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Enabling Communication Networks for Water Quality Monitoring Applications: A Survey

SEGUN O. OLATINWO AND TRUDI-H. JOUBERT, (Senior Member, IEEE)
Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa

Corresponding authors: Segun O. Olatinwo (segunlatinwo@gmail.com) and Trudi-H. Joubert (trudi.joubert@up.ac.za)

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ABSTRACT This paper considers newly emerging wireless technologies that can be explored for potential exploitation in the future wireless sensor network solutions for water quality monitoring applications. The reviewed technologies promise to address long-standing issues that confront existing wireless sensor network solutions devoted to the monitoring of water quality parameters. Such issues include energy efficiency and long-range water quality data communication. These issues can be attributed to the shortcomings of legacy communication networks commonly combined with wireless sensor network solutions, due to a discrepancy caused by traditionally powering the sensors nodes using batteries. In particular, some of the legacy communication networks suffer from short communication range, while others are limited by high power consumption. These shortcomings provide scope for the utilization of newly emerging solutions identified in this study to advance the field of a wireless sensor network for water quality monitoring. To achieve this, three key categories of communication networks have been recommended in this paper, including their architectural design and network deployment for water quality monitoring applications. Also, this paper provides future directions on the identified communication networks to enhance their performance for the next-generation of wireless sensor network solutions for water quality monitoring applications.

INDEX TERMS WSN, IoT, water quality monitoring, QoS, Sigfox, LoRa, INGENU, NB-IoT, IEEE 802.11ah.

I. INTRODUCTION

The journey of wireless sensor network (WSN) technology was initiated by the United States military around the 1950s, and has evolved rapidly, with remarkable impact [1]. Recent developments in silicon technology and wireless networks are key players in the evolution of WSNs, including the increase in their popularity. WSNs are indispensable tools in this present age. WSN technology is a core part of internet-of-things (IoT) paradigm that has transformed the world to a better place for human-kind via machine-to-machine communications which makes it possible for devices - such as sensor-enabled machines - to communicate without any form of human intervention. WSNs have gained wide popularity in the field of environmental monitoring, specifically water quality monitoring (WQM) [2]–[6]. The application area of WSNs is not limited to WQM only [7], they have also been employed to carry out critical monitoring in other application fields that include battlefield surveillance [8], [9], agriculture monitoring and precision agriculture [10]–[14], intelligent transportation [15], [16], industrial monitoring [17], [18], and smart homes [19], [20].

It is noteworthy that there are unique features associated with different applications, and each specific application requires distinctive properties from a WSN solution. Understanding of the differences is important to address the peculiar requirements of a specific application. For example, in applications that include healthcare monitoring (such as the monitoring of cardiac conditions) and urban traffic monitoring, network data interchange is typically characterized by continuous monitoring, at the expense of energy resources. Also, in video-based applications high data rate and low-latency are crucial requirements, and high energy usage for a fixed time becomes acceptable. The peculiar features of WQM applications to be considered are in terms of the types of water quality sensors to be deployed, the sampling rates of water quality parameters, the patterns of water quality data traffic, deployment locations, energy sources, and types of communication networks to be adopted.

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The main reason for the growing popularity of WSNs in monitoring water quality is their advantageous and dynamic capabilities without any form of human intervention. Consequently, they are regarded as essential tools that promise to bring interesting innovations to the field of WQM. Conventionally, WQM is performed based on laboratory analysis, such that water samples are manually collected from different water sources and transported to water testing laboratories for the necessary chemical and microbiological analyses. Unfortunately, laboratory-based strategies are often ineffective due to the operational cost involved, the human intervention required in the context of skilled personnel, and the failure to provide measurement results in a timely manner [21]. To guarantee the supply of clean water needed for good health, there is a need to communicate reliable and real-time measurements of water quality parameters to water management personnel. A high level of pro-activity in combating any possible water pollution can be achieved. Indeed, WSNs have emerged as a good alternative to achieving the requirements involved in realizing modern WQM systems [4], [5], [22], [23].

WSN systems for WQM are characterized by stringent quality of service (QoS) requirements that include reliable and timely delivery of WQM application data over long distances to various remotely located water control centers, while maintaining energy efficiency. WSN system criticality in the context of WQM monitoring ensues from the impact of water on human health, as any water ingested has a direct influence on health. Incorporating WSNs in such applications requires robust and reliable data transmission. However, the existing WSN solutions for monitoring water quality are plagued by limited energy, low computational performance, insufficient data storage, and communication capability issues [4], [22]–[24]. These issues have attracted the attention of industry and academic research communities in recent years in attempts to find solutions to the problems associated with WSN systems. Typically, water quality monitoring WSN systems employ sensor nodes that incorporate batteries. Unfortunately, the batteries used for powering water quality sensor nodes cannot have large energy capacity because of a portability size constraint, as well as cost factors. The tiny batteries that are accommodated severely limit the power budget, and it is expedient to ensure efficient use.

A crucial pivot upon which the usefulness of WSN in WQM revolves is the context of guaranteed and timely detection of any possible water contaminations to protect the public health, which places strict demands on the energy source. Similarly, it is possible for water quality sensors to be installed in places that are difficult to access after deployment, such as inside underground water pipes. In such an application scenario, replacing the in-built batteries may not be feasible. Importantly, it is expected of such sensors to be operational for a meaningful number of years.

At the sensor node level, the battery is responsible for providing suitable energy to the node load, including at minimum the application sensor(s), the microcontroller, and the communication module. Compared to the sensing and processing modules, the communication unit usually dominates regarding energy consumption [2]. Because of the high energy consumption during data communication, which often leads to the quick depletion of the available energy in a battery, it may be difficult to meet the specific requirements of WQM applications. This challenge may be mitigated by energy efficient strategies on the level of network design. It becomes important to ensure that WQM applications employ low transmission power communication technology solutions for disseminating data. Yet, long communication range remains a key design goal in WSNs that are dedicated to WQM applications because the water quality sensors may need to transfer their measurements to monitoring centers a great distance away from the application environment. Consequently, both low transmission power and long communication range are crucial requirements to realizing energy efficient communications in modern WSN-based systems for monitoring water quality applications.

The majority of the available communication technology solutions are not optimized for low-power applications that include WSNs, internet-of-things (IoT), and machine-to-machine communication [25]. Examples of such network solutions are conventional cellular network solutions that were primarily conceived to target mobile devices (such as laptops, smart-phones, tablets, personal computers), communications in mobile broadband, and communications in human-to-human applications [26], without taking low-power devices into consideration [27], [28]. Although water quality sensors in WSN applications are not originally designed to be interfaced with networks that provide high bandwidth such as the conventional cellular networks, the lack of suitable alternative solutions for long distance communication has made them the standard means in WSN-based systems. As a result, a large percentage of the existing WQM solutions based on WSNs have been built using the conventional cellular network solutions for remote data communications, as well as for remote access to the application environment [29]–[32]. For example, the WSN solutions for monitoring the quality of water in [33]–[40], have either employed a GSM network, GPRS network, 3G network, or a 4G network.

Apart from the high energy consumption associated with the conventional cellular network solutions, they also suffer from issues that range from huge operational cost for the networking service provided by mobile network providers, to hardware outage issues [22]. Hardware outage is one of the key issues associated with any telecommunication network, a problem often caused by a communication failure on the system level. This type of failure can often be attributed to unplanned outages, such as a power outage. Unfortunately, the hardware outage problem brings a disruption to the operation of any wireless communication systems that employ the networks of the conventional cellular-based infrastructure. As a consequence, a WSN system built on the conventional cellular network solutions will automatically incur the shortcomings of conventional cellular networks as identified. This is worrisome; as such shortcomings will directly influence the reliability of WSNs. Currently, there are existing communication technologies in the market that primarily target low-power wireless systems, including WSNs. Examples of such communication technology solutions include ZigBee and IEEE 802.15.4. Regrettably, these solutions are only suitable for low-power transmission over short distances. Their limited communication coverage is a major shortcoming as far as the realization of modern WSN in WQM application is concerned. Because of their low-power property, they are mostly considered as a suitable solution for data communication between water quality sensors and a local data gathering node or a base station (BS). For example, the WSN solutions for monitoring the quality of water in [34]–[37] and [39]–[41] have either employed a ZigBee radio, or an IEEE 802.15.4 radio.

Typically, the communication coverage of ZigBee and IEEE 802.15.4 radio solutions span a range within tens of meters [42]. The coverage of these solutions typically limits WSN systems for WQM applications to contexts with low spatial resolution [43]. Another possible solution for extending the coverage range for data communication is the introduction of relay nodes to a network. These nodes typically use the unlicensed industrial, scientific and medical (ISM) spectrum bands for data communication. However, this strategy is not secure due to the overcrowding of the ISM communication platform and may likely encounter security attacks and interference. Also, the strategy does not guarantee low cost communication routing.

To achieve the dream of realizing low-power and long range communication capabilities in modern WSN systems for monitoring water quality applications, new energy efficient communication technologies that target devices with low energy requirements are emerging, which promise to advance the field of WQM. Examples of such communication technology solutions include Sigfox [45], LoRa [46], INGENU [47] and NB-IoT [48]. These solutions are cheaper in terms of operational cost for providing a low-power interface to sensors for water quality data communication, compared to the conventional cellular network solutions [48], [49]. Since the water quality sensors traditionally run on battery, with the new communication technologies the battery life of the water quality sensors may operate for years compared to the conventional cellular network solutions that typically last for only a few days [42], [48]. Also, the new technologies are promising solutions to deal with the short range limitation of ZigBee and IEEE 802.15.4 networks.

II. RELATED LITERATURE

The field of WSN in WQM is presently under growth and there are few state-of-the-art surveys in the field. For example, in [2] energy efficient solutions for solving energy problems in WSN systems for WQM applications are presented. In the research study presented in [2], a detailed survey of several techniques that could be employed to make WQM systems more productive and to assist them in achieving their appealing promises. Different from [2], the focus of this survey is on improving the data communication efficiency and usefulness of WSN solutions in WQM through the exploration and exploitation of energy efficient communication networks, as well as to bring the notice of the research community in WQM to unfolding developments in the field in the context of the utilization of energy efficient, long-range, low-cost, and reliable communication networks. This survey also focuses on giving insights into the strengths and weaknesses of the existing and new wireless networks suitable for WQM for further improvements. This research effort is believed to catalyze the widespread acceptance and deployment of modern WSN solutions for WQM. Reference [50] presents a survey on research issues such as underwater communication and deployment, which confronts WSN solutions devoted to WQM applications in underground settings. The survey presented by [51] considers localization and water leakage issues in WSN solutions designed for the monitoring of the quality of water. In addition, only a few surveys have considered the traditional data networking solutions and the new state-of-the-art wireless network solutions in WSN solutions for WQM applications. For example, in [22] the traditional data networking solutions in WSNs for WQM are considered. Also, a few types of new wireless network solutions, including their communication coverage and power consumption capabilities, are surveyed. The paper also explores other issues about the security of WSN-based solutions for WQM applications, and the connectivity and coverage of WSNs in WQM applications by exploiting cellular network solutions. A brief review of the legacy wireless technologies that could be employed for data networking in WSN-based solutions for WQM applications is presented in [52]. In [23], a survey of the traditional wireless network solutions that include short range and cellular network technologies are presented. New state-of-the-art wireless technologies that are promising to realize long range and low-power communication in WSN systems for WQM applications are not considered in this survey paper. In [53], a short review on short range wireless technologies, and a new data networking solution for WSN in WQM applications, is considered. In [43], a short review is presented on both the legacy and new wireless technologies. The reviewed technologies include ZigBee, Z-Wave, Wavenis, INSTEON, Wi-Fi, NB-IoT, 6LowPAN, and LoRaWAN.

Importantly, the study presented in this paper serves as a complement to the existing studies in literature, with the aim of extending works that focus on enabling networking solutions for long range communication and low power capabilities in WSNs for WQM. The existing reviews have not explored the possibilities of the newly emerging wireless technologies in the category of low-power and wide area network solutions in the context of their utilization and suitability, as the interface of communication for delivering water quality application data in WSN systems devoted to the monitoring of water quality. Additionally, the few surveys in literature on new wireless networks in WSNs for WQM applications have not considered the strategies for the deployment of the new solutions.

Unlike the existing surveys that focus mainly on WSN systems, there is a shift in paradigm in this survey to WSNs for WQM. The focus of this survey is on the exploration of the newly emerging wireless network technologies and deployment strategies specifically for WQM application communication. This survey also considers the quality-of-service (QoS) support of WQM applications, alongside the network deployment for WSN in WQM applications. The key contributions of this paper are described as follows:

- Consideration of the extensive existing surveys of the traditional communication technologies for WSN-based solutions for WQM applications.
- Consideration of the newly emerging low-power wireless technologies for long range communication in WSN-based systems for WQM applications.
- Consideration of QoS support in the network design of WSN-based solutions for WQM applications, alongside the exploration of the new wireless network solutions.
- Presentation of the implementation of network architectures for WSN solutions in WQM using new long range communication and low power wireless technologies.
- Proposal of recommendations and future prospects in these contexts are discussed.

The presentation of the order of this paper is arranged as follows. The conceptual overview of WSN in WQM, analysis of energy resource consumption in WSNs, and quality-of-service requirements, is discussed in Section III. In Section IV, an insight into wireless sensor network communication networks is provided. The comparison of the existing state-of-the-art surveys on communication networks for WQM applications is considered in Section V, towards proposing new architectural design and network deployment. In Section VI, recommendations and future prospects are suggested for improving WQM applications and the newly emerging communication network solutions for the next-generation of applications for the monitoring of the quality of water. The paper is concluded in Section VII.

III. CONCEPTUAL OVERVIEW OF WSN AND COMMUNICATION TECHNOLOGIES IN WQM APPLICATIONS

A. WATER QUALITY MONITORING AND WIRELESS SENSOR NETWORKS

WQM practice is vital to the wellbeing of mankind and a healthy eco-system, and is therefore strongly required [54]–[57]. WQM is concerned with the monitoring of the key parameters of water. Such parameters include physical, chemical, and microbiological characteristics. These parameters are essential measuring yardsticks for investigating the quality of water. Globally, microbiological and chemical contaminations are essential water quality issues [58].

Water is used for many purposes that include agriculture, industrial consumption, drinking, and recreation, among others. For instance, in agriculture, plants depend on water to obtain necessary nutrients, and such water is expected to be clean and meet the precise water quality requirements (such as dissolved oxygen and pH levels) for the optimal growth and productivity of plants. This also applies to humans, animals, and the fish of the water, as precise levels of water quality are crucial for their survival. As advantageous as water is to mankind and the eco-system on one hand, it could also be disadvantageous on the other hand if it is not well maintained. Poor water maintenance practices would result in unclean water, which may not be fit for any of the aforementioned areas of consumption. The presence of contaminants in water systems poses a threat to the health of animals and humans [54]–[57]. Contamination could be attributed to man-made activities and naturally occurring events (such as volcano eruptions, soil erosion, natural minerals, flora, fauna, and global warming). Examples of man-made activities are extensive industrialization accompanied by urbanization, livestock waste disposal, mining operations, septic tank leakage due to poor construction or ageing, industrial effluent, household waste disposal, excessive use of fertilizers and pesticides, and uncontrolled deforestation. These activities go a long way in contaminating the environment, especially water sources such as rivers, groundwater, reservoirs, streams, and lakes. For example, many important rivers in Europe (such as the Danube river) and across the globe, suffer from contamination [58]–[60].

Contaminated water is a carrier of dangerous components that may include micro-organisms, heavy metals, and chemical compounds. Micro-organisms are characterized by bacteria, parasites, and viruses. An important indicator organism is fecal coliform [58], with E.coli often used as the indicator organism of choice for microbiological contamination of water [61], [62]. Water sources can be contaminated by micro-organisms through underground storage waste leakage (such as septic tanks), animals waste, agricultural run-off, and rainfall run-off. These processes allow micro-organisms to be washed into, or seep into, water sources. Water sources can also be contaminated by heavy metals through leaching from natural minerals, cement plants, waste disposal (household and industrial), petroleum refineries, and mining processes. Examples of harmful heavy metals are mercury, lead, copper, and arsenic [63], [64], which are poisonous. Nitrite (NO_2) and nitrate (NO_3) are other types of contaminants, which are found in fertilizers, animals waste, and human sewage. Their entrance into water sources through disposal or run-off introduces nitrite and nitrate into the water systems, which eventually results in water contamination. Contamination by heavy metals, nitrite and nitrate affects the chemical composition of water. Also, water can be contaminated through soil erosion, suspended solids, and oil spills. This type of contamination affects the physical characteristics of water. The summary of key parameters that can exploited in assessing the quality of water is presented in Fig. 1.

When contaminated water is ingested, it may lead to the manifestation of chronic illnesses, accompanied by untimely death. As an example, in the case of micro-organism

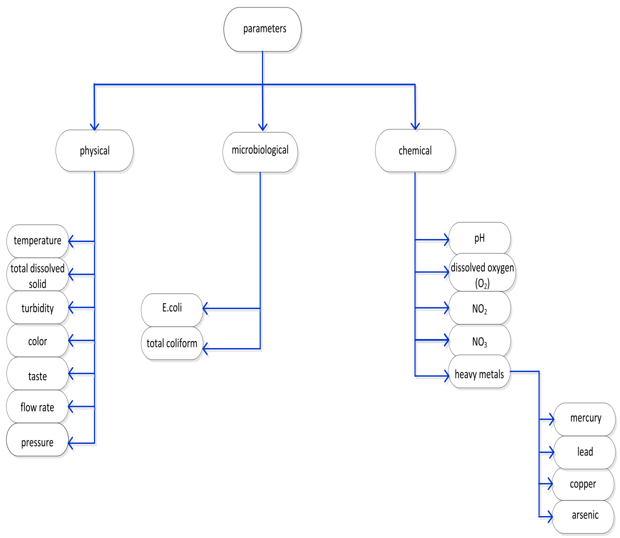

FIGURE 1. Summary of water quality parameters.

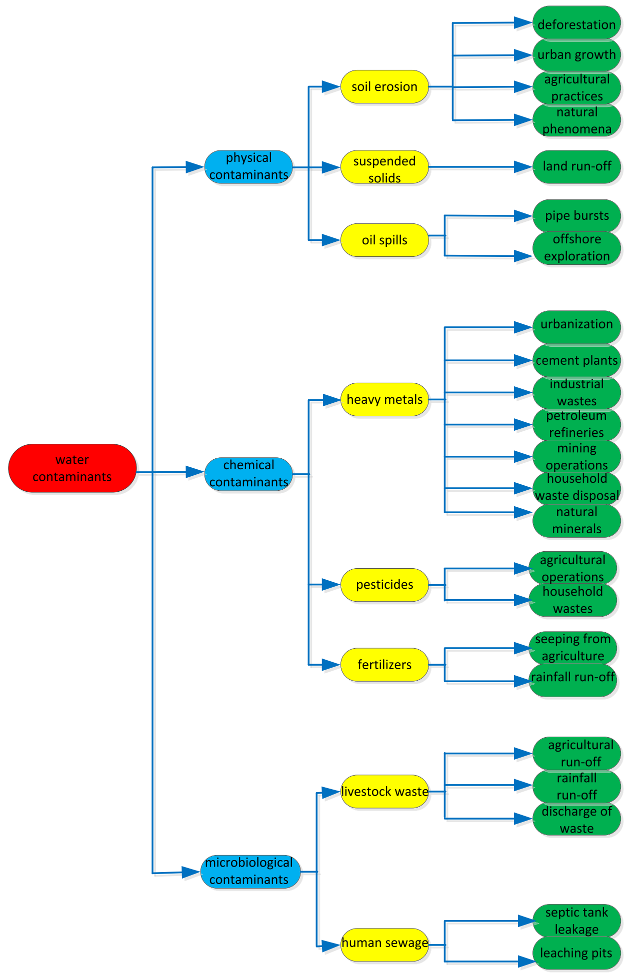

FIGURE 2. Taxonomy of water contaminants.

contamination, possible health issues include infections and gastrointestinal illness, as well as hazardous impacts on animals such as livestock. In the case of heavy metal contamination, possible health issues include failure of the renal system, damage of organs such as the intestine and liver, and cancer [63], [64], while the impact of water contaminated with heavy metals on the eco-system is devastating [65]–[67]. Water contamination due to nitrite and nitrate may cause illnesses that include the hindering of blood from carrying oxygen (methemoglobinemia) [68]. Apparently, a methemoglobinemia patient will be prevented from breathing normally, and this may result in premature death. For the sake of clarity, a taxonomy of water contaminants is presented in Fig. 2.

As discussed in this section, the negative side of water quality can be addressed through efficient monitoring systems. Importantly, the issues raised have necessitated the need for monitoring water quality to safeguard human lives, as well as protect the eco-system. Traditionally, laboratory-based systems are employed to carry out WQM. The traditional approach to WQM encompasses four stages, namely water sampling, transportation of water samples to laboratory, water sample testing, and analysis. These offline processes waste much time, and does not guarantee reliable results as parameters that include temperature and pH are best measured in-situ [69], [70]. The traditional approach is based on laboratory-based systems like optical spectroscopy, optical-infrared spectroscopy, [71], [72], membrane filtration [73]–[75], and fermentation tubes [76]–[78]. These systems are limited by several drawbacks that include requirement for operational expertise (which may include manual handling), human errors, high operational cost, few data sets, and inaccurate detection of contaminants [79]–[82].

The shortcomings of the laboratory-based systems make them unsuitable for efficient WQM. An efficient WQM system is expected to possess characteristics that include fast response time, low cost, ease of deployment, real-time results, and reliable measurements [51], [61]. These requirements are essential, as highlighted by various international bodies that include WHO and EPA [50]. To meet the challenges of WQM systems today, WSNs have been proposed as a promising technology [4], [5], [22], [23].

The integration of WSN technology to WQM applications involves the deployment of water quality sensors at water fields of interest to monitor the desired water parameters and forward measured data to the appropriate quarters such as local water stations and remote water stations, in a real-time manner. Unlike the traditional approach to WQM, a devoted WSN solution to WQM applications involve stages that include water quality data sampling, processing of data, transmission of data, storage of data, and data analysis for intelligent decision making. It is obvious that the stages involve in WSN solutions for WQM applications make them a more robust approach, as the need for human intervention is eliminated, including high cost and unnecessary waste of time.

B. HARDWARE ARCHITECTURE OF WATER QUALITY SENSORS

The hardware architecture of water quality sensor nodes is composed of four key sections that include sensors, micro-controllers, transceivers, and power sources [83], [84]. These sections work collectively in water quality sensor nodes to achieve the objective of monitoring water quality parameters, as well as reporting measurement data. For instance, the sensor section is composed of the water quality application sensors and analog-to-digital converters (ADCs) that work hand-in-hand to generate data about water quality [85]. Specifically, the application sensors (such as pH, E.coli, temperature) are responsible for collecting data about the quality of water in an analog fashion. The analog data is delivered through an analog front end to the ADC, which is responsible for transforming the received analog data to a suitable digital form for the micro-controller. The micro-controller performs the function of a processor, coordinates the entire sections of a water quality sensor, and integrates a memory for data storage. As an example, it is responsible for collecting water quality data from the ADC of the sensor section [62]. The collected data can be stored in the micro-controller's memory and transferred to the neighboring sensor nodes through a transceiver device [84].

CMOS technology is usually considered in the design of memory devices and micro-controllers because it is cheap due to economy of scale and offers a small form factor. Examples of commercial micro-controller devices that may be deployed in water quality sensors are Texas Instruments (TI) series (MSP430 [86]–[88], MSP 430F 16 1 1 [89]), ARM series (ARM9 [90], ARM Cortex M3 [91]), and the series of ATMEL ATMega (ATMega 128L [Atmel 2011], [92], ATMega 256RFR2 [93]). It is worth mentioning that the ATMega series and MSP430 micro-controllers from ATMEL and TI are often employed in commercial sensors [94]. However, the MSP430 micro-controller is preferred to the ATMEL ATMega micro-controllers in terms of processing speed, cost, low-power, and RAM memory: for example, the size of the RAM memory of the MSP430 micro-controller is 10 kB, while the size of the RAM memory for the ATMEL ATMega micro-controllers is typically around 4 kB [24], [95]. The memory of a micro-controller can be classified into three categories, namely a flash memory, a random-access memory (RAM), and a read only memory (ROM) or data memory. The sizes of these memories are typically within the range of kilobyte (kB) to a few Megabyte (MB or M).

The flash memory is usually an external memory, while the ROM and RAM memories are internal memories [96]. A flash memory is a special type of memory employed for providing additional and general-purpose storage in the sensor node architecture, and belongs to the family of the Electrically Erasable Programmable Read Only Memory (EEPROM). It is advantageous in speeding up the rate of operation of a micro-controller and is not volatile. No energy is needed to hold the data stored in a flash memory, unlike in a RAM memory, and as a result it can be used by a micro-controller device to provide either a permanent or a temporary data storage service due to the limited storage capacity of the internal memories. Depending on the type employed, flash memory may provide a storage space of about 8 kB to 8 MB [24]. An example of a flash memory device that can be incorporated in a sensor node architecture is AT45DB from ATMEL [97].

RAM memory provides fast data reading and writing access services to a micro-controller. This type of memory is volatile in nature. That is, the data written or stored in such memory requires energy to be maintained. Once the energy supply to such memory is off, then the stored data is wiped away. In the perspective of sensor nodes and subject to the type of micro-controller employed, RAM memory may provide temporary storage space of about 1 kB to 1 MB [24].

ROM memory is used for permanent data storage, which implies that it is non-volatile in nature. This type of memory is only suitable for small data storage space, typically less than 4M [24].

A transceiver is employed to provide a suitable communication service for exchanging information among water quality sensors, including a BS, in a network. It is the most energy consuming device in a sensor node [24]. The choice of a transceiver is essential in terms of energy efficiency. A transceiver may be implemented using different types of communications that include radio frequency (RF), satellite, microwave, infrared (or optical), magnetic-induction, ultra-wideband, and acoustic [98]. Typically, the transceiver in WSN solutions for WQM is implemented as RF communication based on radio technology. The transceiver for underwater communication may be implemented as acoustic communication because of the underwater channel characteristics, which is not really suitable for RF communication in terms of diffusion and absorption [99]. RF communication covers the electromagnetic frequency in the range of 3 kHz and 300 GHz. The transceiver in WSN solutions for WQM may also be implemented as the more expensive satellite communication depending on the application environment. Consequently, in WSNs for WQM applications perspective, the medium of communication may be a radio- or a satellite-frequency. However, a radio-based frequency is advantageous compared to a satellite-based frequency because line-of-sight (LoS) is not a requirement between a transmitter and a receiver, reasonable error rates at acceptably low energy rate are possible, and a long communication range is provided. For radio-based communication, the recommended radio frequencies for WSN applications fall in the category of the industrial, scientific, and medical (ISM) spectrum as a result of the cost of operation [83], [85], [100]. For the transmission of a bit or a byte, the transceiver module provides a suitable platform for the medium access control (MAC) layer for initiating the transfer of data from a sensor node's memory storage and handing it over to the transceiver of the sensor node.

A transceiver is a dual system, containing a data transmitter (Tx) and a data reception (Rx). The primary function of a Tx

is to transfer the data of a sensor node to a desired receiver (or sensor node). This function is achieved by the *Tx* of such specific sensor node by first converting the obtained data (which could be in the form of a bit, a byte or frame) from the micro-controller module of the sensor node to radio waves. The transmitted radio waves are picked up by the destination sensor node receiver (*Rx*). To achieve the *Tx* and *Rx* functions, a transceiver employs key electronic circuits such as mixers, filters, amplifiers, modulators, and demodulators [101]. For instance, binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) are typical examples of modulation schemes that may be employed in the communication section of a sensor node for physical (PHY) layer communications. The data rate settings of a BPSK scheme operating in the 915 MHz ISM spectrum include a bit rate of 20 kb per second (kb/s), or 20 ksymbol per second for a binary symbol type, while the data rate settings of an QPSK scheme over the 2.4 GHz ISM spectrum may be configured using a bit rate of 250 kb/s,or 62.5 ksymbol per second for an orthogonal 16-ary symbol type [101].

In practice, there are four key modes that define the possible operation of a transceiver, including sleep, idle, receive, and transmit. These modes fall under two states, namely non-active and active. When a transceiver is in a non-active state, then such a transceiver is in a sleep (or off) mode. When a transceiver is in an active state, it can switch between the idle, receive and transmit modes, and although idle consumes less power, comparable energy is expended in all these modes. Importantly, the different levels of energy that are consumed in the various states could be advantageously exploited to conserve a sensor node's battery power by optimizing the operation of the transceiver through duty cycling, as no or little energy is consumed during the sleep mode.

The power section is the most important of all the sections in water quality sensors, and plays the role of energy supply to the sensor node components such as the sensor, ADC, micro-controller, and the RF transceiver. As a result, the power source section is responsible for making a water quality sensor node operational. Traditionally, the crucial components in the power section of a sensor node for WQM are a battery, an implementation of energy management schemes, and a DC-DC converter. The power section may be equipped with an energy harvesting technology to improve the availability of power within a sensor node, mitigating for the limited lifespan of batteries. Fig. 3 gives a diagrammatic representation of the hardware architecture of a sensor node for water quality monitoring, indicating the key components discussed in this section.

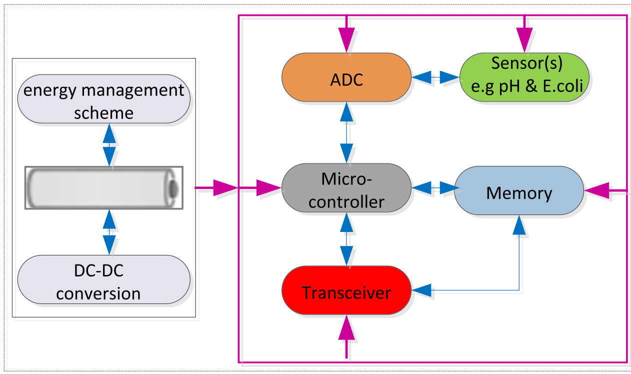

FIGURE 3. Hardware architecture of a water quality sensor.

C. ANALYSIS OF ENERGY RESOURCES CONSUMPTION IN WSNs

Since network sensor nodes traditionally run on battery power, it is important to analyze how energy is being expended in WSN solutions. This is essential because the finite energy budget of a battery directly causes limited operational lifetime of a sensor node. Consequently, the understanding of energy expenditure will assist to efficiently optimize modules that dissipate significant energy in a sensor node, namely sensing, processing, and communication.

For the purpose of energy resource dissipation analysis, the total energy dispensed by a sensor node is taken as due to (i) sensing of the application parameters which involves sensor(s) and ADC, (ii) processing of data which involves a micro-controller and memory devices, and (iii) communication of data which involves a transceiver. The energy expenditure for sensing is application dependent, and is generally low compared to other functionalities. According to [102], the energy expenditure of an ADC is a function of the performance of an application sensor and is proportional to the relationship between the sampling rate of the application and the amount of data gathered by a sensor in one sensing cycle (number of bits or resolution), and is formulated in (1) as:

$$E_{SS} \propto S_r * 2^{BN} \tag{1}$$

In (1), S_r denotes the frequency of sampling (or sampling rate) and BN represents number of bits of a sensor's data. Commonly adopted sensing rates are continuous and periodic, based on the requirement of an application. Continuous sensing may dispense more energy compared to periodic sensing since it usually has a higher sampling frequency rate which obviously involves energy dissipation. An example is in a case event detection application that requires constant monitoring with about 1 ms sampling rate. In the case WQM applications, periodic sensing is acceptable and consumes less energy. For instance, in WQM applications, it takes minutes to hours for temperature to change in state [103]. This makes it reasonable to use periodic sampling at a rate that ranges from once in minutes to hours. As a consequence, the exploitation of sampling rate is an effective approach to minimizing energy dissipation of the sensing system.

Energy dissipation due to the processing of data is low compared to the energy involved in the communication of data, a disparity that has been sufficiently illustrated in [104]. The energy consumption for data processing has been presented in [85] as (2):

$$E_{DPS} = JQ_d^2 f + Q_d I_c e^{\left(\frac{Q_d}{m*Q_T}\right)} \tag{2}$$

The model in (2) is a function of the behavior of CMOS transistor technologies employed in the design of micro-controllers. The first term of (2) relates to the dynamic power dissipation, where J stands for a switching capacitance, Q_d represents the voltage supplied to the processor, f is used to denote the clock frequency. The second part of the expression in (2) accounts for the loss in energy as a result of current leakage [105], where I_c denotes the leakage current, m is a constant defined based on the hardware of a processor, and Q_T represents the defined voltage threshold.

The transceiver dispenses more energy compared to other sections [103], and contains key components which consume a significant amount of energy. Such components include a power amplifier, a frequency synthesizer, a demodulator, a phased locked loop, a voltage-based oscillator, and a mixer. The energy consumption for data communication by a radio has been presented in [85] and [106] as:

$$E_{DC} = T_n \left(E_t \left(T_i + T_k\right) + E_o \left(T_i\right)\right) + R_n \left(E_r \left(R_i + R_k\right)\right) \tag{3}$$

In (3), T_n denotes the number of periods a transmitter is turned on, E_t defines the energy consumed by a transmitter's voltage-based oscillator and a synthesizer, T_i represents the turn-on time of a transmitter, T_k defines the energy consumed during the start-up time of a transmitter, E_o means the output energy of a transmitter, R_n accounts for the number of periods a receiver is turned on, E_r is the energy dissipated by a receiver during data reception, R_i connotes the turn-on time of a receiver, and R_k is the energy expended during the start-up time of a receiver. T_i can be further described as the ratio of transmitted bits of data s, and data rate q. Therefore, T_i can be written as $\frac{s}{q}$. It is worth mentioning that the number of periods a transmitter is turned on (i.e. T_n) or a receiver is turned on (i.e. R_n) is determined by the algorithms deployed at the operation layers of the WSN protocol stack (such as MAC), and application requirements.

The energy dissipated by a radio for data communication can also be formulated using other energy consumption models, for example from [107], as (4):

$$T_X^E \left(s, d\right) = \left(s * T_e\right) + \left(s * d^{\varphi} * T_a\right) \tag{4}$$

Equation (4) models the energy spent by a transmitter to transfer data to a receiver. The first term in (4) defines the energy expended by the transmitter circuitry in association with processing the data, such that s is the bits of data and T_e is the electronics of the transmitter. The second part in (4) describes the energy dissipated by a transmitter's amplifier T_a in association with communication of data over a distance d, with an exponent of φ which range from 2 to 4, and is related to transmission path loss.

The energy consumed by a receiver to collect data is modeled in (5):

$$R_X^E \left(s\right) = s * R_e \tag{5}$$

From (5), it can be established that the energy consumed to receive s bits of data from a transmitter is a function of the circuitry of the receiver R_e, and the number of bits defined by s.

Consequently, the total energy spent by a sensor node to transmit and receive data can be modeled as (6) :

$$E_{DC} = T_X^E \left(s, d\right) + R_X^E \left(s\right) \tag{6}$$

$$E_{DC} = \left[\left(s * T_e\right) + \left(s * d^{\varphi} * T_a\right)\right] + \left[\left(s * R_e\right)\right] \tag{7}$$

(7) is a simplified energy cost model that can be employed to find the energy dissipated by a radio to transmit data of s bits to a receiver at a distance of d, as well as data reception.

For the purpose of clarity, the comparison of the energy dissipated by the different systems of a sensor node is depicted in Fig. 4, and shows the disparity in the various levels of energy consumed by them.

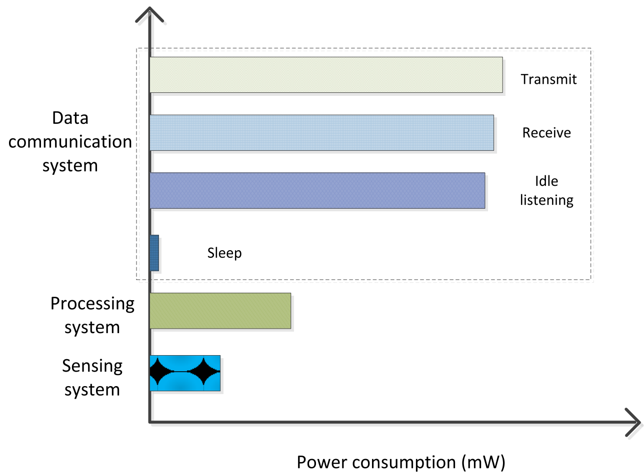

FIGURE 4. Comparison of representative energy dissipation in typical sensor systems.

From Fig. 4, it is apparent that the energy cost of data communication is expensive compared to sensing and processing activities. Also, the transceiver wastes a valuable amount of the battery power through idle listening, over-hearing, packet control, and collision issues during the data communication process of a network's sensor nodes. The aforementioned issues have contributed to the energy resource problems in WSNs. As a consequence, energy efficient radios (or communication networks) and MAC protocols are crucial to minimize the energy cost for data communication in order to optimize the battery power.

D. QUALITY OF SERVICE (QoS) REQUIREMENTS OF WSN SOLUTIONS FOR WQM APPLICATIONS

The concept of QoS focuses strictly on the key stringent requirements of a specific WSN solution. QoS is an indispensable parameter in WSN applications, and as a result, QoS parameters are critical design goals in WSN solutions for WQM applications. QoS parameters provide a platform for satisfying the service requirements of a WSN-based system for monitoring the quality of water [108], [109]. Specifically, this section highlights some key QoS requirements to be satisfied when deploying WSN solutions for WQM applications. Examples of such requirements are energy efficiency, deployment cost, large communication coverage and reliable delivery, efficient data transmission rate, and strict real-time operation. The aforementioned requirements are briefly discussed in the subsequent subsections.

1) ENERGY EFFICIENCY

Typically, water quality sensor nodes run on battery power, which determines the lifetime of a specific water quality sensor node in a network devoted to the monitoring of water. It is important to emphasize that the system availability requirement, which is a function of the battery life, should be satisfied at any possible cost as a result of the critical nature of WQM applications. To maintain a balance between the battery life and system availability, it is obvious that an energy efficiency requirement is of the highest priority. Basically, WSN solutions for WQM applications are anticipated to operate indefinitely without any form of human intervention such as battery replacement, which may be not be feasible or costly to realize in many cases. The software and hardware design of WSN solutions should consider energy efficiency in order to build a sustainable network. This can be realized through strategies that include energy harvesting, energy efficient communication technologies, energy optimization techniques, and duty cycling. Energy harvesting is a promising strategy that allows water quality sensors to receive energy from their environment. Communication technologies are key to realizing energy efficient data communication in WSN solutions for WQM application. As a consequence, it becomes crucial to consider energy efficient communication technologies for WQM application data networking since a huge amount of the battery power is often dissipated during the data communication process. Energy optimization techniques are highly important to optimize energy resource allocation to achieve low-power operation. Duty cycling is another interesting strategy that can be employed to lower the power consumption at the MAC layer. This can be achieved by adopting MAC modulation schemes that implement duty cycling techniques. Such modulation mechanisms that implement duty cycling allows the communication radio to alternate between the active and sleep states, such that they are only active during data communication when they have data to either receive or transmit, and they switch back to a sleep state once they have accomplished their periodical data communication tasks and are not expected to participate in data communication for a period of time.

2) EFFICIENT DATA TRANSMISSION RATE

Data transmission rate describes the number of water quality application data that may be transferred at a specific time. Data transmission rate is vital to a fast response rate in the delivery of WQM application data to water monitoring centers. However, there exists a challenging trade-off within the data transmission rate and power consumption, such that the power consumption level increases as the data transmission rate increases. Therefore, efficient strategies are required to strike a balance between the two parameters: to achieve an efficient data transmission rate for an appreciably fast response in WSN solutions for WQM applications with adequately low power communications.

3) LARGE COMMUNICATION COVERAGE

This requirement demands attention to make the dream of modern WSN solutions for WQM applications come true. The simple reason for the necessity of large communication coverage requirements can be attributed to the distances of water control centers and water monitoring centers to various water stations. In many cases, the remote water centers are situated in the range of kilometers away. So, for timely and reliable delivery of water quality application data to various remote water centers, large communication coverage is an important design requirement in the deployment of WSN solutions for WQM applications.

4) SUPPORT STRICT PERIODIC REAL-TIME DATA COMMUNICATION

Because of the critical nature of WQM applications, this requirement describes the response time of the water quality sensors in WSN-based solutions for WQM applications. Specifically, WSN solutions for WQM applications require a strict periodic real-time transmission of water quality application data to various water monitoring centers. It is important to emphasize too that quite a number of the microbiological and chemical parameters involved in assessing the quality of water are best measured in-situ. Consequently, the in-situ measurements demand a strict real-time transmission to water quality analysts for reliable and accurate decision making. To support timely delivery of data, the latency of the employed communication network(s) in WQM applications should be low.

5) DEPLOYMENT COST

The deployment of WSN solutions for WQM applications should consider a low-cost design requirement. This will enhance the global acceptance, mass-market and the popularity of WSN solutions that are dedicated to WQM applications. As a consequence, the design phase of WSN solutions should consider the total production cost for deploying a solution, while the aspect of energy efficiency is not neglected. Once the energy efficiency aspect is compromised, the solution becomes useless no matter how cheap.

6) RELIABLE DATA COMMUNICATION

This requirement has to do with the provision of reliability in data communication within the architecture of WQM applications, as WSN solutions for WQM applications require a high reliability. To realize this, the consideration and integration of reliable communication technologies are crucial. Such communication technologies need to have robust resistance against interference for a reliable delivery of water quality signals to various water monitoring centers. The robustness of the employed communication technologies depends on techniques that include the efficiency of the modulation strategy adopted by such communication technologies. In addition, an efficient communication technology should not only provide reliable data communication, but should also be highly secure. The security aspect of data communication depends on the robustness of the cryptography techniques employed in the communication technologies.

7) ADAPTIVELY FLEXIBLE

WSN solutions for WQM applications should take flexibility into account. Such consideration will enhance the productivity of WSN solutions in WQM application, including satisfying the needs of WQM stations in terms of easily adapting to new changes based on water station requirements. As an example, to enhance the points (or positions) interest that need to be closely monitored, there may be need to add a few sensor nodes to a network by the water monitoring personnel or engineers, or in a situation whereby there is a need for a WQM station to re-locate to another location which could probably be out of the signal coverage of the data transmitted by the sensor nodes on the water field. These issues should be adaptively managed by WSN solutions for WQM applications in a flexible manner.

Consequently, it is important to take into account the aforementioned peculiar requirements of WQM applications during the process of network deployment. By taking such unique requirements into account, sustainable WSN systems will be implemented for WQM applications.

E. COMMUNICATION ARCHITECTURE OF WSN FOR WQM APPLICATIONS

Typically, the communication architecture of WSN solutions in WQM applications can be classified into two, namely local communication and remote communication. In both cases, the water quality sensors employed for the monitoring of water can communicate over either a radio link or a satellite link, depending on the adopted communication technology. Meanwhile, radio communication technologies are mostly employed in the perspective of WSN solutions for WQM applications. However, a satellite-based communication technology may represent a viable data networking solution in application environments where radio technologies are not viable due to the lack for the necessary supporting infrastructures such as terrestrial systems. Examples of such application environments include large open seas. Nevertheless, it is worth clarifying that both technologies may be combined in WSN architectures for WQM applications, subject to the environment.

In a local communication setup, the water quality sensors in the network are controlled by a base station (BS), which also means a controller or a sink node. Consequently, the water quality sensors communicate with the BS through a radio- or a satellite-link. In a remote communication setup, the BS acts as an intermediary (or proxy) between the network water quality sensors and a remote monitoring system (or an application station) by providing communication connectivity to the remote monitoring centers, including the remote control systems.

The interconnection of the sensors and a BS may be realized through the employment of short range wireless technologies, while the interconnection of a BS and remote centers require long range communication technologies. An architecture of a typical WSN solution configured with both local communication and remote communication for a typical WQM application is illustrated in Fig. 5. An insight into the understanding of communication media for data networking between the sensors and the BS, as well as the BS and the remote WQM application is discussed in the subsequent section

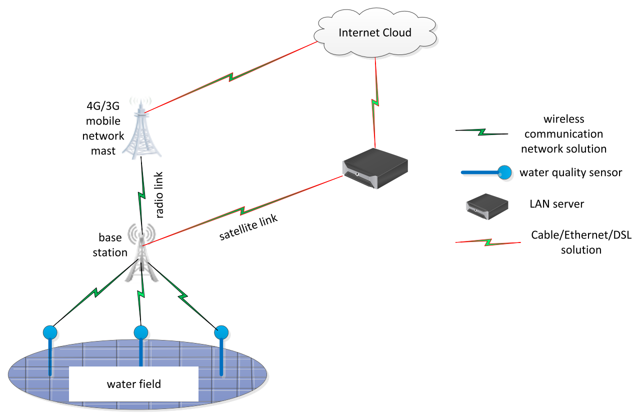

FIGURE 5. General communication structure of a typical WSN solution for a WQM application.

IV. OVERVIEW OF WSN COMMUNICATION NETWORK

Due to the energy problem in WSNs and IoT applications, low-power and low-rate communication technologies are important for efficient data communications in a way to optimize the rate of energy consumption. As a consequence, this section presents a review of communication technologies with the view of identifying their strengths and weaknesses in the context of power consumption, coverage range, data rate, latency, and cost.

A. CLASSIFICATION OF WSN COMMUNICATION TECHNOLOGIES

Communication technologies are powerful tools in WSNs that provides a platform for connecting devices for the purpose of information transmission. Specifically, they provide a communication platform for devices such as sensor nodes in WSN applications to communicate with the neighboring sensor nodes, as well as with the base station (or sink node). Communication technologies could be classified into two types, namely wireless communication technologies and wired communication technologies. Wireless communication technologies are connectivity solutions designed to eradicate the use of wires in communication systems, while wired communication technologies involve the construction of cable networks for connectivity. To circumvent the shortcomings of wired technologies in terms of mobility, suitability, complexity, cost, coverage range, and maintenance, communication technologies that are based on wireless solutions are typically employed. However, wired solution technologies may be combined with wireless solution technologies depending on the application. This is an indication that wireless applications are not often built completely without wires. Key examples of notable wireless communication technologies that have been explored and exploited for water quality data networking are ZigBee, Wi-Fi, IEEE 802.15.4, cellular technology (examples are GPRS, 3G, 4G, LTE), and WiMAX. Any of the aforementioned communication technologies can be incorporated to a water quality sensor node by embedding the module of such technology. For example, a sensor node that is equipped with a ZigBee radio can communicate in a wireless fashion with another ZigBee compliant sensor node in a ZigBee network at a distance that is typically greater than 100 m, depending on the application environment. On the other hand, key available communication technology solutions based on wired connectivity are PLC, Ethernet, PON, and DSL. Unlike the aforementioned wired technologies which are employed to connect a base station to remote locations, UART is an example of a local, short distance wired technology for directly connecting sensors to a base station. PLC and Ethernet are used for neighborhood area network (NAN) communications in the range from 10 m to 10 km, while PON and DSL are used for wide area network (WAN) setup that covers 10 m to 100 km. The shortcomings of the legacy wireless communication technologies in terms of limited communication range and high power consumption in WSNs have been a subject of concern in the research community, and have motivated the need for developing advanced wireless network solutions. Recently, advances in wireless communications have produced novel wireless network solutions. Such solutions are classified as low power and wide area networks (LPWANs). It is hopeful that the new LPWAN solutions will advance WSN solutions for WQM applications because of their longer range and low-power characteristics. The need for these features cannot be over-emphasized in WSN solutions for WQM applications. The key solutions for WSNs in the category of LPWAN are reviewed in this work. Therefore, this section presents a review of wireless communication networks under three categories that include personal area networks (PANs) or short communication networks, local area networks (LANs) or medium communication networks, and wide area networks (WANs) or long communication networks. Examples of wireless network solutions based on PAN technology include IEEE 802.15.4, ZigBee, 6LoPWAN, Bluetooth, and Bluetooth Low Energy. Wi-Fi and Low-power Wi-Fi are examples of solutions in the category of LAN, while solutions based on cellular networks and LPWAN variants fall under the category of WAN. For illustrative purposes, the taxonomy of the various classifications is presented in Fig. 6. The solutions in the different classes of wireless technologies are discussed in the subsequent sections.

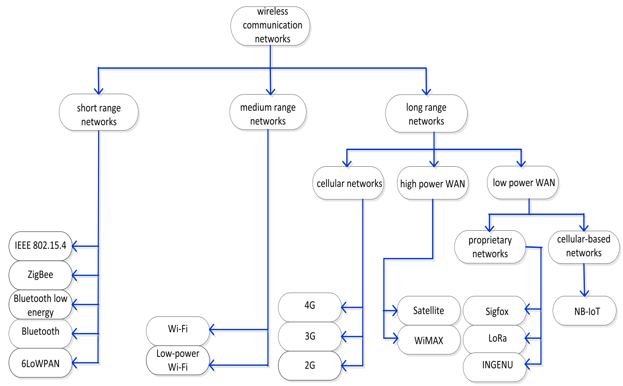

FIGURE 6. Taxonomy of wireless communication technology for WSNs and IoT sensors.

B. SOLUTIONS BASED ON WIRELESS PAN TECHNOLOGY

The wireless technology solutions in the category of wireless PAN (WPAN) are typically employed to achieve a short range data communication within meters. This section reviews some of the legacy solutions commonly employed for short range networking. The newer amendments are also discussed.

1) IEEE 802.15.4 SOLUTION

The IEEE 802.15.4 communication technology was developed by an IEEE Working Group, and it has been defined as a de facto standard for low-rate, low-power, and low-cost wireless communications standard employed by wireless end-devices such as sensor nodes. Consequently, the IEEE 802.15.4 technology has become an acceptable standard that provides a suitable platform for mounting other communication technologies, to extend wireless communications coverage and connectivity between the sensors and the sink node. As a result, the ZigBee and other communication technologies in the class of IEEE 802.15.4 can be deployed on top of the IEEE 802.15.4 standard. The IEEE 802.15.4 technology is suitable for wireless communication over a short range within a coverage range that is typically less than 100 m. The essence of the short coverage range is to ensure low power consumption in order to extend the sensor node lifetime. The IEEE 802.15.4 technology operates at the first two layers of the protocol stack, including the PHY and the MAC.

The PHY layer is responsible for the downlink communication, which involves a base station (a sink node or an access point) sending signals to the sensor nodes connected to it in a network. The PHY layer of the IEEE 802.15 4 radio can operate at the free-license ISM RF bands such as 2.4 GHz, 915 MHz, and 868 MHz [110]. When operating in the 2.4 GHz band, the achievable data transmission rate is 250 kb/s and a QPSK data modulation scheme may be employed at the PHY layer. This band supports sixteen channels (occupies channels eleven to twenty-six) as depicted

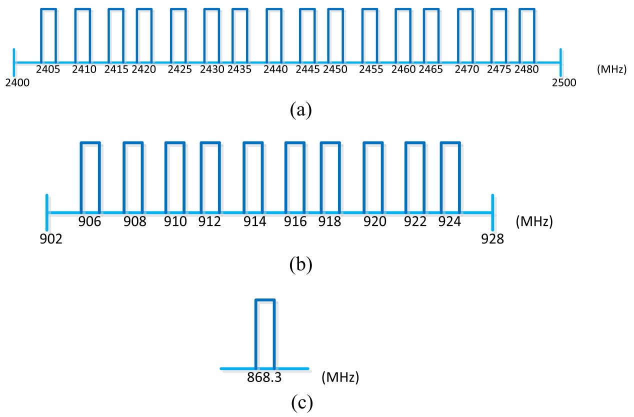

FIGURE 7. PHY layer and channel assignment in IEEE 802.15.4.

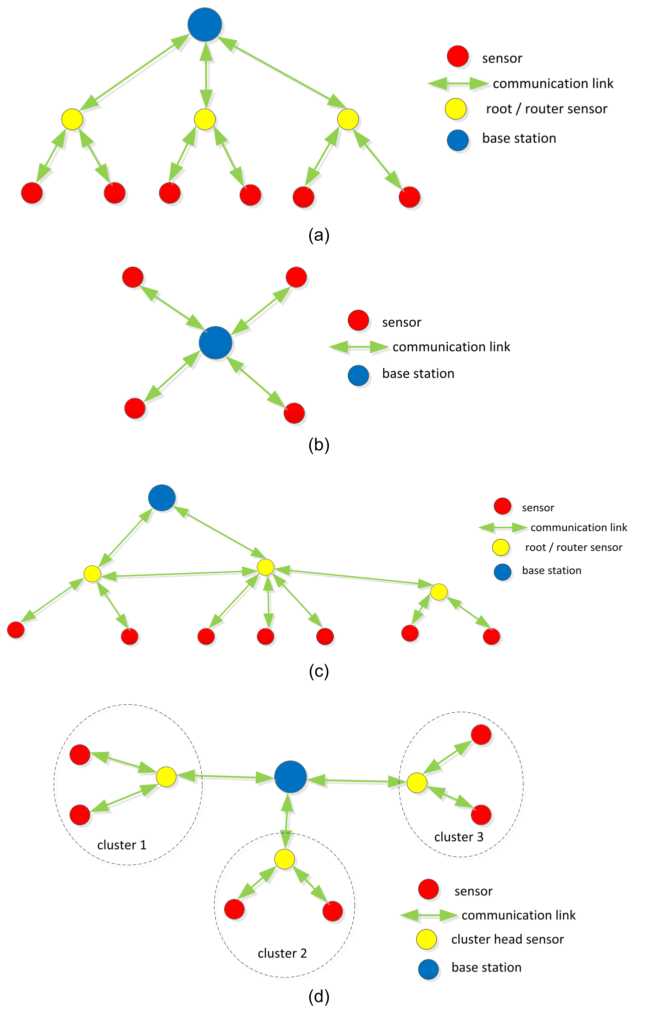

FIGURE 8. Network topology scenarios for WSN. (a) Typical tree network. (b) Typical star topology. (c) Typical mesh network. (d) Typical cluster tree topology.

in Fig. 7(a). When operating in the 915 MHz band, it is possible to achieve a data transmission rate of 40 kb/s and a BPSK data modulation scheme may be deployed at the PHY layer. This band supports ten channels (occupies channels one to ten) as shown in Fig. 7(b). When operating in the 868 MHz band, a data rate of 20 kb/s may be achieved, and a BPSK data modulation scheme may be employed [110]. This band has one channel (occupies channel zero) as illustrated in Fig. 7(c).

The MAC layer takes care of the uplink communication and involves the sensor nodes transferring their signals to a base station they are connected to in a network. The IEEE 802.15.4 standard employs a carrier sense multiple access based collision avoidance (CSMA-CA) modulation mechanism as the MAC protocol to manage channel access, while a direct sequence spread spectrum (DSSS) modulation scheme is employed at the PHY layer, as well as at the data link (DLL) layer.

Since the PHY and the MAC layers are defined by the IEEE 802.15.4 standard alone, the specification of the remaining layers (i.e. network, transport and application) of the protocol stack is defined through company alliances. The IEEE 802.15.4 communication technology is suitable for monitoring applications, and may as well be linked with an Internet Protocol (IP) network for internet capability.

Examples of network topologies supported by IEEE 802.15.4 technology are tree, star, mesh, and cluster tree. These topologies are shown in Fig. 8 (a) through (d). In a star network topology, the sensor nodes are connected directly to a coordinator node (such as a base station). This type of network model is employed to implement single-hop routing in WSNs practices. In a tree network model, the sensor nodes communicate through a root node towards the base station. The sensor nodes that are connected to a root node are referred to as the children nodes. An important variant of the tree network topology is a cluster tree. In a cluster tree network topology, sensor nodes are organized into clusters using a parent-children relationship such that each of the cluster(s) contains a parent and the children. The parent is otherwise referred to as the cluster head, while the children are the cluster nodes. It is worthy of mentioning that each of the clusters in a network is configured with a unique cluster ID, and the main essence of the cluster ID is to recognize each of the clusters. A mesh topology also connotes a peer-to-peer (P2P) topology. In a mesh topology, a sensor node may communicate via any of its neighbors to the coordinator. It is important to mention that there can only be one coordinator in a mesh topology. In practice, a mesh topology is utilized to implement a multi-hop routing in WSNs. Some important advantages of multi-hop routing are battery power optimization and self-healing. The battery power of a sensor node is optimized since it may communicate through any of its nearest neighboring sensor nodes to the base station. As a result of the multi-hop communication technique, the energy consumed by each of the sensor nodes is minimized. On the self-healing characteristics, a sensor node may use any of the available connecting links to its neighboring sensor nodes in case any of them is not available or fail.

Examples of works on WSN for WQ monitoring where IEEE 802.15.4 technology have been employed are in [37], [38], and [111]. In the mentioned references, IEEE 802.15.4 radio was used for data communication between the sensor nodes and the sink node.

2) ZigBee SOLUTION

ZigBee is a variant of a WPAN technology. It was developed and managed by a group known as the ZigBee Alliance [112]. The ZigBee can be described as a low-power wireless technology that is used for short range communications in WSNs [113]. Its standard supports the IEEE 802.15.4 communication standard, and is defined by the specification of IEEE 802.15.4 of 2003. As a consequence, the ZigBee technology depends of the IEEE 802.15.4 technology to provide transport services at the MAC and PHY layers. For example, the MAC layer of the IEEE 802.15.4 standard determines what occurs at the radio link of a ZigBee network in the context of control such as flow control, data transmission, retransmission, network synchronization, and acknowledgement. Similarly, the MAC layer standard of the IEEE 802.15.4 technology is responsible for controlling how the radio communication channel (or radio frequency link) of a ZigBee network is accessed by employing CSMA-CA mechanism services to ensure that the radio communication channel of the ZigBee network is free from the occurrence of any form of packet collisions. Importantly, the ZigBee technology is responsible for enhancing the IEEE 802.15.4 technology through the addition of new functionalities that include application services and mesh network topology.

ZigBee utilizes the free-license ISM RF bands such as 2.4 GHz, 915 MHz, and 868 MHz for communication [114]. Because of ZigBee's low-power characteristic, its transmission coverage spans less than100 m range, depending on the environment. For example, it may cover a distance of up to 100 m in areas such as rural and open space locations where there are less or no obstructions, while it may cover a distance that is typically less than 40 m in environments where there are obstructions, such as in urban settings. ZigBee devices require line-of-sight, and they may achieve a maximum data transmission rate of 250 kb/s depending on the used frequency band. For example, when operating at the frequency band of 868 MHz, a data transmission rate of 20 kb/s is achievable, while at the 915 MHz and 2.4 GHz bands, data transmission rates of 40 kb/s and 250 kb/s can be achieved, respectively.

A ZigBee network is composed of three fundamental elements, which include ZigBee sensor nodes, a ZigBee router, and a ZigBee coordinator. The aforementioned ZigBee entities and ZigBee compliant devices may be connected based on three possible network topologies, which include tree, star, and mesh or peer-to-peer (P2P) [115]. With tree topology, a ZigBee network is managed by a ZigBee coordinator in terms of deciding on critical network parameters. A ZigBee router is employed to extend a ZigBee network. These situations are also applicable to a mesh-based ZigBee network. The routers in a tree-based ZigBee network employ a hierarchical routing approach to control signals and route data, while the routers in a mesh-based ZigBee network provides complete P2P communication. With star topology, the ZigBee sensors are connected directly to only one device known as a ZigBee coordinator. Consequently, the ZigBee sensor nodes communicate their individual signals to the ZigBee coordinator in a direct pattern. In a star-based ZigBee network, the ZigBee sensor nodes are controlled and managed by the ZigBee coordinator. It is essential to note that with ZigBee, a cluster tree network cannot be implemented.

ZigBee is a suitable technology for WSN applications because of its communication features. Since environmental monitoring is an important application domain in WSN and IoT, then ZigBee technology would have great potential for water quality sensors employed for monitoring the quality of water. For example, the ZigBee communication technology is designed specifically to fit in environmental monitoring applications such as WQ monitoring, and can also be easily connected to an IP network through the IEEE 802.15.4/IP internet gateway. A gateway is a platform for connecting to the internet. ZigBee technology is suitable for industrial system control, home automation, and monitoring applications. It is worth mentioning that the battery life of ZigBee sensor nodes is typically around a thousand (i.e. 1000) days [116], where the most commonly employed battery types are NiMH and alkaline, in size AA. Examples of works on WSN for WQ monitoring where ZigBee technology has been employed are in [33]–[36], [40], [118], and [119]. ZigBee technology was used for data communication between the sensor nodes and the sink node in the aforementioned works.

Another promising communication technology solution for monitoring purposes that could push the advancement of WSN and IoT applications forward is Z-wave. Currently, Z-wave is utilized as a low-power and low-rate proprietary communication technology, and is managed by the alliances of Z-wave. Presently, the Z-wave solution is not common in public research like other technologies because of the alliance requirements. Z-wave is employed by a control unit of a wireless network to control the network devices [117]. This can be achieved by configuring devices in a network as slave devices, and connected to a controller device, which has a controlling capability. Z-wave solutions support sub-1 GHz bands such as the ISM 868 MHz and 915 MHz.

Some other key examples of short range communication technologies which are based on the IEEE 802.15.4 standard, are ISA-100.11a, WirelessHART, and WIA-PA. They are defined in the specification of IEEE 802.15.4 2006, and they operate on the 2.4 GHz ISM band. The communication solutions are often employed in industrial automation applications. For example, ISA-100.11a communication technology is mostly employed in industrial and process automation for control, monitoring, and alerting purposes. WirelessHART communication technology may be used for monitoring and alerting functions, while WIA-PA may be utilized to control the nodes in a wireless network, as well as monitoring and measurement of processes.

A recent enhancement of the ZigBee technology has resulted in a newer variant of ZigBee technology, namely ZigBee-IP. The new version is designed to house internet connectivity standards and currently incorporates 6LoWPAN technology, to provide internet connectivity. As a consequence, an IP-based network can be formed using ZigBee-IP solution. Also, the ZigBee-IP offers an IPv6 end-to-end wireless connectivity solution.

3) 6LoWPAN SOLUTION

6LoWPAN technology simply denotes an IPv6 Internet protocol on Low Power Wireless Personal Area Networks. This communication technology was developed by the Internet Engineering Task Force (IETF) in RFC 4944 to add IPv6 internet capability to IEEE 802.15.4 networks for ease of internet connectivity [120], [121]. Specifically, the IETF IPv6 working group was responsible for standardizing the 6LoWPAN as an IPv6 on LoWPAN. As a consequence, the LoWPAN sensor nodes have an in-built internet ability, hence, they can directly communicate with an IP-enabled system, and can be accessed from the internet directly without utilizing any gateway. This is unlike a ZigBee node that indirectly connects to IP-enabled systems through the help of a special gateway known as the 802.15.4/IP [110]. This is the key difference between the standard ZigBee solution and the 6LoWPAN solution. The 6LoWPAN solution provides a standard compression service by introducing a new adaption layer that converts sensor data in the IPv6 packet format to a LoWPAN-based packet format which carries a compression format header to make them fit for transmission on the low-rate and low-power links of the IEEE 802.15.4 networks (PHY and MAC layers) [122], [123]. The 6LoWPAN technology mostly employs user datagram protocol (UDP) as the traffic agent. It is worth mentioning that the battery life of 6LoWPAN sensor nodes is around a year (i.e. 365 days) [116]. The 6LoWPAN technology supports the 868 MHz, 915 MHz, and 2.4 GHz license-free ISM bands, and a maximum of 250 kb/s data transmission rate is supported by these bands over a typical distance of less than 100 m. 6LoWPAN technology may be employed in control (such as automatic light control), industrial and monitoring applications. 6LoWPAN is envisioned to have great potential for WSNs and IoT applications because of its low-power and low-cost capabilities. The 6LoWPAN technology achieves the transmission of its packets through the help of an Application Programming Interface (API) standard socket.

4) BLUETOOTH SOLUTION

Bluetooth technology was developed by the IEEE 802.15.1 Working Group in 1999. However, the Bluetooth Special Interest Group (SIG) Alliance [124] has presently taken over the maintenance of the technology. The group is equally responsible for defining and managing the technical specifications of Bluetooth technology. Bluetooth is a WPAN-based technology that was intentionally proposed to replace the usage of wires in mobile applications. It employs a Gaussian frequency shift keying (GFSK) scheme or a frequency-hopping spread-spectrum (FHSS) scheme at the PHY layer. Interestingly, the conventional Bluetooth technology has recently enjoyed widespread acceptance as a means for wireless connectivity in systems such as WSN solutions for WQM applications. This can be attributed to its cheap operational cost and high-rate features. This feature makes it a suitable candidate for WSN systems that specifically require a high data transmission rate. Bluetooth is a low-power wireless technology that is used for short range communications in WSNs and can cover a distance that is typically up to 100 m. It is an IP compliant wireless connectivity solution and supports the IEEE 802.15.1 communication standard [125]. Examples of network topologies that can be created with Bluetooth end-devices are star, and peer to peer (P2P). Unfortunately, this technology is limited by the number of devices that can be connected at a time, which are typically two. One of the devices is configured as a master, while the other is a slave. Bluetooth devices operate at the 2.4 GHz free-license ISM band, and can achieve a typical data rate transmission of 1 Mb/s on the band. Because of the high transmission rate of the conventional Bluetooth solution, it suffers from higher energy consumption as a drawback. Due to the high energy consumption of Bluetooth devices, which is typically more than the energy demand of its counterpart solutions such as ZigBee, a newer variant of the Bluetooth device known as the Bluetooth Low Energy (BLE) technology as defined by Bluetooth Version 4.0 [125], has recently been proposed to circumvent the energy consumption constraint of the conventional Bluetooth, and at a lower cost. The new BLE device supports both the GFSK and FHSS modulation schemes of the conventional Bluetooth solution, and also uses the same ISM frequency band. Also, the 802.15 group has proposed a new communication model named as Bluetooth Smart for defining new structures for the BLE devices, to ensure its efficient deployment, and to improve its communication coverage for WSNs. The new technology offers massive connections of BLE devices. For example, the technology allows about 5,917 BLE slave devices to be connected to one BLE master device [126]. As an example, the new BLE technology can provide a data rate of 1 Mb/s, covering a typical distance of 200 m. The energy consumption of BLE devices can be controlled by setting the communication cadence, which could be in the range of 7 – 32 ms, between the BLE devices configured as slave devices and a master device [126].

In the context of energy efficiency, the BLE solution provides energy efficient data communication through the exploitation of low energy chipsets, including the implementation of optimized maximum data transmission and reception energy strategy [127]. The new chipsets employed by the BLE solution and the optimized usable maximum power helps to achieve ultra-low energy consumption at various operation modes (such as receive, transmit and idle) compared to the classic Bluetooth solution. The BLE solution implements a simple protocol stack that provides low-complexity communication links which supports easy

TABLE 1. Summary of short range solutions.

Technology	Communication standard	Data latency	Data Rate	Coverage Range	Network type & topology	Carrier RF	Power requirement	Cost	Strength	Weakness
IEEE 802.15.4	IEEE 802.15.4	Low	Low 10 to 250 kb/s	Short Less than 100 m	WPAN Mesh, tree, star	868, 915, 2400 MHz	Very low	Low	Energy efficient	Lack support for long range communica tion; Low reliability
ZigBee	IEEE 802.15.4	Low	Low 20, 40, 250 kb/s	Short Above 100 m	WPAN Mesh, tree, star	868, 915, 2400 MHz	Very low	Low	Energy efficient	Limited by short range coverage; Low reliability
6LoWPAN	IEEE 802.15.4	Low	Low Less than 250 kb/s	Low Typically < 100 m	WPAN Star, mesh	868, 915, 2400 MHz	Very low	Low	Support internet capability	Not energy efficient, Short range limitation; Low reliability
Bluetooth	IEEE 802.15.1	Low	Low 1 Mb/s	Short 10 – 100 m	WPAN Scatternet, Star, P2P	2.4 GHz	Low	Low	High-rate, Cheap operationa l cost	Not energy efficient; Low reliability
Bluetooth Low Energy	IEEE 802.15.1	Low	Low 1 Mb/s	Short 10 – 200 m	WPAN Star, P2P	2.4 GHz	Very low	Low	Energy efficient	Limited by short range coverage; Low reliability

and rapid connections. This interesting development makes BLE radios to be energy efficient. The BLE technology also incorporates energy efficient energy saving schemes that include low and adaptive duty cycling techniques that sleeps the BLE sensors often and wakes them up at a scheduled time for necessary data communication. This strategy adopted by the BLE technology helps to save a significant amount of energy. Note that BLE sensors could be woken up within a few ms, while the classical Bluetooth solution requires a longer period in the ms range. To further minimize energy consumption, the duty cycle operation of the BLE transceiver, as well as the length of data that can be transmitted may be adapted [127].

Considering the features of the new BLE technology, it holds great potential for wireless connectivity in the next generations of WSNs and IoT applications for WQM systems, since the development of the BLE solution captures their needs in the context of energy demand for short range communications. The new BLE solution is also envisaged as a suitable technology for healthcare monitoring, wearables, and industrial application control systems.

Examples of works on WSN for WQM where the conventional Bluetooth technology have been employed are in [125], [128], and [129]. In these works, the conventional Bluetooth technology was used for data communication between the water quality sensors and a base station. For example, [128] developed a WSN-based system for detecting E.coli bacteria through a pre-conditioned microfluidic and impedance sensor. Consequently, the WSN solution transfers its measurements to a local smartphone-based base station using conventional Bluetooth technology.

Summary of WPAN Technologies: The summary of short range communication technologies is provided in Table 1. The solutions in the category of short range technologies typically span distances of ten to hundreds of meters. The coverage range of, for example, ZigBee networks can be extended by employing a multi-hop strategy for data networking, but unfortunately this strategy is not energy efficient. The summary of the short range solutions presented in Table 1 will help WSN designers to determine a suitable technology for WQM application deployment purpose, while taking important parameters that include energy dissipation, data rate, and communication coverage, into consideration. Since wireless devices and water quality nodes are often powered by batteries, examination of the aforementioned parameters is necessary for the realization of energy-efficient WSN systems for WQM applications. Other important considerations are cost and data latency.

C. SOLUTIONS BASED ON WIRELESS LAN SETUP

The wireless technology solutions in the category of wireless LAN (WLAN) are typically employed to achieve medium range data communication, with coverage of up to a few kilometers. This section reviews both legacy and new solutions for implementing a LAN setup.

1) IEEE 802.11 NETWORK: Wi-Fi SOLUTION

Wi-Fi is a WLAN-based technology, managed by the Wi-Fi Alliance, and defined in IEEE 802.11 standard specification [130]. Wi-Fi can be described as a high-rate wireless technology that is used for medium range communications in WSNs. It employ schemes that include offset QPSK (OQPSK), BPSK, and a multiple code DSSS (MC-DSSS) at the PHY layer. Wi-Fi solution dissipates more energy compared to other communication technologies such as Bluetooth and ZigBee. Wi-Fi devices can utilize either 5 GHz or

2.4 GHz of the free-license ISM bands for data transmissions at rates of 11 - 54 Mb/s, over a distance of about 200 m. Wi-Fi is an internet-based technology that could be employed as an internet solution by WSN systems for internet connectivity. It is important to emphasize that a Wi-Fi solution does not provide energy efficiency for the transmission of data among the sensors in a network, as well as the base station, because of its high energy dissipation characteristics. However, it may be employed as an internet access point for remote data transmissions at the base station, and it could also potentially be utilized at remote monitoring stations for internet connectivity. It is suitable for monitoring and control applications at homes and water stations to gain access to the internet.

Examples of works on WSN for WQ monitoring where Wi-Fi technology has been employed are in [38] and [53]. In the mentioned references, Wi-Fi technology was used for data communication between the base station and the sensors.

2) IEEE 802.11ah NETWORK: LOW-POWER Wi-Fi SOLUTION

The conventional Wi-Fi network was originally designed to meet the internet connectivity needs of high data transmission rate applications over short distances, without taking low-power devices (such as sensor nodes) into consideration. Examples of applications suitable for the conventional Wi-Fi solution include consumer electronics such as personal computers and home appliances. Consequently, Wi-Fi solution was not optimized to be employed in WSNs [131]. As a result, Wi-Fi solution is not a suitable candidate for low-power devices such as water quality sensors. This is one of the key reasons that orchestrated further enhancement in the IEEE 802.11 standard in order to develop an optimized solution for WSN applications [131]. With the advances in wireless communication technologies, the IEEE 802.11 network (Wi-Fi) was extended by the IEEE 802 working group to IEEE 802.11ah network [132], as an optimized solution for WSN applications. The IEEE 802.11ah is managed by Wi-Fi alliance. The IEEE 802.11ah solution employs an orthogonal-frequency-division-multiple-access (OFDMA) mechanism at the PHY layer. Also, new types of PHY layer schemes were proposed based on the desired data transmission rate, such as the 256 quadrature amplitude modulation (256 QAM), the 64 QAM, and the 16 QAM schemes for high transmission rate, or the QPSK and the BPSK for low transmission rates. The availability of several data rate options makes the IEEE 802.11ah wireless solution to attain energy efficiency and as well meet the various requirements of different applications. To further attain energy efficiency, the IEEE 802.11ah wireless solution implements an energy efficient grouping strategy. The strategy is aimed at reducing possible collision during channel access and data communications. This consequently helps to the energy of the network sensors.

The IEEE 802.11ah network serves as a representative of the IEEE 802.11 standards developed to target the need of low-power devices and WSN applications with an enhanced communication range capability. It also caters for the massive connection of sensor nodes [131]. Specifically, the IEEE 802.11ah is a low-power Wi-Fi solution, and is advantageous for creating IP-network capable built-in sensor nodes [131] conveniently, since the deployment is compatible with already available infrastructure of conventional Wi-Fi solutions. The energy consumption of low-power Wi-Fi is typically around hundreds of milliwatt, which is considered acceptable for water quality sensors. With the new low-power Wi-Fi solution, a data transmission rate of about 7.8 Mb/s can be realized by the IEEE 802.11ah devices over the sub-1 GHz free-license ISM spectrum [132]. The IEEE 802.11ah solution technically supports the sub-1 GHz spectrum to achieve energy efficiency since there is typically a low propagation loss when transmitting on a low frequency such as 915 MHz [133]. As a consequence, at a low transmission power, it is possible to achieve the required communication coverage since the 915 MHz spectrum is characterized by a minimal signal pathloss and this in turn results in longer communication coverage, thus, saving the energy cost of data communications. The IEEE 802.11ah solution further achieves energy efficiency through the incorporation of a new scheduling scheme for data transmission recently proposed by a research group known as the Task Group ah [134]. The scheme may also be referred to as a restriction-based window access mechanism.

It is important to mention that the devices in the IEEE 802.11ah can span a coverage range of about two hundred meters to a few kilometers. In an attempt to further improve on the energy consumption rate of the IEEE 802.11ah solution, the Wi-Fi working group has recently introduced Wi-Fi HaLow, which is low-power solution, into IEEE 802.11ah. This is the Wi-Fi solution that is envisaged as the low-power solution that promises to advance the field of monitoring water quality in the context of long communication coverage and low-power capabilities.

Summary of WLAN Technologies: The summary of the traditional Wi-Fi and the new Wi-Fi technologies are provided in Table 2.

It is noticed that the new Wi-Fi optimizes key parameters that makes it a reasonable wireless technology solution in WSNs for WQM applications. Such parameters are communication range, energy, data transmission rate, and efficiency (battery life). These are important design considerations to be critically examined since water quality sensors are traditionally operated by batteries, and for the realization of energy-efficient WSN solutions for WQM applications. Other important considerations are cost and data latency.

D. SOLUTIONS BASED ON WAN SETUP

This section reviews different categories of wireless technology solutions, including legacy and new technologies, for implementing a WAN setup.

Cellular Network Solutions: Cellular networks are mobile networks that could be used as an internet access point in wireless systems such as WSNs and mobile phones. Examples of communication technologies that fall into this

TABLE 2. Summary of medium range solutions.

Technology	Communication standard	Data latency	Data rate	Coverage Range	Network type & topology	Carrier RF	Power consumption	Cost	Strength	Weakness
Conventional Wi-Fi	IEEE 802.11	Low	High 11 to 54 Mb/s	Low 200 m	WLAN Star	2400 MHz, 5 GHz	High	Low	Support internet capability, High-rate	Not energy-efficient, Short coverage limitation; Low reliability
New Wi-Fi	IEEE 802.11ah	Low	Low >150 kb/s, <7.8 Mb/s	Long 1 km	WLAN Cluster tree, mesh, star	ISM Sub 1 GHz	Low	Low	Energy efficient, High-rate	Short range issue; Low reliability

category are 2G, 3G, and 4G. The aforementioned communication technologies represent the generations of cellular networks. These generations can be attributed to the developments in mobile telecommunications in the perspective of data transmission speed. For instance, with a new generation, a better data transmission speed is provided. Thus, it is important to note that the key difference that lies between the cellular network evolutions is data transmission speed. A quick overview of the above-mentioned cellular networks is given as follows.

1) 2G NETWORKS

2G represents the second generation of the mobile cellular networks and is defined in the Global System for Mobile Communications (GSM) standard of 1991. The network operates globally in the licensed cellular network bands of 900 MHz and 1800 MHz, while it operates at 1900 MHz in American alone data [135]. 2G GSM networks employ the frequency division multiple access (FDMA) as a communication protocol to carry data such as voice call over the licensed cellular network bands. In an attempt to improve on the capacity of the 2G GSM network, two key protocols were introduced. The protocols are the time-division-multiple-access (TDMA) and the code-division-multiple-access (CDMA). The TDMA protocol is used in 2G networks to divide the frequency bandwidth available in the 900 MHz band, which is 25 MHz, into eight possible time-slots. The essence of the frequency division into time-slots is to allow multiple users to communicate on the frequency concurrently. For example, with the created time-slots on the same frequency, eight voice calls is possible at the same time. On the other hand, the CDMA protocol is used to identify caller, improve messaging and voice call QoS requirements, and enhance the wireless connection of the user's access to the network airwaves [136]. It is important to mention that the 2G GSM network was specifically designed for voice call services, and it works as a circuit switched system [135]. Therefore, it is not efficient for applications that demands fast data transmission such as multimedia. As a result, it is commonly used for fax, voice and messaging applications at a data rate of 2.4 kb/s to 9.6 kb/s. To circumvent the problem of slow transmission in 2G GSM networks when used for messaging purposes, a new communication standard known as General Packet Radio System (GPRS) was incorporated to 2G to achieve an improved data transmission speed capability. With the integration of the GPRS standard to 2G, a new cellular network is formed and the network is known as 2.5G or 2G GPRS. Consequently, for 2G technology to support GPRS standard, there is a need for transitioning the 2G GSM network to a packet switching system, since the switching circuit system does not have the capability for packet data [136]. The GPRS is efficient for data transmission and can provide a data rate of 114 kb/s. With the 2G GPRS network, the number of short message service (SMS) messages that can be transmitted within a minute is increased. The GPRS network is an IP compliant system [136]. With the incorporation of GPRS to 2G network, the network provides a suitable platform for services that include multimedia messaging service (MMS), wireless application protocol (WAP), and point-to-point (P2P) protocol. The data transmission speed of the 2G GPRS network was further improved by extending the GPRS to the enhanced data rates for global evolution (EDGE). With the 2G EDGE network, the data rate of the network is increased to about 384 kb/s. The EDGE technology, which is defined in the 3GPP standard, is also recognized as a member of the 3G network having met the specifications highlighted by the ITU.

Examples of works on WSN solutions for WQM applications that combined 2G networks are in [33]–[36], [38]–[40], [119], and [137]–[139]. In the identified references, 2G technology was used for delivering WQM application data to remote water monitoring centers, which are far away from the local water site.

2) 3G NETWORKS

3G stands for the third generation of the mobile network.3G technology was designed based on the telecommunication standards defined by the International Telecommunication Union (ITU) and it was officially named by the ITU as IMT-2000 [135]. The essence of this technology is to provide services that one could also achieve by the internet technology under the initiative of a personal wireless internet access (PWIA). This became necessary as the internet technology has been overcrowded by huge numbers of mobile and wireless devices across the globe. Since the internet has been bombarded by many devices, communications over the internet has been negatively impacted. One of the key objectives of 3G networks was to provide the network users with global wireless access to telecommunication network infrastructure by using both satellite and terrestrial systems. This objective helps to harmonize a global interoperability among several network operators to ensure reduced cost. As a result, the ITU recommended different requirements in the context of data transmission speed for various users under the universal mobile telecommunications system (UMTS) standard in 2001. For example, under the 3G UMTS network, a data rate of 144 kb/s, 384 kb/s and 2 Mb/s is proposed for a user in motion, a pedestrian user, and a fixed user respectively. 3G networks employ a wideband code division multiple access (WCDMA) communication protocol to carry data over the licensed cellular network bands in the range of 850 MHz and 1900 MHz, and to also ensure that the maximum data transmission speed is achieved. From WSNs perspective, the proposed requirement for a fixed user indicates that WSN applications can achieve a data rate of about 2 Mb/s for remote data transmissions. Consequently, 3G UMTS networks has been a central tool for ubiquitous computing which specifically means computing anywhere and anytime. With the advent of a high speed access (HSPA) standard in 3G, the data transmission speed of the network was increased. This makes it possible for high data rate applications on wireless devices in the 3G HSPA network. The HSPA was later upgraded to HSPA+ in 2008, to further increase the data transfer speed of the 3G HSPA network. The 3G HSPA+ network is often referred to as a 3.5G network. The third generation partnership project (3GPP) is an important standard in 3G.

Examples of works on WSN for WQ monitoring where a 3G network has been employed are in [36], [119], [140], and [141]. In the identified references, 3G technology was used for delivering WQM application data to remote water monitoring centers, which are far away from the local water site.

3) 4G NETWORKS

4G technology was designed based on the International Mobile Telecommunications (IMT) Advanced standards defined by the ITU. Different from 2G and 3G technologies, 4G technology is designed to provide a much better data transmission speed. 4G technology has been defined in two key standards, namely Long Term Evolution (LTE) and worldwide interoperability for microwave access (WiMAX). LTE provides a data rate of about 100 Mb/s, while WiMAX has a data rate of 50 Mb/s. This has given birth to a 4G LTE network and a 4G WiMAX network, even though the networks are mostly branded as 4G by the cellular network service providers. In recent times, new variants of the LTE and the WiMAX standards have been proposed as LTE Advanced and WiMAX 2, and incorporated to the 4G networks accordingly.

An example of a WSN solution for WQM application that employed 4G network can be found in [142]. In the mentioned reference, the 4G network was used for delivering WQM application data to remote water monitoring centers, which are far away from the local water site.

Summary of Cellular Networks: The cellular networks discussed in this work may be used for long range communication purposes in WSN applications. Similarly, since they operate as a mobile internet provider, they can be employed to provide internet connection to WSN systems for WQM application data delivery. The summary of the reviewed cellular network solutions are presented in Table 3. However, they are not suitable for WSN solutions dedicated to the monitoring of water quality because of their low energy efficiency. WSN solutions in WQM applications are energy constrained systems that require low-power and long-range communication solutions. From a technical perspective, cellular network solutions are not optimized for utilization in WSN systems. For example, the battery life of cellular network devices is days to a few months, whereas, WSN solutions for WQM applications require little to no human intervention, since they may be deployed in critical places. Other important considerations are cost and data latency. It is worth noting that cellular networks have high data latency.

E. SOLUTIONS BASED ON HIGH POWER WAN TECHNOLOGY

1) SATELLITE TECHNOLOGY

Satellite technology is a useful communication technology for implementing a high transmission rate remote-based WSN solution for WQM applications. For example, satellite technology was employed in [143] as part of the architecture for the proposed WSN solution for the WQM application. The application of satellite technology is not limited to only WSN systems, as it is also employed in fields like television (TV) broadcasting, and providing communication services for aircrafts and ships. In many cases, satellite technology is considered a candidate of choice in locations where there is a lack of telecommunication systems (such as WiMAX and LTE/3G/2G) and terrestrial infrastructure, or to circumvent the shortcomings of terrestrial technology that include complex propagation [144]. Examples of such locations where satellite technology are mostly employed include large open seas, forests, and islands [145]. As an example, the adoption of satellite technology for sea water quality may be a reasonable communication solution to establish data communication [146], [147]. Using satellite technology, two types of communication architectures can be employed, such architectures are indirect and direct communication.

In the indirect communication architecture, the sensor nodes are connected to a satellite through gateways, consequently, the sensor nodes in an indirect satellite-based architecture gain access to the satellite via the employed gateways. Basically, there are two categories of gateways in an indirect satellite-based architecture, namely fixed gateways and mobile gateways. The fixed gateways are installed on ground stations, while the mobile gateways can be realized through the adoption of ships and unmanned aerial vehicles. In both cases, the water quality sensors, which may employ ZigBee radio, are mostly connected in a multi-hop

TABLE 3. Summary of cellular network solutions.

Wireless radio	Standard	Data latency	Data rate		Coverage Range	Network type & topology	Carrier Frequency	Power consumption	Cost	Strength	Weakness
2G	TDMA	High	9.6	kb/s	Long (for example 30 km)	WAN Cellular system, mesh	Licensed Cellular network bands such as 850 MHz to 1900 MHz	Low	High	Long range coverage; Reliable	Hardware outage issues; Lack support for energy efficiency; Costly
	GSM		9.6					High	Low		
	CDMA		14.4								
	GPRS		115								
	EDGE		384								
3G	W-CDMA / UTMS	High	Mobile user: 144; Pedestrian user: 384;	kb/s	Long			High	Low	Long distance coverage; Reliable	Low energy efficiency; Hardware outage issues; Costly
			Fixed user: 2	Mb/s							
4G	LTE	High	100	Mb/s	Long			High	Low	Long communication coverage; Reliable	Low energy efficiency; Costly; Hardware outage issues
	WiMAX		50	Mb/s							

pattern to a sink node (or a gateway) that is responsible for gathering the measurements of the sensors in each cluster. In practice, no less than two-hops is required. The gateway is responsible for forwarding the aggregated data through some of the existing satellite communication technologies such as OrbComm [148], Iridium [149], O3b satellite [148], the digital video broadcasting S2 [150], [151], to the satellite in the space. The architecture of an indirect satellite-based WSN solution for WQM applications using a fixed type of gateway and a mobile type of gateway are presented in Figs. 9 (a) and (b).

In direct communication architecture, the water quality sensor nodes are configured with satellite radios and are directly connected to a satellite over some of the aforementioned satellite-based communication technologies. The sensor nodes in the direct communication architecture can be deployed in two ways in practice, namely mobile deployment and specified deployment. In the former, the sensors may be connected to mobile objects that include aircrafts and ships, while the latter requires the placement of sensor nodes at specified locations. The direct connection of a WSN solution for WQM application to the satellite is described in Fig. 10.

A satellite technology solution supports different types of MAC modulation mechanisms for various satellite communication architectures. Examples of such mechanisms are the conventional-based slotted ALOHA [152], the enhanced spread spectrum ALOHA [153], the slotted ALOHA based on conventional resolution diversity [154], and the ALOHA based on multiple coded slots [155]. It is worth mentioning that the frequencies in the Ka-band (26 – 40 GHz) and S-band (2 – 4 GHz) are employed for data communication, unlike other wireless technology solutions that utilize either the ISM license free spectrum or the licensed cellular network spectrum. Satellite technology may only find more suitability in WSN solutions that employ high-technology-based sensor

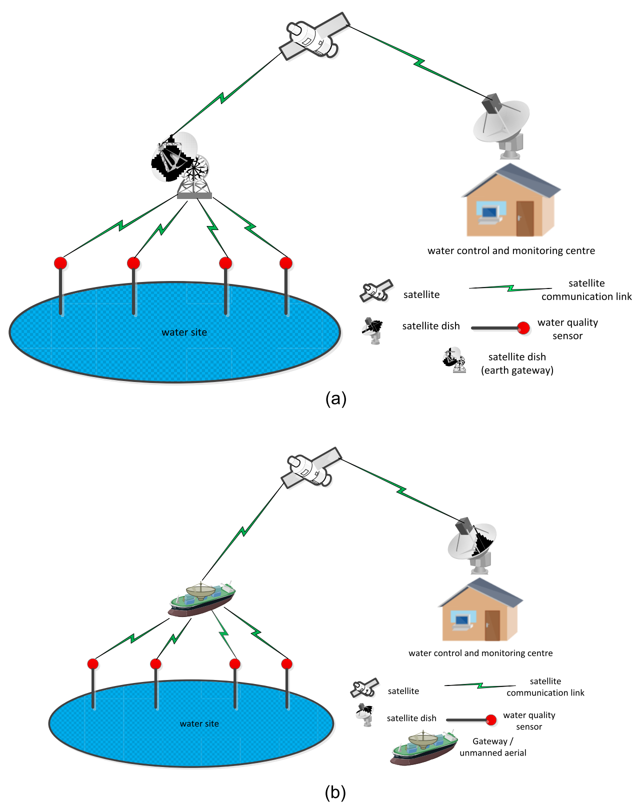

FIGURE 9. Architecture of an indirect satellite-based WSN solution for WQM applications. (a) An indirect connection based on a fixed gateway. (b) An indirect connection based on a mobile gateway.

nodes for real-time data transmission of image and video recording in applications that include disaster monitoring.

2) WiMAX

WiMAX is a high-speed (or data rate) communication technology that is based on wireless broadband technology.

TABLE 4. Summary of high power WAN technologies.

Technology	Communication Standard	Data latency	Data rate	Coverage Range	Network type & topology	Carrier Frequency	Power consumption	Cost	Strength	Weakness
Satellite	OrbComm; Iridium; O3b satellite	High	High About 50 Mb/s	Long Typically less than 6000 km	WAN Tree, star	High frequencies (Ka bands); Low frequencies (S bands)	High	High	Suitable for long communica tion coverage	Not energy efficient; Expensive
WiMAX	IEEE 802.16	High	High Up to 80 Mb/s	High Up to 50 km	WMAN Mesh	2000 MHz to 11 GHz; 10 GHz to 60 GHz	High	High	Long range data communica tion; Reliable	Lack support for energy efficiency; Expensive

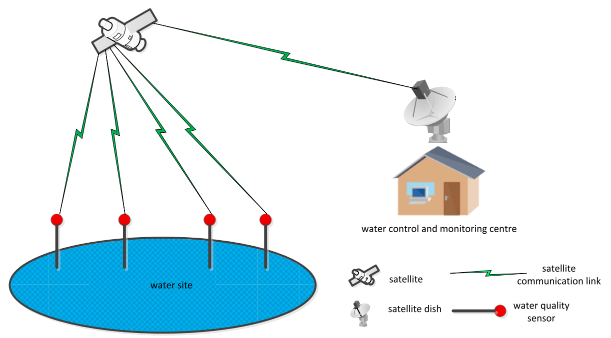

FIGURE 10. Architecture of a direct satellite-based WSN solution for WQM applications.

WiMAX communication technology is defined according to IEEE standard 802.16, and is compliant with the 3GPP specification. Based on IEEE 802.16, WiMAX is suitable for fixed devices. To make WiMAX suitable for mobile devices, a new IEEE standard is defined as 802.16e, to allow them to be connected to the internet. In practice, the technology is employed as a substitute to the DSL and wired technology to provide wireless internet access to wireless applications [156], and is compatible with the networks of various radio access models to ensure its compliance with IP networks. WiMAX transmission rate can go as high as 80 Mb/s, and it can cover a distance of 50 km [157]. Two types of license plans and propagation requirements are possible in WiMAX technology. The two types of possible license plans are free-license plan and paid license plan. The free-license plan is suitable for non-line-of-sight propagation (NLOSP), while the paid license is suitable for line-of-sight propagation (LOSP). With the free-license plans, WiMAX operate within the frequency bands of 2 - 11 GHz of the ISM to provide internet connection to sensor nodes. Information transmission in this category can reach 50 km. With the licensed plan, WiMAX technology operates in the range of 10 – 60 GHz. It is worth clarifying that WiMAX services are mostly provided by network service providers.

Examples of a WSN solution for WQM applications based on WiMAX technology can be found in [158]. In the work, WiMAX technology was used for delivering WQM application data to remote water monitoring centers, which are far away from the local water site.

Summary of High Power WAN: Satellite and WiMAX are good examples of high transmission rate and long range technologies that may be employed in WSN solutions for WQM applications. However, both solutions are characterized by extremely high energy use because of their high transmission rate property as they consume more power during water quality data transmission to remote water monitoring centers. Even though they can be utilized to meet the long range communication requirement of WSN solutions for WQM applications, their power consumption rate makes them unfit to realize the goals of modern WSN systems dedicated to WQM applications as the system's water quality sensors operate on batteries and are expected to operate at least for a reasonable numbers of years. Secondly, the water quality sensors in the WSN solutions for WQM applications are not designed to be interfaced with high transmission rate communication technologies, which draw more power. Since energy efficiency requirement is of top priority in WSN solutions for WQM applications, then it will be reasonable to explore other efficient solutions. Other notable considerations are data latency and cost. Both the satellite and WiMAX have high data latency. In Table 4, the summary of the reviewed high power WAN technologies are presented.

F. SOLUTIONS BASED ON LOW POWER AND WIDE AREA NETWORK VARIANTS

The wireless network solutions in the category of low power and wide area networks (LPWAN) are envisaged to address the need for long range communication and low power requirements of modern WSN systems because of the traditional powering nature of the water quality sensors in such networks, which is battery power. The LPWAN solutions attain energy efficiency by adopting strategies that include novel modulation schemes (such as ultra-narrowband and spread spectrum) and duty cycling techniques. One of the key advantages of the ultra-narrowband (UNB) scheme is the provision of a low-power transmission and a low receive signal demodulation power of about −142 dBm [159]. The variants of the spread spectrum modulation scheme include the chirp spread spectrum (CSS) and the DSSS [28]. The UNB, CSS, and the DSSS are the available choices of the PHY layer modulation schemes which are employed by different LPWAN solutions at their PHY layers. The duty cycling technique is employed for switching the energy hungry communication radio (or RF transceiver) of water quality sensors, in an opportunistic manner [48], [160], [161]. This allows the RF transceiver radio of a sensor node to be duty cycled such that a sensor node can switch off its transceiver radio when it is not in use to save the battery power.

The LPWAN solutions offer a novel paradigm in data networking. The solutions are suitable for reliable data delivery at low-power rates [48], and promises to offer what the traditional networks lack (such as low-power and long communicate range). With LPWAN networks, water quality sensors can be linked to the internet by using a proprietary-based technology solution [162], as in LoRa [163] and Sigfox [44], for example, or a cellular-based technology solution (such as NB-IoT). The aforementioned two categories of wireless network solutions are discussed in the following subsection.

Proprietary Technology: The wireless technologies in this category are designed for LPWAN and are commercial solutions that are based on proprietary infrastructures such as gateways. As a consequence, the technologies in this category employ proprietary gateways to connect water quality sensors' data to the internet (or network server). The solutions include LoRa, Sigfox, and INGENU networks. The proprietary-based wireless technologies are discussed as follows.

1) LoRa SOLUTION

LoRa is a LPWAN based wireless technology and is managed by the LoRa Alliance. LoRa can be described as a low-power wireless technology that is used for long range communications in WSN systems. Its standard supports the IEEE 802.15.4 communication standard. LoRa technology does not require line-of-sight and this property makes it a suitable candidate for both rural and urban locations. LoRa technology is established on a technology known as LoRaWAN, which is based on the pure ALOHA scheme [164]. LoRa uses a proprietary LoRaWAN modulation scheme which is a CSS solution or a GFSK scheme for DL communication at the PHY layer [165], to perform signal modulation on the Sub 1 GHz free-license ISM RF bands such as 915 MHz and 868 MHz. Pure ALOHA scheme is used at the media access control (MAC) layer for UL communication [164]. The ALOHA MAC scheme offers asynchronous random access to the LoRa sensor nodes in an orthogonal manner to schedule the data transfer process of each of the sensor nodes. The ALOHA MAC scheme is considered as an optimal scheme to circumvent the hardware complexity and design cost issues associated with most of the schemes employed in short range and cellular network solutions, to make the radio transceiver of sensor nodes energy efficient, cheap and simple [48]. LoRa offers different modes of operations such as Classes A, B, and C, to further attain energy efficiency. The various modes provide different levels of data rate, energy consumption and latency. As a consequence, an adaptive mechanism may be employed to enhance energy efficiency, for example the data rate can be adapted to optimize the utilization of energy resources. It is worth mentioning that a typical LoRa network spans a transmission range of about 5 km and 15 km in urban and rural locations respectively, and it can provide a typical transmission rate of 50 kb/s [166]–[168].

In the context of LoRa architecture, a LoRa gateway is needed [169]. LoRa supports the Third Generation Partnership Project (3GPP) specification to enable IPv6 connectivity on LoRa LPWA networks.

An example of a possible network topology that can be created with LoRa devices, which include sensor nodes, is star-to-star such that each sensor node in the network is connected directly to the gateway of the LoRa network in a single-hop fashion. In WQM perspective, the structure of a LoRa network will include a LoRa gateway, LoRa sensor nodes, LoRa server, and a LoRa remote device (such as a computer terminal). For the purpose of clarity, it is worth mentioning that LoRa-based water quality sensors are realized by buying an off-the-self LoRa module and embed it into the communication unit of a water quality sensor node to provide LoRa communications. The LoRa-based water quality sensors are used for monitoring the quality of water and disseminate their water quality data to the LoRa gateway using the pure ALOHA protocol. The LoRa gateway helps to gather the individual signals of the LoRa-based water quality sensors in a LoRa network and provides an internet backhaul role. The LoRa server performs the role of network management to the LoRa network server. The LoRa remote device is responsible for processing the acquired water quality data by the LoRa-based water quality sensors, and also carries out data analysis.

2) SIGFOX SOLUTION

Sigfox is a LPWAN based technology and is managed as a proprietary network. Sigfox can be described as a low-power wireless technology that can be employed to realize end-to-end long range communications in WSN applications [44]. Its standard supports the IEEE 802.15.4 communication standard. Sigfox employs an UNB scheme at the PHY layer. Because of the shortcomings of the commonly used MAC schemes, Sigfox resorted at using the ALOHA scheme, which provides a random communication channel access service at the MAC layer [48]. Similarly, a random FDMA (RFDMA) scheme may also be employed at a Sigfox network MAC layer [170]. Sigfox technology is suitable for transmission of small amounts of information in a line-of-sight fashion over the Sub 1 GHz free-license ISM RF such 868 and 915 MHz. Sigfox devices can transmit at a low data rate of 100 b/s over the bands and can cover a typical range of 10 km and 50 km in urban and rural settings respectively [168]. The possible coverage range is an indication that Sigfox technology prospers well in rural areas where there are fewer obstacles compared to the case of urban settings. Sigfox supports the Third Generation Partnership Project (3GPP) specification to enable IPv6 connectivity on Sigfox LPWA networks. In the context of a Sigfox structure, the provision of a gateway is required and determined by a network service provider. In the perspective of WQM application, the structure of a Sigfox network will take elements that include Sigfox sensor nodes, privately-owned base stations that incorporates cognitive software defined radios, and IP-based backend servers, into consideration. The base stations are connected to backend servers, which are based on IP networks. For clarity sake, Sigfox water quality sensors can be realized incorporating a commercial solution of the Sigfox into the communication unit of a water quality sensor node to provide Sigfox communications.

3) INGENU SOLUTION

This communication technology solution is based on a new communication protocol known as random phase multiple access (RPMA), which was developed by INGENU [171]. In INGENU, a two-way communication, namely uplink (UL) and downlink (DL) are possible in a half-duplex manner, based on a DSSS and a CDMA schemes, respectively, on the 2.4 GHz ISM license-free band.

In the DL communication phase, the base stations in an INGENU network employ a CDMA scheme at the PHY layer to synchronize the frequency and time among the base stations (sink nodes or access points) and the nodes (such as sensors) that are connected to the base station in order to transfer a continuous signal to the connected sensor nodes [172].

In the UL communication phase, INGENU employs a DSSS based RPMA modulation scheme at the MAC layer to carry out various demodulations of the communication links from the sensor nodes to the base stations in a concurrent manner, using a random delay strategy [173]. The DSSS can be described as a variant of the CDMA scheme that permits the sharing of a single communication channel (or time-slot) among several sensor nodes in the UL phase. To achieve the realization of sharing a single channel among various sensor nodes, the DSSS apply a delay strategy to the sensor nodes that occupies the same channel, in a random off-set manner, to reduce the occurrence of any possible over-lapping among the sensor nodes [174]. This technically means that the transmission of signals by the sensor nodes is randomly delayed. Based on this strategy, the DSSS increases the ratio of the signal-to-noise interference in the communication link of each of the sensor nodes.

Specifically, this solution was developed to target long range communication in low-power applications that include WSN and IoT. INGENU technology can be described as a proprietary solution and is flexible compared to other LPWAN communication solutions in the context of the utilization of a frequency band [175]. As a consequence, wireless networks that employ this technology enjoy autonomy as per the allowable data transmission rate over the used spectrum, for example 2.4 GHz, compared to its counterpart solutions. The INGENU network, which is based on RPMA mechanism, has a receiver sensitivity of −142 dB and the capability to withstand interference, due to the overcrowded nature of the 2.4 GHz band [172].

Low Power Cellular-Based Technology: This section briefly examines an example of a new relevant wireless networking solution that can be employed in WSN solutions for WQM application data delivery. The wireless technology in this category is based on cellular-based infrastructures (such as 4G/3G/2G). Consequently, unlike other technologies that employ proprietary infrastructures (i.e. gateways) to connect water quality sensors' data to the internet, the cellular-based technology solution eliminates the usage of gateways and connects water quality sensors' data directly to the internet. As a result of the direct connection to the internet in this category, the NB-IoT solution is envisaged to be cheaper compared to its contemporary technologies such as LoRa, Sigfox, and INGENU. An example of a communication network in the category of cellular-based technology that is promising for WSN systems in WQM applications is NB-IoT. Other available solutions in the category of cellular based technology suffer from high power dissipation due to their high data rates, for example is the new LTE-M (or Cat-M1) network.

4) NARROWBAND IoT

Narrowband (NB) IoT is a LPWAN cellular network based technology that was proposed by the Third Generation Partnership Project (3GPP) Release-13, as a new promising solution for long range and low-power communication in future WSN and IoT applications. NB-IoT was designed to overcome the shortcomings of the legacy cellular network solutions which were not originally designed to suit WSN applications [176], [177]. One of the key reasons of the NB-IoT technology is to extend the coverage range of low-power end-devices (such as sensor nodes) communication over larger areas. The NB-IoT solution can also be referred to as Cat-NB1, which is a variant of the Long Term Evolution in M1 category (LTE M1). The NB-IoT was designed and optimized to support the cellular network bands and co-exist with the legacy conventional cellular network technologies, at 180 kHz minimum system bandwidth requirement. As a consequence, it is achievable to deploy a carrier of an NB-IoT system into possibly a GPRS or GSM network by a legacy network operator (such as GPRS or GSM operator), by just dedicating one of their (GPRS or GSM network) physical resource blocks (PRBs) to NB-IoT system bandwidth of at least 180 kHz. This minimum system bandwidth represents one PRB in the transmission of LTE.

NB-IoT networks are mostly operated by cellular network operators. NB-IoT is suitable for the transmission of small amounts of information over the free-license ISM bands (non-cellular network spectrum) and the licensed cellular network bands. NB-IoT devices can transmit at a low data rate of 250 kb/s within a coverage range of about 25 km depending on the environment. NB-IoT is a low-power wireless

TABLE 5. Summary of LPWAN wireless technology variants.

Technology	Communication Standard	Data latency	Data rate	Coverage Range	Network type & topology	Carrier Frequency	Power consumption	Cost	Strength	Weakness
LoRa	Proprietary protocol LoRaWAN R1.0	Low	Low 50 kb/s	Long Urban: 5 km, Rural: 15 km	LPWAN Star	ISM Sub 1 GHz	Very low	Low	High energy efficiency; Long-range coverage; Low operational cost; No need for SIM card and maintenance cost	Low reliability;
Sigfox	Proprietary protocol	Low	Low 100 b/s	Long Urban: 10 km Rural: 50 km	LPWAN Star	ISM Sub 1 GHz	Very low	Low	High energy efficiency; Long-range communication; Low operational cost; No need for SIM card and maintenance cost	Low reliability
INGENU	Proprietary protocol	Low	20 kb/s	Long Urban: 3 km Rural: 15 km	LPWAN Tree, star	2400 MHz	Very low	Low	Energy efficient; Long-range data communication; Low operational cost; No need for SIM card	Low reliability
NB-IoT	GSM, GPRS, LTE	Low	Low 250 kb/s	Long Urban:8 km, Rural: 25 km	LPWAN Star	Licensed cellular network spectrum & unlicensed spectrum	Very low	Low	Energy efficient; High reliability; Long communication coverage	High operational cost; Requires SIM card and maintenance cost

technology that can be employed for long range communications in IoT and WSN applications.

In the context of energy efficiency, NB-IoT attains energy efficiency through energy saving mechanisms that include a prolonged discontinuous data reception, an internal interrupt enabled duty cycling strategy, and modulation schemes [178], [179]. As an example, NB-IoT uses a single carrier FDMA (SC-FDMA) modulation scheme at the MAC layer for UL communication, while an OFDMA scheme is employed at the PHY layer for DL communication, as in the LTE [178]. The schemes employed are capable of handling efficient allocation of radio resources [48]. In the perspective of WQM application, it is worth mentioning that the NB-IoT structure will include four key elements, namely NB-IoT water quality sensor nodes, base stations of cellular networks, an internet cloud platform, and WQM application servers. The NB-IoT water quality sensor nodes are built by adding the commercial solution of an NB-IoT module to the communication unit of a water quality sensor. The module is further connected to core elements necessary to provide an NB-IoT communication in an NB-IoT network. Such elements are an antenna and a SIM card.

Summary of Low Power WAN Variants: Without any iota of doubt, it is clear that the new wireless network solutions are capable of playing crucial roles in WQM applications, specifically in the areas of energy efficiency, long communication range, and a reliable delivery of WQM application data to remote water control and monitoring centers in a timely manner. It is worth mentioning that the battery life of the sensor nodes of LPWAN solutions is around years. For example, the battery of Sigfox and INGENU sensor nodes is approximately around ten years, while LoRa and NB-IoT sensor nodes' battery life is more than ten years [179]. These are good energy consumption figures that indicate how promising the LPWAN solutions are. The comparison of the reviewed LPWAN solutions is provided in Table 5. Other important considerations are cost and data latency.

In summary, based on the review presented by this work, the choice of a communication technology depends on factors that include cost, installation simplicity, reliability, and bandwidth requirements (or data rate) for a required QoS guarantee. For efficient WQ monitoring, it is important to note that a reliable communication technology is required. Communication technologies such as IEEE 802.15.4, Wi-Fi, and ZigBee are mostly employed to transfer the measured WQ data to a local monitoring station, while 3G, 4G, and GPRS technologies are good examples of wireless communication connectivity for sending WQ measurements to remote WQ monitoring centers from a local monitoring station. The collected WQ data by the local monitoring station can be used for the analysis of the local data, while the WQ data obtained by the remote monitoring WQ center is used for remote data analysis. The provision for the remote monitoring of WQ is crucial as it facilitates a proactive and a quick response to any changes in WQ due to contaminations. Among the communication technologies that were reviewed in this work,

TABLE 6. Comparison with the existing surveys with respect to traditional and new long range wireless technologies.

References	LPWAN solutions				Low-power Wi-Fi	Legacy
	Proprietary-based solution			Cellular-based		
	LoRa	Sigfox	INGENU	NB-IoT	IEEE 802.11ah	ZigBee, Cellular networks, Bluetooth, WiFi
Pule *et al.* [22]	Yes	Yes	No	No	No	Yes
Rahim *et al.* [52]	No	No	No	No	No	Yes
Adu-Manu *et al.* [23]	No	No	No	No	No	Yes
Geetha and Gouthami [53]	Yes	No	No	No	No	Yes
Y. Chen and D. Han [43]	Yes	No	No	Yes	No	Yes
Proposed	Yes	Yes	Yes	Yes	Yes	Yes

the variants of LPWAN solutions such as LoRa, INGENU, NB-IoT, and Sigfox, are promising technologies for long range water quality data communications as they have longer coverages and consume less power. These technologies have not been harnessed by the WSN research community in WQM.

V. COMPARISON OF EXISTING AND PROPOSED WSN SOLUTIONS FOR WQM APPLICATION VIS-À-VIS LPWAN AND IEEE 802.11ah CONSIDERATION

A. COMPARISON OF COMMUNICATION NETWORKS

The consideration of communication technologies for providing wireless connectivity requires two key factors. One is the energy efficiency of the solution technology in connection to the lifetime of the batteries in the sensors, and the second factor is the communication range of the wireless technology. Unfortunately, the existing solutions for wireless communication technologies in WQM applications are currently confronted by two key issues, namely the short range communication capability, as well as the high power consumption issue.

The commonly engaged legacy wireless technologies in water quality applications for delivering the data are ZigBee, IEEE 802.15.4, Wi-Fi, 4G, 3G, and GPRS solutions. The identified issues are barriers to the realization of modern WSN solutions for WQM applications in the context of energy efficiency and long range communication. To address the aforementioned issues, which have been lingering for years, this survey explores new promising LPWAN communication technologies that may be employed in WQM applications. Also, this survey is compared with the state-of-the-art surveys on WSN solutions for WQM applications with respect to the new long range wireless technologies, as shown in Table 6.

From Table 6, it is clear that the existing surveys on WSN for WQM applications have not fully explored the promising opportunities of LPWAN solutions or the low-power Wi-Fi solution. These issues are not considered in [22]. Apart from a brief survey of the LPWAN solutions in [22], there is no other work on WSN solutions for WQM that demonstrates LPWAN solutions' suitability in WSN-based systems for WQM applications. There is more to consider for the new solutions (LPWAN and low-power Wi-Fi) in terms of architecture, suitability, and network deployment.

B. ARCHITECTURE DESIGN AND NETWORK DEPLOYMENT OF WSN IN WQM USING LPWAN AND IEEE 802.11ah TECHNOLOGIES

This section presents the architectural design and network deployment of WSN solutions for WQM applications using LPWAN variants (proprietary-based and cellular-based) and IEEE 802.11ah solutions for the realization of a reliable delivery of water quality data to remote water stations over long distances at a low-power rate as shown in Fig. 11. The reason for considering the solutions is because they serve as the representative network solution for long range and low-power communication.

Fig. 11 shows how an LPWAN network can be designed to achieve long range and low-power communication in modern WSN solutions for WQM applications. As depicted in Fig. 11, the proprietary-based LPWAN solution is connected to an internet cloud through a gateway since the solutions in the category does not define schemes for the higher levels, they only cater for only the MAC and PHY layers. As a result, the proprietary-based solutions cannot be directly connected to the internet, except through a gateway.

For the cellular-based solution described in Fig. 11, it is based on the utilization of the NB-IoT solution, and the NB-IoT water quality sensors are connected to the base stations of cellular networks. Consequently, they are connected to the internet cloud via a cellular system's network core. It is clear from the architecture in Fig. 11 that the NB-IoT wireless network circumvents the need for gateways, compared to the proprietary-based solutions.

Also, the IEEE 802.11ah architecture presented in Fig. 11 can be employed to realize long range and low-power communication in modern WSN solutions for WQM applications in two manners, namely through a direct internet connectivity strategy or through an indirect strategy. The direct strategy can be realized through the adoption of an Ethernet solution, while the indirect strategy goes through a cellular gateway.

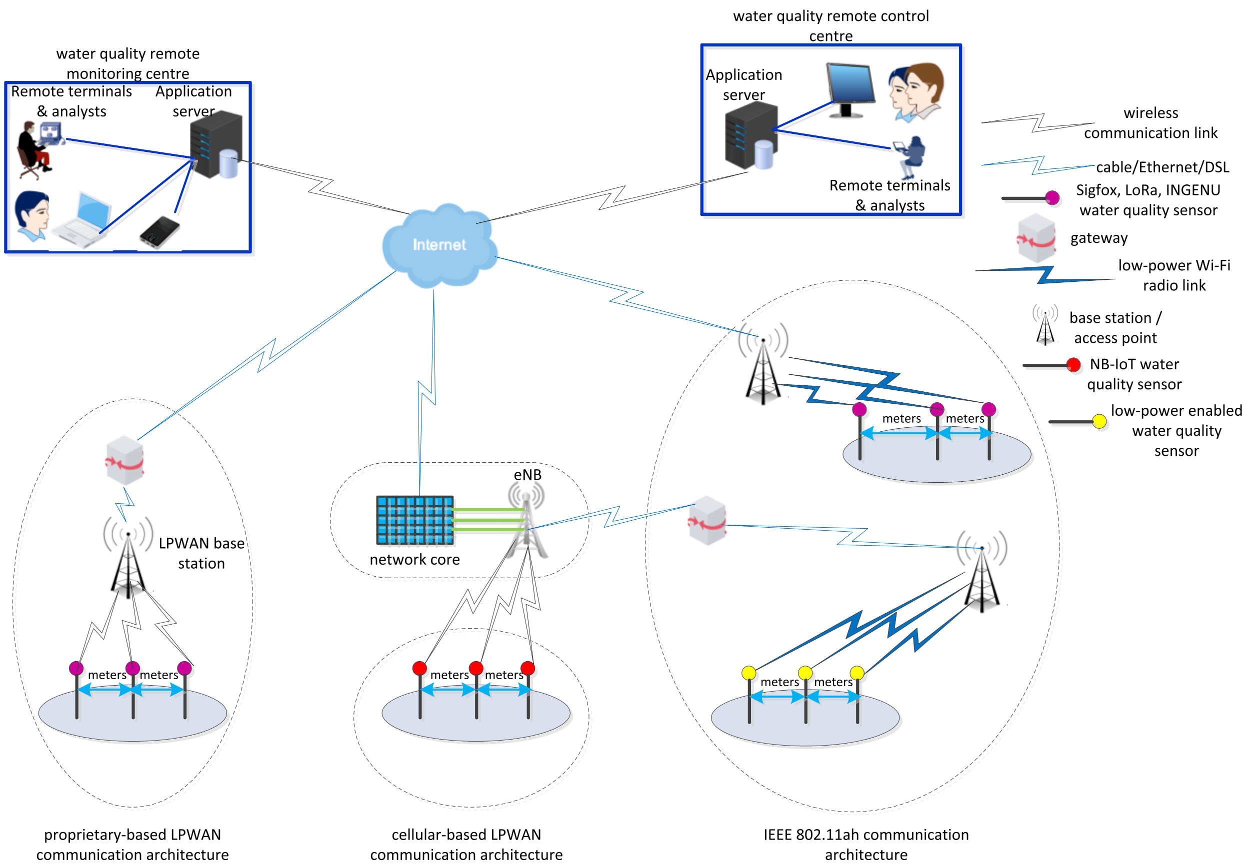

FIGURE 11. **Proposed architecture of a modern WSN-based solution for WQM applications using LPWAN solutions and IEEE 802.11ah wireless network.**

In the context of high reliability of WQM application data delivery to water monitoring stations, the NB-IoT solution may be advantageous compared to the proprietary-based solutions. The main reason for this is because of the massive presence of cellular infrastructure in urban locations.

It is worth mentioning that the LPWAN architectural design in Fig. 11 is suitable to realize higher energy efficiency, as well as satisfying the individual QoS demands of the water quality sensors in a network. These developments can be attributed to the performance of the channel access modulation schemes employed by the LPWAN technologies at the MAC layer, as the schemes used by the solutions at the MAC layer are energy aware and minimizes energy consumption.

VI. RECOMMENDATIONS AND FUTURE PROSPECTS FOR WQM APPLICATIONS, LPWAN SOLUTIONS AND IEEE 802.11ah NETWORK

As discussed in this work, the new wireless technologies represented by the LPWAN variants and the IEEE 802.11ah are promising solutions for achieving the requirements of modern WSN solutions for WQM applications in terms of energy efficiency, data rate, and long range communication. As a consequence, recommendations are given to advance the field of WSN for WQM, as well as future directions on the recommended communication network solutions.

1) DEVELOPMENT OF ENERGY-EFFICIENT COMMUNICATION NETWORKS FOR WSN SOLUTIONS IN WQM APPLICATIONS

Most existing solutions on WSN for WQM have not harnessed the utilization of LPWAN communication technologies for water quality wireless connectivity over long distances, instead 4G, 3G, and 2G networks are mostly employed. LPWAN communication technologies can be incorporated into WQM applications, which are believed to advance the development of energy efficient and reliable communications in WSN for WQM applications. Also, based on the interesting features of LPWAN-based solutions, including long range communication and low-power consumption, it is therefore envisaged to be a promising WAN technology that could be employed as a communication media to deliver WQM application data to different water centers.

2) ENERGY EFFICIENT MAC LAYER FOR DATA COMMUNICATION

Considering the fact that energy is a crucial resource in WSNs, energy efficient communication mechanisms are necessary at the MAC layer of the protocol stack of WSNs. Without energy efficient mechanisms at the MAC layer, more power will be dissipated during data transmission by the radio transceiver of a sensor node. This can be attributed to different issues. Examples of issues that waste energy resources at the MAC layer include idle listening, the overhearing problem, and packet re-transmission due to packet collisions. Therefore, for energy resources to be efficiently utilized during data communication, energy efficient communication networks are crucial. To achieve this, LPWAN solutions are promising communication networks because of their novel channel access modulation schemes. This will help to minimize the energy dissipated by water quality sensors that traditionally run on battery power.

3) CONSIDERATION OF SUITABLE ENERGY HARVESTING TECHNIQUES

Because of the limited battery life of water quality sensors, suitable energy harvesting technique(s) may be combined with the power section of the water quality sensors to complement the battery power. It is worth mentioning that energy harvesting technology is presently an open research problem.

4) LONG RANGE AND LOW-POWER WQM APPLICATION NETWORKING

Both long range and low-power are essential features in WSN for WQM applications. To meet the aforementioned requirements, the IEEE 802.11ah is another promising communication network since the IEEE 802.11ah network optimizes its battery life, data transmission rate, and communication coverage. However, the IEEE 802.11ah communication coverage is not as large as the LPWAN communication networks, and also consumes more power compared to the LPWAN solutions with their more moderate data transmission rates. For IEEE 802.11ah to fulfill its potential in this application calls for more improvement in the energy efficiency.

5) IMPROVING THE POWER CONSUMPTION OF IEEE 802.11ah NETWORK

Because of the power requirement of the IEEE 802.11ah network, which is slightly higher than the LPWAN variants, future directions should focus on designing new strategies to improve on the communication network to support low-power dissipation. This can be realized by exploring the design of novel and adaptive hardware that supports different modulation schemes at the PHY layer (or multi-PHY layers). Based on this, different power dissipation levels at different data transmission rates will be achieved, while adaptive communication schemes are employed for the selection of a PHY layer, depending on the pattern of traffic.

6) IMPROVING THE PERFORMANCE OF THE CELLULAR-BASED LPWAN COMMUNICATION NETWORK DATA LATENCY

The new LPWAN NB-IoT communication network may experience high data latency because of the scarcity of random access channel resources. Considering the critical nature of WQM application data to proactive actions by water management personnel, it will be good to improve the data latency of NB-IoT for timely delivery of water quality data to various water control and monitoring centers. This will make future WSN solutions for WQM applications that adopt NB-IoT technology more robust. To address the high latency issue that is associated with the NB-IoT technology, the mechanisms employed in the design of the technology, which are aimed at minimizing power dissipation during communication, should be improved through optimization to enhance the latency performance of NB-IoT. Also, efficient decoding techniques for detecting multiple sensor nodes should be designed and deployed at the NB-IoT base stations. The decoding techniques should have low-complexity.

7) IMPROVING THE PERFORMANCE OF THE PROPRIETARY-BASED LPWAN COMMUNICATION NETWORK DATA LATENCY

The new proprietary-based LPWAN communication networks may encounter high data latency because of their co-existence with the existing legacy wireless technologies on the unlicensed bands. Considering the critical nature of WQM application data to proactive actions by water management personnel, it will be good to improve the data latency of the proprietary-based LWPAN solutions for timely delivery of WQ data to various water control and monitoring centers. This will make future WSN and IoT solutions for WQM applications that adopt LoRa, Sigfox, and INGENU technologies more robust.

8) NEED FOR ANALYTICAL MODELS FOR IMPROVING THE POWER CONSUMPTION OF THE PROPRIETARY-BASED LPWAN SOLUTIONS

There is need to develop novel analytical models to investigate and improve the energy consumption performance of the proprietary-based solutions (Sigfox, LoRa, INGENU) for the next-generation of WSN solutions for WQM applications, as there are few analytical models on the aforementioned solutions at present. The analytical models will further facilitate the growth and popularity of Sigfox, LoRa, and INGENU, as they are crucial for designing optimization problems to improve on their performances. The few analytical models in literature focus on communication range, while power consumption consideration is also essential for analytical studies.

9) NEED FOR EFFICIENT CLEAR CHANNEL ASSIGNMENT SCHEME IN PROPRIETARY-BASED LPWAN SOLUTIONS

The current proprietary-based LPWAN solutions support the pure ALOHA scheme at the MAC layer. The pure ALOHA scheme does not include a clear channel assignment (CCA) scheme, which is useful in minimizing packet collisions. As a consequence, the proprietary-based LPWAN communication networks may encounter an excessive number of packet collisions. Therefore, to improve the energy efficiency of the proprietary-based LPWAN solutions, a CCA scheme may be combined with the pure ALOHA, like the case of the CSMA-CA scheme. Based on this development, the network computational overhead for handling packet collisions is envisaged to improve.

10) IMPROVING CHANNEL RESOURCE ALLOCATION PERFORMANCE OF PROPRIETARY-BASED LPWAN SOLUTIONS THROUGH HYBRIDIZATION

The random access operation of the pure ALOHA scheme employed in the proprietary-based LPWAN solutions provides scope for improving the allocation of the communication channel resources. As a consequence, the performance of the ALOHA scheme, which allocates communication channel resources in a random manner, should be improved by investigating the hybridization of ALOHA and a scheduled access technique (such as TDMA). This development will improve channel allocation and data transmission performance.

VII. CONCLUSION

This paper has presented a survey on the legacy and new communication technologies that are suitable for WSN solutions in WQM applications. This is necessary to address the shortcomings of the existing WSN solutions for WQM applications due to the inefficiency - such as short communication range and high power consumption - of the legacy communication networks often combined with the WSN systems in WQM applications. To achieve this, long range and low-power communication networks are desired in WQM applications. These requirements can be achieved by incorporating the newly emerging low-power wide area network (LPWAN) solutions into the communication architecture of the WSN systems for WQM applications. As a result, three categories of potential solutions for WQM applications have been proposed in this paper. These categories include the proprietary-based LPWAN, the cellular-based LPWAN, and the low-power WiFi-based IEEE 802.11ah solutions. The variants of the LPWAN technology employ different modulation schemes to offer low power consumption at a low data rate. These features make the reviewed solutions of the LPWAN variants suitable and promising data networking candidates for WQM applications. Also, the IEEE 802.11ah solution, which is an improved version of the legacy Wi-Fi network, is another promising candidate for water quality data networking in terms of energy efficiency and long range communication. However, it offers a lower communication range and higher power dissipation compared to the LPWAN solutions, because its data rate is higher than that of the LPWANs. Based on the identified new communication networks, new architectural design and network deployment have been proposed for WSN solutions in WQM applications. These developments are expected to advance the field of WSN for WQM in terms of energy efficiency, long range communication, reliable delivery of water quality data to different water monitoring centers, addressing the long-standing energy issues that have hindered the wide popularity of WSN solutions. Also, critical recommendations are provided to revolutionize WQM applications. Moreover, key future directions are provided to improve the performance of the recommended LPWAN variants and the IEEE 802.11ah network for the next-generation of WSN systems for WQM applications.

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SEGUN O. OLATINWO received the B.Sc. (Hons.) and M.Sc. degrees in computer science and engineering. He is currently pursuing the Ph.D. degree with the University of Pretoria, South Africa. He is currently a Chartered Engineer. His research interests include energy efficient communications in wireless sensor networks for water quality monitoring applications, energy harvesting, optimization, wireless powered networks, resource allocation, wireless systems, and half duplex and full duplex communications.

TRUDI-H. JOUBERT received the B.Eng. and M.Eng. degrees (Hons.) in electronic engineering and the Ph.D. degree in electronic engineering from the University of Pretoria, South Africa, in 1996.

From 1987 to 2000, she was promoted from Lecturer to Assistant Professor with the University of Pretoria. From 2001 to 2013, she consulted to the microelectronics industry through solid state technology. She has worked on 28 projects for the South African industry, writing 125 technical reports in the process, and contributing to 31 integrated circuit chips. From 2013 to 2014, she was a Senior Research Engineer with the Council for Scientific and Industrial Research, South Africa, before returning to the University of Pretoria, since 2015. Her core pursuit is CMOS and BiCMOS mixed signal circuit design, mainly in readout and signal processing for imaging arrays, biologically inspired electronic circuit applications, and specialized devices for analog IC design. She has published 16 journal papers, and presented and co-authored 46 conference proceedings papers. Her most recent endeavor is printed electronics biosensors and networks, particularly for water quality monitoring.