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Research paper

Design of smart sensors for real time drinking water quality monitoring and contamination detection in water distributed mains

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Abstract

Drinking Water Distribution Systems facilitate to carry portable water from water resources such as reservoirs, river, and water tanks to industrial, commercial and residential consumers through complex buried pipe networks. Determining the consequences of a water contamination event is an important concern in the field of water systems security and in drinking water distribution systems. The proposed work is based on the development of low cost fuzzy based water quality monitoring system using wireless sensor networks which is capable of measuring physiochemical parameters of water quality such as pH, temperature, conductivity, oxidation reduction potential and turbidity. Based on selected parameters a sensing unit is developed along with several microsystems for analog signal conditioning, data aggregation, sensor data analysis and logging, and remote representation of data to the consumers. Finally, algorithms for fusing the real time data and decision making using fuzzy logic at local level are developed to assess the water contamination risk. Based on the water contamination level in the distribution pipeline the drinking water quality is classified as acceptable/reject/desirable. When the contamination is detected, the sensing unit with ZigBee sends signals to close the solenoid valve inside the pipeline to prevent the flow of contaminated water supply and it intimates the consumers about drinking water quality through mobile app. Experimental results indicate that this low cost real time water quality monitoring system acts as an ideal early warning system with best detection accuracy. The derived solution can also be applied to different IoT (Internet of Things) scenario such as smart cities, the city transport system etc.

***Keywords**: Water quality monitoring, water distribution system, wireless sensor network, fuzzy logic, network lifetime, ZigBee, in Pipe.*

1. Introduction

Clean drinking water is a significant resource which is required to sustain life and plays a major role in the well-being of the human beings [1]. In the real time process, drinking water utilities and water supply to the consumer end taps at urban area face new challenges to safeguard water supplies from deliberate or inadvertent contamination. Contaminated drinking water serves as a transmission medium for several hazardous agents which produce adverse effects in humans and cause serious health issues. Therefore, there is a need for better real time in-pipe water quality monitoring system to be deployed in the water distribution network and at consumer sites. Among the applications of wireless sensor networks for smart cities, monitoring the drinking water quality in water distribution pipeline is essential for the well being of the human beings as in [2]. However, the design of wireless sensor networks for the water distribution network has many challenges.

As the sensor nodes are with limited battery power, the energy efficiency of the sensor node has to be maintained to enhance the network lifetime and to avoid the replacement of batteries of the sensor nodes. If energy efficient, the sensing performance of the sensor node (i.e. precise monitoring of drinking water quality) with contamination detection algorithm can be achieved easily. To categorize the quality of the drinking water, the traditional methods of water quality prediction in [3], [4], [5], [6], [7] implies the collection of water samples at different locations manually and at different sampling time. As there will be a long time gap between the sampling time and the detection time of the contamination, the real time notification about the contamination to the public/consumer cannot be achieved which may lead to adverse health effects. Another drawback is that, only a limited number of locations are sampled at a time and the equipment operation cost is costlier. Hence, there is a clear requirement for the continuous real time in-pipe water quality monitoring and notification system with high accuracy.

Various extensive experimental assessments are carried out by the US Environmental Protection Agency (USEPA) to measure the performance of the water quality sensors on different concentrations as [8]. The main conclusion behind the analysis is the physical, chemical and biological contaminants have major consequence on many water quality parameters such as pH, Temperature, Turbidity, Electrical Conductivity and Oxidation Reduction Potential. Hence, it is sufficient to monitor the changes in these parameters to predict the quality of the drinking water. The products that are commercially available can monitor the water quality parameters but are huge in size and are costlier to deploy and maintain. In the proposed work, the designed water quality monitoring system monitors all the essential parameters and predicts the drinking water quality distributed through pipes, analyze by using fuzzy logic and stops the contaminated water stream with a solenoid valve fitted in the pipe. Further, the households/consumers are informed about the occurrence of contamination in a particular region through messaging service or mobile app.

Fig. 1: Model of water distribution network

A model of the water distribution networks using wireless sensor networks is depicted as in the Fig.1. At each point of water supply in the distribution pipeline to the household, the sensor nodes in the water distribution network will be placed to active mode for sensing. The sensing unit efficiently transmits real time data to the central processing unit for further analysis regarding water quality. All the sensed water quality parameter data are analyzed using fuzzy logic and are transmitted wirelessly to the notification unit in the administrator's office. The algorithm for detecting the contamination and decision making are performed in the processing unit. Finally, the notification node receives information about the contamination occurrence and alerts the consumers. The designed water quality monitoring system is promising as it detects contamination even at low concentrations.

The rest of the paper is structured as follows; Section II reviews the related works that were developed for the real time water quality monitoring using wireless sensor networks. Section III illustrates the methods/factors that were taken into consideration when designing the real time monitoring system. Section IV provides the overall architecture of the system. Section V describes the validation and performance of the designed real time system and finally the paper ends with a conclusion in Section VI.

2. Related works

Real time water quality monitoring system should provide a good balancing between the maintenance cost and easy implementation of the system in the water distribution network and at consumer sites. Various techniques implemented in the design of the water quality monitoring system are found in the literature. Commercially available [11] water quality monitoring systems are inadequate and few are Hach HST Guardian Blue [12] and J-MAR BioSentry [13], etc. These systems are very bulky and of high cost and in turn take regular samples of water quality but at very limited number of locations in the water distribution network. Due to the limited spatial-temporal sampling process, the real time contamination detection and prediction is impossible for the consumers to identify the quality of the portable water delivered to the households. For large scale deployment, several water monitoring sensor nodes are designed based on the sensor network technology.

In [14] for monitoring the salinity and temperature in the ground and surface waters respectively, a sensor node called CSIRO Fleck-3 is designed. In a distributed system for measuring water quality [15], the turbidity, temperature, conductivity and pH sensors are well coupled with a field point. The data from the sensing unit is processed using kohenen maps and then it is sent to the land based station using a GSM (global system for mobile communications) network.

A wireless sensor network based water environment system in [16] senses water quality parameters such as turbidity, conductivity, pH, dissolved oxygen and temperature. The sensor network has three processing units: data monitoring nodes, data video based monitoring system and the remote monitoring centre. The sensor node data are sent from the data monitoring nodes and data video base station acts as a communication centre in the monitoring network, which uses ZigBee and CDMA (Code Division Multiple Access) technology. The water monitoring system designed in [17] analyses and process water quality parameters such as pH, conductivity, dissolved oxygen and temperature. These parameters are sensed with prefabricated sensors and a change in the water quality is notified using an alarm. The sensed data are sent to the base station through GPRS (General Packet Radio Service).

A ZigBee based wireless sensor network water quality monitoring and measurement system as presented in [18] facilitate the remote probing and real-time monitoring of the different water quality parameters. It maintains records of current and historical water quality parameter status, which is easily accessible by the users. In [19] a wireless sensor network system is designed in such a way that the data collected from different sensor nodes are transferred to the base station or sub-base node via monitoring station by using a GSM network. The system measures the quality of fresh water and it uses a daylight harvester for better optimization of power management. A real-time low cost in-pipe sensor node as developed in [21] has an array of sensors used for measuring the flow, pH, conductivity, ORP and turbidity of the water. When contaminations are detected, the event detection algorithm fused in the sensor nodes triggers an alarm to notify the consumers. In [20] for monitoring the surface water bodies, a WSN based ISO/IEC/IEEE 21451 standard is designed to capture critical events and collect total sampling periods of data.

Apart from the development of sensor nodes and other microsystems for the water quality monitoring process, the development of software algorithms for the detection of contamination events also plays a major role. Event detection software such as Hach Event Monitor [12] and BlueBox [22] are commercially available for contamination detection. CANARY software [23] developed in collaboration with the USEPA is a freely available tool. It uses a set of mathematical and statistical methods to predict the contamination events. It identifies the water contamination incidents from online raw sensor data. Additional event detection and data validation methods are discussed in [24]. Though, further event detection methods are developed based on the multisensory data fusion methods as in [25]. The literature study of the reviewed papers helps to identify various methods used in the design of the water quality monitoring system and the communication process involved between the sensor nodes and the base station. The key objective of the designed water quality monitoring system is to detect the water contamination; stop the contaminated water flow using a valve; notify to the public/consumers and to supply good quality water to the public.

3. Methods

The World Health Organization (WHO) [1] determined a set of standards and guidelines for the drinking water quality parameters. In order to prevent the spread of water borne diseases and to protect the public from drinking contaminated water, certain physical and chemical parameters must be monitored and tested on a regular basis. Table I specify the suggested parameters to be monitored from high to low correlation importance when inferring the water contaminations. Table II presents the health effects associated with the suggested parameters based on the calibration procedures and probe lifetime, specifications in Table III concerning these parameters. Therefore, the parameters selected to be monitored are: 1) Turbidity, 2) Oxidation Reduction Potential, 3) Temperature 4) pH, and 5) Electrical Conductivity.

Table I: Suggested Parameters to be Monitored

S.No	Parameter	Units	Quality Range
1	Turbidity	NTU	0.5 – 1.0
2	ORP	mV	650 - 800
3	Temperature	ºC	20∘C – 40∘C
4	pH	pH	6.5 – 8.5
5	Electrical Conductivity	µS/cm	500 - 1000

4. Architecture

System design

A standard but integrated approach is implemented for the design and development of the system. It enables the real-time analysis and sampling of all parameters and the helps to take into account several operations like calibration and replacement of faulty parts in the water quality monitoring system. The overall methodology of the water monitoring system is depicted in Fig.2.

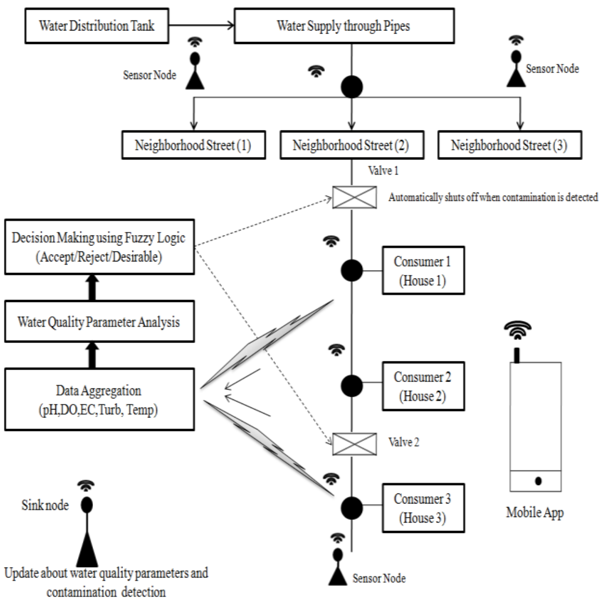


Fig. 2: Methodology of water monitoring system

The overall process includes a water distribution tank to store the water to be supplied to the public/consumer through the pipelines in the water distribution mains. There is an automatic valve near the water tank to regulate the water supply when it receives signal from the server. The water is allowed to flow concurrently in all the neighborhood streets as shown above. The sensor nodes in the pipe analyze the various water quality parameters such as pH, temperature, oxidation reduction potential, conductivity and turbidity. Finally, the sensor data are aggregated and the quality of the water is predicted using fuzzy logic as acceptable/reject/ desirable. For example, the sensor node 1 in the neighborhood street 1 crosschecks with the values (contamination level) received from the other sensor nodes in the same neighborhood 1 and other nearby neighbors.

When contamination is detected in a particular region, the solenoid valve automatically shuts off and the contaminated water flow through the pipeline is blocked. The houses/consumer near the contaminated area receives an alert message through mobile app regarding the level of contamination in the water supplied. Every consumer can query about the water quality through the app to confirm the quality of drinking water. All the water quality parameter analysis and real time monitoring data are updated to the sink (server unit) using ZigBee. The server sends alert to the monitoring station (administrator office).

Communication links between the sensors

The challenges regarding the communication are the power requirements and the transmission medium through which the signals travel. At high frequencies, the signal transmission through the drenched medium is highly affected by signal attenuation [26]. Therefore, key challenge is that wireless communication between the sensors and signal transmission from the sensors. The Fig.3 represents the schematics of the communication link between the sensor nodes and communication between the sensor node and the monitoring station. The low frequency communication link between the smart sensors is pipe-to-pipe data transfer and at the same time long distance. The high frequency communications are all digital in nature. The smart sensor communicates with the server in administrator office using ZigBee module located at the sand surface.

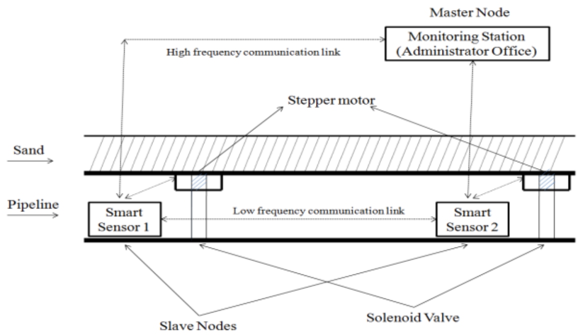
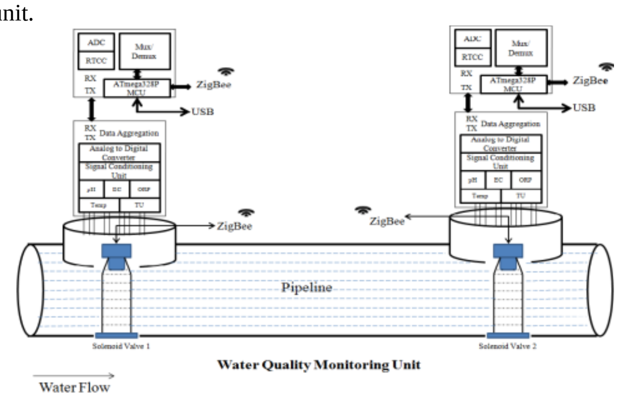


Fig. 3: Schematic of different communication links

Sensor development and integration

The main aim is to propose a prototype which acts as a generic secure real time water quality monitoring system. The overall architecture is depicted as in Fig.4. The proposed system is portable, mobile and secure, further consumes less power and energy, ease of deployment with supporting connectivity in the remote location. The designed water quality monitoring system can be used as one of the most important sub-systems in building smart cities to track water quality in various water bodies including rivers, lakes and reservoir etc. The overall system architecture is comprised of the following subsystems: a water quality monitoring unit, central processing unit and a notification unit.



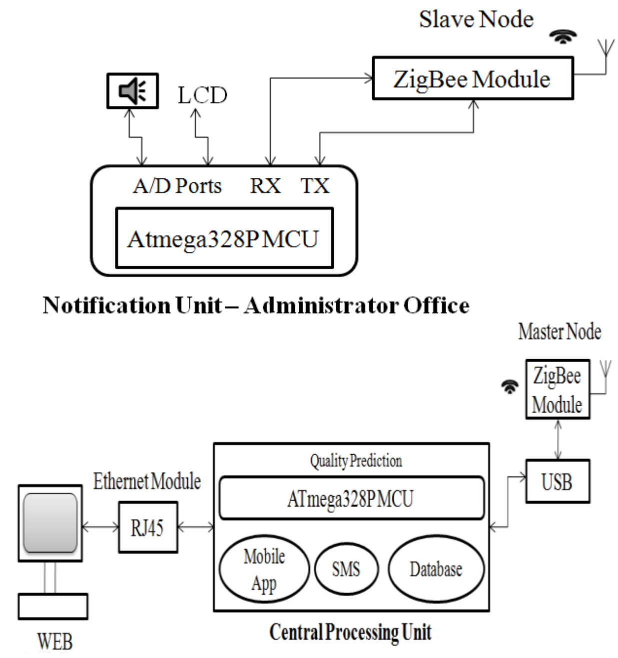


Fig. 4: System architecture

The water quality monitoring unit (Atmega38P MCU based board) collects the water quality parameters such as pH, temperature, turbidity, oxidation reduction potential and conductivity from the sensors as in Fig.5 deployed in the pipeline. The sensed parameter values are aggregated to a single data unit with real time timestamp and transferred to other units using ZigBee as shown above. The data are grouped together using a data aggregation algorithm. The central processing unit is comprised of 'Quality Prediction using Fuzzy Logic' and classifies the sensed data. It stores the water quality data received from the water quality monitoring unit in a database and it acts as an interface to the internet providing data visualization and notification to the consumers/public through mobile app/sms alerts. The unit is embedded with set of fuzzy rules, which verifies whether the water in the pipeline is contaminated or not. Based on the classification, the water quality is classified as accept/reject/desirable. The notification node in the administrator office receives information from the central processing unit through a ZigBee RF transceiver and provides notification via LCD, buzzer.

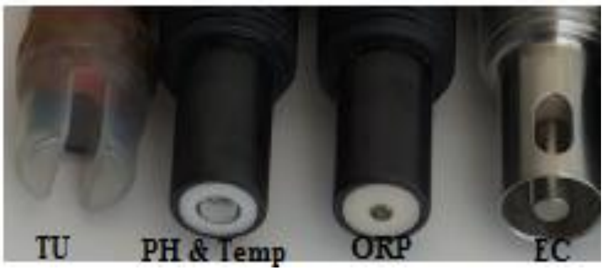


Fig. 5: Sensors deployed in pipeline

Table II: Health Effects Due to Water Contamination

S.No	Parameter	Quality Range	Health Effects
1	Turbidity	0 – 5 NTU	Particles in turbid waters can carry disease-causing pathogens which cause nausea, cramps and headaches.
2	ORP	650 – 800 mV	Goiter, hypertension, ischemic heart disease, gastric and duodenal ulcers, chronic gastritis.
3	Temperature	20°C – 40°C	Metals of sediments have been equilibrated at temperatures ranging from 4 to 25°C
4	pH	6.5 – 8.5 pH	pH > 11 - Eye irritation and exacerbation of skin disorders. pH 10–12.5 - Reported to cause hair fibers to swell and gastrointestinal irritation may also occur. pH < 4 - Redness and irritation of the eyes pH < 2.5 - Damage to the epithelium.
5	Electrical Conductivity	500 – 1000 µS/cm	Adverse health effects may include disturbance of salt and water balance in infants, heart patients, individuals with high blood pressure, and renal disease. Aesthetic effects include a salty taste to the water (if conductivity > 150 mS/m) while water with conductivity > 300 mS/m does not slake thirst.

Table III: Sensor Node Specifications

S.No	Sensor Probes / Parameters	Temperature Sensor	pH Sensor	Electrical Conductivity Sensor	Turbidity Sensor	ORP Sensor
1	Output	4-19mA	4-19mA	4-19mA	4-19mA	4-19mA
2	Range	-50° C to +50° C	0-14 pH	0-5000 µS	0-100% DO	-500mV to +500mV
3	Accuracy	±0.2° F or ±0.1° C	2% of full scale	1% of full scale	+/- 0.5% FS	2% of full scale
4	Operating Voltage	10-36 VDC	10-36 VDC	12 VDC (+5%)	10-36 VDC	10-36 VDC
5	Current Draw	Same as sensor output.	16.6 mA plus sensor output	6.5 mA plus sensor output	11.8 mA plus sensor output	13.5 mA plus sensor output
6	Warm Up Time	5 seconds minimum	3 seconds minimum	3 seconds minimum	10 seconds minimum	3 seconds minimum
7	Operating Temperature	-50°C to +100°C	-5° to +55°C	-40°C to 55°C	-40° to +55°C	0° to +55°C
8	Size of Probe	3/4" diameter x 4 1/2" long	1/4" diameter x 10" long	1" diameter x 12" long	1 ¼" diameter x 11" long	1" diameter x 10 ½" long
9	Weight	1/2 lb	1 lb.	1 lb	1 lb	1 lb

The notification message is sent to the consumer or public as shown in Fig.6. It displays all the quality parameter values and after doing analysis using fuzzy logic, the water quality is predicted as good. The Fig.7 displays the real time sensing from the sensors with the respective House Identification number (HID).

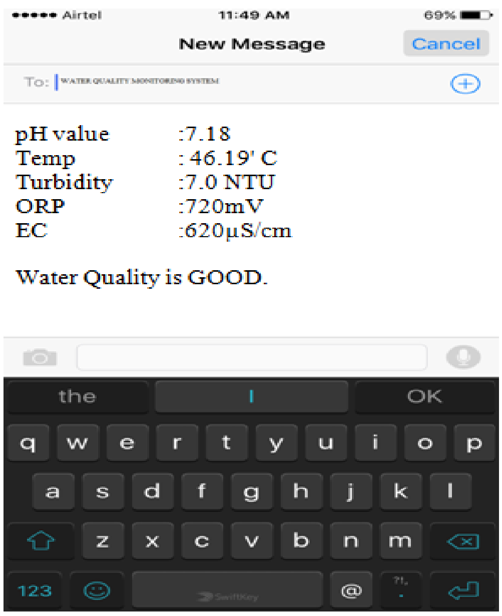


Fig. 6: SMS to consumers regarding water quality

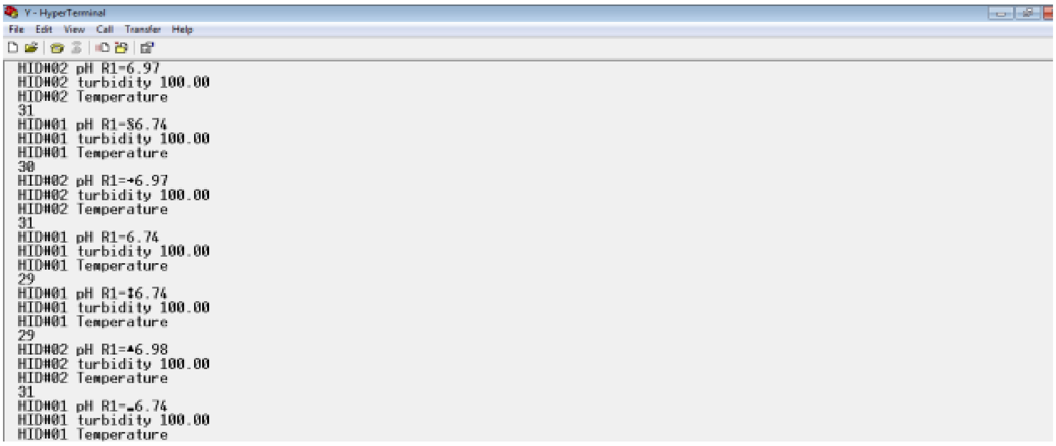


Fig. 7: Real time visualization with house ID and quality parameter values

5. Conclusion

In this proposed work, the design and deployment of the real time water quality monitoring system for drinking water using wireless sensor network has been presented. The developed system has been field tested at Amathur region, Sivakasi for monitoring of water quality parameters. It is a low cost, lightweight system and has low power consumption. Moreover, the system is able to log bulk data and transfer to remote locations. The contamination detection algorithm and the fuzzy rules help to identify the contamination in the pipeline and classify water based on the contamination. This deployment provides rich data to the water consumers/public, authorities in municipal office. The sms alert and mobile app ensures the safety of drinking water. Our future plan is to investigate the performance of designed system against other types of contaminants such as nitrates, lead etc.

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