

Water Quality Monitoring using Wireless Sensor Network and Smartphone-based Applications: A Review

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Abstract: A wireless sensor network (WSN) has a huge potential in water ecology monitoring applications. The integration of WSN to a portable sensing device offers the feasibility of sensing distribution capability, on-site data measurements, and remote sensing abilities. Due to the advancement of WSN technology, unexpected contamination events in water environments can be observed continuously. Local Area Network (LAN), Wireless Local Area Network (WLAN) and Internet web-based are commonly used as a gateway unit for data communication via local base computer using standard Global System for Mobile Communication (GSM) or General Packet Radio Services (GPRS). However, WSN construction is costly and a growing static infrastructure increases the energy consumptions. Hence, a growing trend of smartphone-based application in the field of water monitoring is a surrogate approach to engage mobile base stations for in-field analysis that are driven by the expanding adaptation of Bluetooth, ZigBee and standard Wi-Fi routers. Owing to the fact that smartphones are portable and accessible, mobile data collection from WSN in remote locations are achievable. This paper comprehensively reviews the detection of water contaminants using smartphone-based applications in accordance with WSN technologies. In this paper, some recommendations and prospective views on the developments of water quality monitoring will be discussed.

Keywords: Wireless sensor-based network (WSN), Water quality monitoring, Smartphone-based system, WSN construction.

1. Introduction

An expanding group of water contaminants which are constantly changing is responsible for the breakthrough of various contagious diseases, such as diarrhea, hepatitis, SARS, pneumonia, kidney failure, irritations and pulmonary disease [1]. The tremendous

amount of waste generated is a major concern in sustaining safe and clean water supply. Waste production imposes a significant change in the quality of water due to a breakdown of various contaminants, chemically and biologically, which contains highly toxic substances. Although raw water or wastewater undergo treatment process before distribution process,

water distribution system (WDS) pipeline are easily exposed to intentional or accidental contamination. Intentional sabotage events have been reported to occur within public drinking water supply in north-east Scotland [2] and tap water in Turkey [3] due to the prevalence of mesophilic *Aeromonas* bacteria which is the act of terrorism or mischief. As for accidental contamination occurrence, the breakdown of contaminants is commonly through cracks in WDS pipelines that are easily exposed to polluted environments. The derivation of most common non-biological contaminants is ammonia, arsenic, barium, boron, chlorine, chromium, cadmium, lead, mercury, nickel, nitrate and sodium [4]. Based on the Third Contaminants Candidate List (CCL3) reviewed by United States of Environmental Protection Agency (USEPA), the most commonly found microbial contaminants are Adenovirus, Caliciviruses, *Campylobacter jejuni*, Enterovirus, *Helicobacter pylori*, *Escherichia coli* (*E. coli*), *Legionella*, *Mycobacterium avium*, *Naegleria fowleri*, *Salmonella enterica* and *Shigella sonnei* [5]. These contaminants have been significantly presence in aqueous environments such as river, groundwater, wells, water storage, tap and drinking water. Excessive consumption of substance concentration may lead to toxicity and hazardous to human health. Hence, the principal motivation for water quality monitoring is to provide a safe water supply to public, retail and wholesale consumers.

Recently, water monitoring technologies have expanded to a wide variety of directions. Several monitoring technologies have been introduced in order to provide higher detection sensitivity as well as data accuracies. Such improved technologies are sensor placement approach (SPA) [6-8], microfluidic devices [9-11], spectroscopic techniques [12-14] and biosensor array [15-19]. Often these monitoring techniques correlate with chemo-metric analysis which particularly used in analytical chemistry and biology applications. Multivariate analysis using various chemo-metric techniques provide information on chemical substances extracted from sensing devices to obtain qualitative and quantitative data measurements. Despite the meticulous techniques established from previous studies, providing a fast response, sensitive and accurate detection technique is a necessity for the production of threats-free water supply. Therefore, online wireless sensor network-based detection approach was recently established to measure water quality in real-time whilst having the potential to provide an early warning system as well as true/false detection alarms. According to EPA, online water quality sensors should impose three main objectives, which are (1) reproducibility of data measurements at different contaminants concentration level; (2) predicting baseline water quality level at various locations; (3) interpretations of response data analysis, qualitative and quantitative measures [20].

Detection of low concentration contaminants in water sources are a challenging task, especially when for microbiological contaminants [21]. Traditionally,

analysis of water contaminants has been performed in laboratories and water facilities that often utilizes high-end technological instrumentations. Although conventional method, also known as “off-line analytical methods”, such as multiple fermentation tube (MTF) [22-25], membrane filtration (MF) [26-28], DNA amplification [29-31] and gas/liquid chromatography-mass spectrometry (MS) [32-35] have been remarkably successful in water contaminants data analysis, several researches review the drawbacks of employing these methods in real-time measurements which are primarily time-consuming, limited detection of specified contaminants, relatively high cost, heavy instrumentation setup and provide small data sets [36-39]. This equipment requires expert guidelines for conducting analytical measurements and procedures.

Since the introduction of wireless sensing mechanism, several studies have been reported to established integration of detection techniques with wireless sensor network (WSN) applications. Online monitoring offers portability, compact, flexible and faster response which are suitable for on-site deployments. A surrogate approach utilizing WSN instrumentations is able to identify unlimited water quality parameter as discussed in [40], which are summarized in Table 1.

Table 1. WSN-based online monitoring instrumentations [40].

Online monitoring instruments	Water Quality Parameter
Physical	Turbidity, color, electrical conductivity (EC), hardness, temperature
Inorganic	pH and DO level, metals, nutrients, fluoride
Organic	Carbon, hydrocarbon, UV absorption, pesticides, disinfectant-by-product (DBP)
Biological	Algae, protozoa, pathogens
Hydraulics	Flow, level, pressure

As seemingly promising, not many researchers considered the detection of contaminants at the point of consumption, which is primarily tap and drinking water supply. Today, hand-held devices such as portable microfluidic devices, miniaturized biosensors and spectroscopy have been commercially available, hence, providing an efficient way for on-site monitoring of water quality assessments. The application of WSN within water distribution system is the simplest way to enable in-field and real-time water contaminants detection. An automated detection system reduces the time limitations of a conventional analytical method, having to work with real-time water samples without the necessity for laboratories usage and able to response faster whenever contaminants are detected. Therefore, a comprehensive review on the state-of-the-art WSN

and smartphone-based monitoring technologies, as well as their applications for the detection of water contaminants are presented in this paper. Limitations and future recommendations for present water quality monitoring system will be extensively elaborated.

2. WSN Design Structure

A wireless sensor network (WSN) is a distributed architecture consisting several subsystems that are able to communicate with one another through an electronic device, commonly known as a transceiver or receiver. There have been a numerous research on the constructions of WSN technology for the detection of water contaminants whilst providing low cost, higher detection sensitivity, sufficient data sets, improved data acquisition and low power consumptions [41]. Typically, a WSN system comprises a number of low power consumption sensing station nodes that enable data acquisition process. The basic system of WSN comprises a sensor distribution system, central data station, and a controller unit which permits data analysis process.

WSN technologies often correlate with real-time automated monitoring system equipped with data acquisition, network transmission, and software data analysis. This intelligent technique enables the monitoring system to characterize water conditions, observing changes in water quality, identifying emerging contaminants and providing water assessments [42-45]. There are several network topologies used for implementation of network nodes, such as the star topology, peer-to-peer (Mesh), and cluster tree topology network [46]. Fig. 1 illustrates the network topology. A star topology is a single hop communication architecture in which the PAN coordinator, also known as the router nodes connects to multiple nodes. In contrast, a MESH topology is a multi-hop communication system in which the router nodes are connected to multiple other nodes while a tree topology is a combination (hybrid) of star-mesh architecture. Referring to [47], the WSN design structure monitoring system consists of three main parts which data are monitoring nodes, data base station and remote monitoring center as shown in Fig. 2.

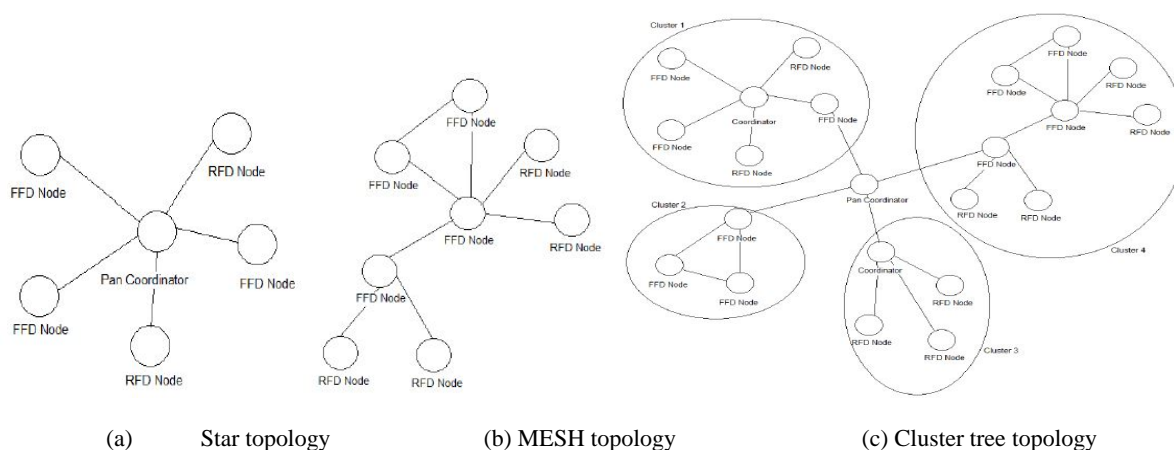


Fig. 1. Wireless sensor-based network (WSN) topologies [46].

Each of the sensing nodes placed at distributed water area does not only assemble parameters such as pH level, dissolved oxygen, EC and temperature, but also capable of obtaining wide coverage of linearization. These collected data measurements are then transmitted to a remote monitoring center from the base station via GPRS network system. The proposed system successfully monitors the temperature and pH level of an artificial lake, obtaining value ranging from 0 to 80 °C and 0 to 12 pH level, respectively. In relation to this, Lindsay et al. [48] have developed the integration of WSN for environmental sensing application in Lakes, which is known as LakeNet. The construction of WSN was embedded onto floating probe consist of waterproof controller unit and sensor nodes. The sensors detect pH level, temperature and dissolved oxygen in water

samples and describe any diurnal fluctuations and photosynthesis. These data are transmitted via a wireless system to relay stations and PC gateway [49]. Similarly, this method has also been applied in Flynn et al. [50] and Yang et al. [51] for the in-situ monitoring of water quality in aqueous environments.

3. Smartphone-based Monitoring System

Recently, smartphones are known as the pocket-sized computer featuring almost any application that interest consumers. WSN applications have been embedded with smartphones due to portability and low-cost devices suitable to be used for on-site monitoring analysis which gives direct information to the users [52, 53].

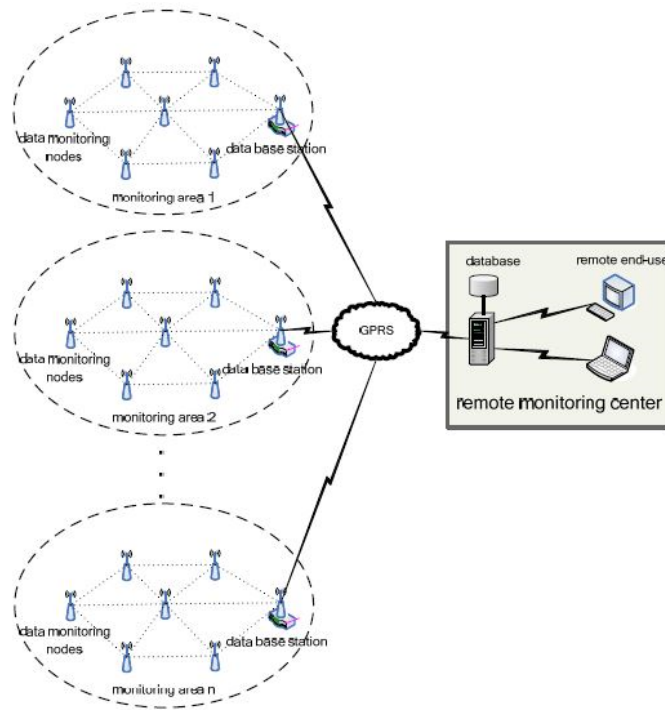


Fig. 2. WSN system consist of three main parts: data monitoring nodes, data base station and remote monitoring center [47].

Smartphones are more accessible and portable in comparison to other laboratory analysis techniques including several in-situ monitoring devices [54]. An expanding development of smartphone-based monitoring apps has increased interest among researchers to fully utilized smartphones as a smart detector. A surrogate approach to exploit smartphones for water monitoring is by integration of RGB camera, Bluetooth, ZigBee, Wi-Fi, GPS, GPRS and GSM communication. Sensing devices capture measurements and smartphones are used to control experimental variables as well as displaying results on a screen that basically resembles the tiny version of a laptop computer. This was illustrated in several studies that developed a sensing device featuring smartphone applications and user interface data analysis for deployment of environmental, nutrition, lab-on-chip diagnostic, point-of-care measurements and biomolecular detections [55-62].

Basically, integration of smartphones is categorized into two applications, which are used as a detector and instrumental interface. Despite the successful developments of mobile sensing and data collection via WSN application, there are very few efforts on the evaluation of smartphones as data collectors in remote locations [63]. The impact of smartphone-based mobility data collection from isolated regions have been investigated by Wu et al. [64], Park and Heidemann [65] and Shepard et al. [66]. As comparison, Zuhail and Murat [67] also studied the feasibility of smartphone-based data collection from wireless sensor networks but in an urban environment. In relation to data collection efficiency, several WSN islands were targeted with various sizes and connection availability resulting in a negative linear

relationship between data collection protocols and sizes of islands.

Currently, smartphones have been reported to integrate with conventional analytical devices, such as a biosensor, spectrometer and microfluidic approach. With superior advancement in sensing techniques, simultaneous multiple analysis is feasible due to smartphone-based monitoring applications. Multiple channel diagnostic devices utilizing smartphones are useful for high-throughput in-situ monitoring with minimal size, weight, cost and data transmissions [68].

3.1. Bluetooth Communications

A Bluetooth is an open wireless technology medium that enables connection between devices at a certain specified distance. It operates through a short-range (10 m-100 m) radio waves ad hoc network which is known as the piconet. A piconet is a basic Bluetooth topology technology which only allows a maximum of seven devices interconnected to a master device. A Bluetooth is a low energy consumption device which is capable of long operation timeframe that requires only coin-cell batteries for power supply. Generally, a Bluetooth wireless technology comprises data rates of up to 721 kbit/s, however, a high speed frequency of 2.4 Mbit/s is achievable by using an 802.11 AMP [69, 70].

The application of Bluetooth transceiver embedded in a smartphone-based for the monitoring of water contaminants has been expanding tremendously due to its low power consumption and low operational cost. A smartphone-based portable bacteria detection have been developed by Jing et al.

[71] using a pre-concentrating microfluidic sensor integrated with an impedance sensing system. The low-cost sensors and sensing system are able to identify and quantify bacteria in aqueous environments. The demonstration of fabricated microfluidic smartphone-based platform successfully detects bacteria with a lower limit of detection (LOD) at 10 *E. coli* cells per milliliter. Data analysis was performed using a well-designed Android application program which allows recording and visualization of data measurements transmitted via Bluetooth circuit module. The schematic diagram of the wireless system is shown in Fig. 3.

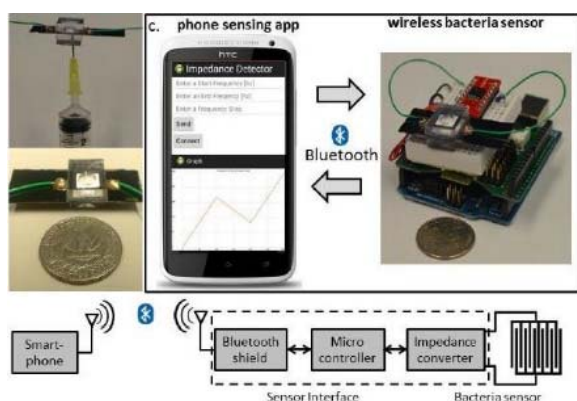


Fig. 3. Schematic of wireless mobile phone bacteria sensing system [71].

Previously, the development of smartphone-based impedance screen-printed electrodes for the detection of 2,4,6-trinitrotoluene (TNT) in water using Bluetooth platform was developed by Diming et al. [72]. The embedded sensing system comprises an alternative current (AC) impedance of 20 kHz, an AD5933 analyzer chip, Arduino microcontroller and a smartphone-based platform. The combined sensing system has a detection limit as low as 10-6 TNT impedance properties. The data transmission was executed using smartphone apps to receive and plot the real-time data. Despite the successful detection of TNT substance in water samples, impedance transducers are dependable to frequencies. Results show that TNT presence is able to be detected at a frequency ranging from 10 kHz to 30 kHz only. Portable smartphone platforms have also been applied to bio-sensing events to receive, analyze and display detected signals. There have been several studies related to bio-detections of bacteria and biomarkers that correlate with the integration of Bluetooth module communication system [73-75].

A similar approach of smartphone-based electrochemical impedance spectroscopy (EIS) was also established for the detection of proteins [76]. A miniaturized biosensor embedded to an EIS detector observes and detects EIS signal measurement of proteins via Bluetooth protocol using a smartphone. With the implementation of smartphone-based protein detection, the system allows fast operational time

responses, cost effective and portability with a detection limit as low as 1.78 $\mu\text{g/ml}$ and 2.97 ng/ml for bull serum albumin (BSA) and thrombin respectively. A mobile sensing for water quality monitoring has also been studied by Anthony and Aloys [77] using integration of water quality sensors (electrical conductivity (EC), pH and oxidation-reduction potential (ORP)) to an Arduino microcontroller unit, a serial Bluetooth module, Android mobile apps and a web-server internet.

Generally, Bluetooth communication modules are among the most favorable wireless communication system via smartphone-based platform due to their relatively low power consumption in comparison to other high data rate system such as Wi-Fi [78-81]. The simplicity of Bluetooth devices and capability to work in a remote location with the absence of the Wi-Fi connection allows the deployments of on-site water monitoring. In addition, Bluetooth is mostly embedded in almost every available smartphones. As reported by Unyoung et al. [82], the detection of bacterial pathogens in water monitoring was investigated using a microfluidic DNA sensor integrated to a mobile interface which allows users to visualize of data results. With the implementation of a wireless interface and electrochemical analyzer unit, the system is able to identify *E. coli* sequences and map out the signal output via a mobile application which is shown in Fig. 4.

3.2 Smartphone Camera

The application of smartphone camera in water monitoring has been used by interconnecting smartphones with a sensing instrument to detect the output signals. Due to camera's high resolution, often it has been used to perform fluorescence imaging, such as capturing bright-field microscopic bacterial and microorganism morphology [83-88]. The concept could overcome the limitation on the detection of various microbiological activity in remote areas, in which the usage of cellphones is extensive.

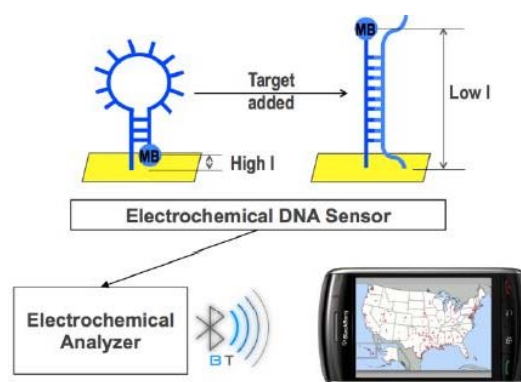


Fig. 4. An overview of microfluidic DNA sensor integrated with mobile interface: an electrochemical sensor provides an electrochemical signal when hybridized to its target pathogen sequence [82].

In addition, a similar concept could also be implemented on a conventional smartphone camera technology without having the necessity to have high-end smartphones. The same concept of lens-free smartphone microscope was also investigated by Tseng et al. [89]. In their study, they used an LED light source excitation to create a hologram of each targeted samples which is then captured by the smartphone camera. The system demonstrates various micro particles images of platelets and parasites. Following this, the detection of analytes concentration based on various fluorescence imaging was reported by Erickson et al. [90] using a portable smartphone camera embedded to a reflectance photometry. Interestingly, the light source used in the system was a built-in smartphone flash which is cost-effective. This adds up the advantages of using smartphone features which do not require additional accessories or instruments setup. A smartphone-based camera was also been used as fluorescence analyzer for the detection of Ochratoxin A, identification of highly pathogenic H5N1 viruses, quantitation of prostate-specific antigen (PSA), detection of E. coli and Salmonella bacteria [91-94]. Since a smartphone camera offers limited functionality, many smartphone-based water monitoring applications often utilize colorimetric and visualization technique to detect analytes concentration. A smartphone camera with a remote server integration is also used as a colorimetric reader for rapid on-site analysis. This was reported by Yu et al. [95] for the detection of catechols in water samples using a 2 x 2 colorimetric sensor array which comprises a pH indicator. In this case, the smartphone is used for data acquisition and processing of the sensor array. A 16-megapixel smartphone camera was used to directly capture the color produced by probe/analytes mixtures. The schematic diagram of overall sensing technique is shown in Fig. 5. The results show the capability of the proposed system to detect 13 different catechols at 12.5 mM concentration. According to the author, previous cis-di-ol-containing analytes use numerous amount of instruments setup. In contrast to the proposed design system, the author managed to reduce the design complexity and probes whilst producing a greater number of analytes detected.

The quality feature of current smartphone camera such as high resolution, sensitive motion detection cameras, built-in light source and advanced wireless connectivity has been fully utilized by researchers to develop rapid environmental monitoring. For instance, it has been reported several microscopic imaging and colorimetric detection that demonstrates smartphone camera platforms [96-99]. According to Hasan et al. [100] the first surface plasmon resonance imaging based on a smartphone was developed by the author itself. However, a more feasible technique was established by Liu et al. [101] and Bremer et al. [102] using smartphone-based LED and camera for light emitting source and sensor, respectively. The system differentiates the others by integrating smartphones with optical fibers probe.

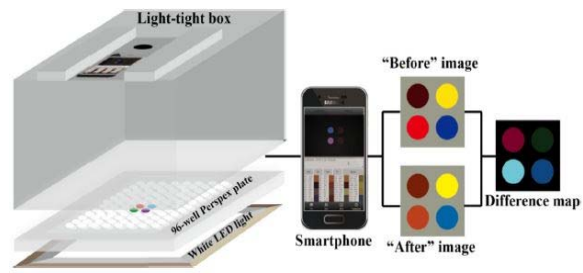


Fig. 5. Schematic diagram of a smartphone-based colorimetric reader [94].

Nevertheless, smartphone camera has limited spatial resolution images due to the pixel size at the sensor, hence providing less accurate data in comparison to a standard microscope. Furthermore, a holographic algorithm is often used to capture the real image, which obviously could not be executed on smartphones because of its high data speed. Despite some potential novelties in utilizing smartphone cameras, its sensitivity is to be questioned since some applications are only able to detect specified analytes or contaminants in medium to high concentration [103]. Since most of the analytes presence in low concentration, hence the lack of device sensitivity is therefore limited.

3.3. ZigBee Protocol

As similar to Bluetooth, ZigBee is a mesh network protocol that enables small data packets transmission over short distances with minimal power consumption. ZigBee operates under a local area network (LAN), hence it connects to devices with a wider range. The traditional wireless communication technology has limited computing power and bandwidth ranges. The wireless infrastructure contributes to low performances of data transmission from one node to another. An alternative solution was established by Yanan et al. [104] to overcome this issue by implementing WSN gateways via ARM processor, which was constructed using ZigBee and GPRS module. The proposed WSN gateways structure is shown in Fig. 6.

The WSN structure design can improve gateways transmission speed and achieve a long-distance transmission with higher performance.

Previously, a study for real-time groundwater monitoring using wireless network system integrated to a pressure sensor [105]. The remote sensing is based on ZigBee wireless local area (WLAN) IEEE 802.11 network. Following this, Ghaffari et al. [106] introduced a low-cost wireless multi-sensor for the detection of nitrate concentration in water sample via ZigBee transceiver. The ZigBee was used for a short distance communication but it can be extended to a maximum of 150 m by using additional antennas. ZigBee wireless communication protocols have also been used in various environmental monitoring

applications [107]. Another ZigBee-based wireless technology using microelectronic sensor was developed by Xing et al. [108] for the detection of cyto-toxicants in a water supply.

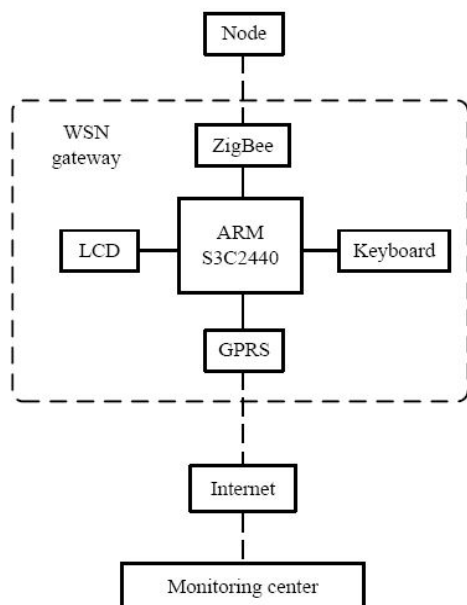


Fig. 6. Structure of WSN Gateways [104].

A ZigBee radio for wireless communication was also being deployed for an on-field measurement of debris in aquatic environments using a smartphone-based robot [109]. A host computer was used to communicate smartphone using Wi-Fi and ZigBee-based fish robot. A PID controller was embedded to the smartphone purposely for the reduction of physical sizes and operational cost. The prototype system integrates a Galaxy smartphone enwrapped with water-proof casing to a robotic fish. The vision-based debris detection does not only improve various dynamic complications but also effectively reduce camera shaking and reflections.

4. Conclusion

Undoubtedly, wireless sensor networks have a huge potential in the field of environmental monitoring sectors due to their advantageous features such as real-time monitoring, ability to operate in remote locations and low power consumption. WSNs application offers a multiple-point of data collection in accordance with a variety of ecological variables. Unexpected contamination events can be monitored and controlled via wireless communication technology. However, exploiting WSN application in rural areas can be a challenging task. Wireless communication is a concept of interconnection between locally based station and station nodes. The construction of WSN may result in global power consumption. In addition, rural areas may have a

limited site for WSN infrastructures. Hence, smartphone-based monitoring technique was introduced for the past few years. In correlation to advanced smartphone applications, water monitoring technologies have been tremendously improved in term of data transmission speed, real-time data collection, low power consumption, system accuracy and operational time responses.

Portable sensing platform is advantageous for multiple detections, semi-quantitative and qualitative analysis, fast operational responses, user-friendly and low cost. It is clear that in order to develop an innovative and effective water monitoring system, the following main criteria must be met: (1) a rapid early detection warning system, (2) the ability to perform continuous real-time data measurements, (3) the ability to respond to the needs and preferences of users, (4) the operational cost reduction with fully utilized devices and (5) the provision of detection abilities in unvisited regions. These requirements are achievable by deploying a smartphone-based water monitoring technology.

There have been many established method utilizing smartphone technology via wireless communication such as GPRS, Bluetooth, and GSM. Since cellular networks have grown linearly over the increment of bandwidth, currently 3G and 4G networks are highly advisable to be fully utilized in water monitoring applications. Up to date, several water monitoring interface with smartphone devices are reported to only display data results rather than performing a qualitative and quantitative analysis. This is obviously due to the lag of data speed and data storage in smartphones which are not suitable to execute a mathematical and statistical algorithm. Hence, it is recommended to use a local hot computer or tablet for data analysis. The disadvantage of using a smartphone to monitor water contaminants is the accessibility and exposure of valuable data to unauthorized personnel if proper precautions are not observed. Cybersecurity and securing wireless system is, therefore, one of the elements that requires further research.

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