that was able to hold 67% of its charge at the end of the distribution cycle despite testing the system at low water pressure. Future work includes implementing this solution on a large-scale geographical area and compares the performance of the system and the satisfaction of end-users compared with the currently used method of fixed timeslots.

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