Energy Efficient Solutions in Wireless Sensor System for Monitoring the Quality of Water: A Review

Segun O. Olatinwo and Trudi-H. Joubert, *Senior member, IEEE*

***Abstract*—This study presents energy-efficient solutions for wireless sensor systems intended for the monitoring of water quality at water stations. Energy problems, such as energy scarcity and energy consumption in wireless sensor networks, are critical issues that raise concerns when it comes to defining the lifetime of a network. This can be attributed to the finite energy budget of water quality sensor nodes and also the lack of energy-efficient schemes. To address these energy problems, a detailed study has been carried out in this paper on some of the major approaches developed to address energy issues in wireless sensor systems, and dedicated to the monitoring of water quality applications in a way that contextualizes the considered solution methods. Furthermore, the solution methods are classified, while their strengths and weaknesses are also identified. Also, several suggestions are made on solution methods towards further improvement. Therefore, this study suggests a reasonable direction for future studies on developing energy-efficient solutions in wireless sensor systems for monitoring water quality applications.**

***Index Terms*-Energy harvesting, Energy consumption, Energy scarcity, Optimization, Internet-of-Things Sensor systems, Water quality monitoring.**

I. INTRODUCTION

WIRELESS sensor systems employ wireless sensors to carry out specific task(s), and include wireless sensor networks (WSNs) and internet-of-things (IoT). WSNs and IoT are key resourceful technologies that have revolutionized the field of environmental monitoring in recent years [1]. An important domain in the field of environmental monitoring is water quality monitoring (WQM). The term water quality (WQ) is used to describe the physical, the chemical, and the microbiological characteristics of water, while the idea of sampling and analyzing the characteristics of water on a periodic basis is described as WQM [2].

WQM systems can be realized in an efficient manner through the incorporation of wireless sensor technologies such as WSNs [3], [4]. Although the emphasis in this paper is on WQM systems, the application of WSNs is not limited to only to this field, but is useful in several other domains such as water leakage monitoring [5], [6], waste management [7], [8], structural health monitoring [9] – [11], traffic monitoring [12] – [14], and farm animal condition [15], [16], to collect, process, and disseminate data to various data centers [17], [18]. Importantly, WSNs are valuable tools in WQM [17], [18], [19]. As an example, in [19], a WQM solution was deployed to monitor the salinity in ground water, and also to monitor the temperature of surface water, providing crucial details about the water quality status.

WSN for WQM (WSN-WQM) applications may contain a large number of water quality sensor nodes (WQN) that have the capabilities to measure and detect the physical, chemical and microbiological parameters of water. An Escherichia coli (E.coli) bacteria is an example of a microbe that can be detected in water, while examples of chemical parameters that can be detected in water are heavy metals. Examples of other parameters that can be considered in water monitoring will be described further in Section II.

The incorporation of WSNs to WQM facilitates the effective monitoring of WQ parameters at water sites, as the WQN in a network are devoted to the monitoring of WQ at a particular water site and disseminates their measurements to a data gathering station, which is referred to as a base station (or sink node) in practice. Similarly, WSNs are capable of transferring the measured water information at a local station to remote WQ centers through the application of communication network technologies such as the internet. As a result, a WSN

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S. O. Olatinwo is with the Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria, South Africa, 0001, (email: segunlatinwo@gmail.com).

T.-H. Joubert is with the Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria, South Africa, 0001, (email: trudi.joubert@up.ac.za).

based WQM system can effectively communicate with the remote end user devices in a timely fashion, enabling efficient monitoring of WQ parameters.

However, the WQN contained in WSN-WQM applications have several resource constraints that range from communication capabilities, limited energy, processing capabilities, to limited memory for data storage [20], [21]. Among the aforementioned constraints in resources, energy is the most crucial resource of all [22]. The main reason for its high significance is that all components of a sensor node depend on it, as it is used for powering sensors. Energy limitation has been a long-standing issue in WSN applications [23], [24], [25], [26], while seeking solutions to the problem has been an active area of research in recent years. Typically, when there is a lack of energy in a network, one can say that there is an energy crisis in such network, which is technically referred to as energy scarcity. This is an indication that energy resource is a scarce commodity among the energy-hungry WQN in WSNs. The energy scarcity problem in WSNs is a major issue that hinders the development and the continuous popularity of WSN applications [27], [28], [29].

The primary reason for the energy scarcity problem in WSN-WQMs is because the sensors that form a WQN are based on battery power. As a result of the nature of WQNs, small batteries with finite energy are typically embedded in them. Because of the small size of the batteries, their energy budgets are restricted and are quickly depleted during sensors' operations, which include sensing, processing, and data communication. These operations determine the total energy consumed by each sensor node, which could be determined from the addition of the power dissipation of all the operational modules of a sensor node. These modules include all the sensors with their read-out front-ends, the micro-controller, and the radio frequency (RF) radio. One the reasons responsible for the quick depletion of the energy in a sensor node's in-built battery during long operations can be associated with the embedded high energy consumption components - for example, the communication unit. Unfortunately, once any of the WQN nodes has exhausted the available energy in its in-built battery, its inactivation in the network compromises the data reliability.

Since WSNs have different applications and WQM is one of key use cases, it is important to underline the peculiarities of WSN systems for WQM applications in relation to energy problems. Typically, each application area of WSNs has different requirements in the context of measurements, and this determines the types of sensor modules in application sensor nodes. This disparity impacts the energy requirements of WSNs in different applications as energy consumption varies from sensor to sensor. For instance, the energy consumption of a temperature sensor in a WQM application differs from the energy requirements of a gas sensor in an air quality monitoring application as a gas sensor typically consumes more energy. The WSNs in different applications may also adopt different operation modes such as periodic data acquisition and continuous data acquisition. Periodic mode allows the network sensor nodes to be in a sleep state for a given time period, while a continuous mode requires the network sensor nodes to be active at all times. Another difference may be how often the sensor nodes in an application have to communicate their measurements. These differences create a disparity in energy consumption among different WSN systems as the power requirements of an application caters for peculiar features that include type of sensor module, operation mode, sampling rate of measurements, processing of the measured data, and rate of communication of measurements. Furthermore, in the case of WSN for WQM application, commercial low-power WQNs is currently not available, and this gives scope for the provision of energy-efficient solutions in WSN systems devoted to WQM applications since energy is a scarce resources. Other distinctive features of WSN systems for WQM applications are water sampling location(s) selection and number of WQNs required for optimum coverage, taking energy and cost into consideration. Taking the disparities among different application areas of WSNs into consideration, it is important to underline the need for energy-efficient solutions to address the peculiarities of WSN for WQM application regarding energy consumption problems so as to meet the requirements of WSN systems for WQM applications.

In order to meet the requirements of WSNs for WQM that include reliable and timely delivery of WQ information [30] through sustainable quality-of-service (QoS) for information transmission such as throughput rate [32], the economical exploitation of energy resource is crucial. Energy utilization efficiency is an example of WSN-WQM application requirements [32]. Consequently, the research community in industry and academia has been making efforts to address the energy problem in WSNs so as to improve the lifetime of WSN systems. Because of the current lingering energy problem in WSNs, it may not be possible to satisfy the requirements of WSN-WQM applications since sending a high volume of the measured WQ information in a timely fashion at a high throughput would consume more energy. To meet the aforementioned requirements of WSN-WQM systems and facilitate the successful and wide-spread deployment of their application, it is important to incorporate energy efficient strategies into WSN-WQM application designs.

Because of the growing interest in WSN systems, there are a sizeable number of surveys on WSNs in the literature. However, there are presently only a few of survey works on WSN-WQM systems in the literature. Examples of survey works that focus on WSN and WQM are discussed as follows. In [33], the authors presented the survey of WSN-WQM. In their survey, the authors emphasize key research problems in WSN for underground WQM application. Examples of the issues considered in their survey are deployment, architectural, protocol stack, and underwater communication. The authors in [34] considered the survey of WSN-WQM systems. Their survey work focuses on the recent developments which include communication models, WQ data acquisition, potential power models, and network architecture. The goal of this survey was to bring the awareness of the research community in WSN-WQM to recent advances, research issues, and possible solutions. The authors in [35] present a survey on WSN for WQ. Their goal was to highlight the key solution models to address the problem of water scarcity through the loss of water, which could be attributed to water leakages. Examples of such solution models include water leakage detection algorithms and localization approaches. Reference [37] considered the survey of environmental monitoring applications such as WQ and air quality. In their survey, they focused more on the problems that relate to WSN-WQM. Examples of the issues considered by the authors are security, energy, coverage, and wireless sensor node architecture. The existing surveys have not considered the aspect of the energy consumption problem, and less attention has been given to the problem of energy scarcity. In a similar manner, none of the surveys in literature on WSN-WQM applications has considered potential optimization techniques for seeking solutions to energy problems. Different from the existing survey works on WSN-WQM, this work considers possible energy solution models and energy minimization inspired by optimization techniques. These are crucial design goals for sustainable energy supply and network communications in WSN-WQMs. To handle these energy problems, insight into the knowledge of different energy solutions and energy optimization models are important. The key contributions of this paper are described as follows:

- Survey of key energy solution approaches for solving energy scarcity problems in WSN-WQM.
- The application of optimization techniques to solving energy consumption problems in WSN-WQM, including the presentation of examples on optimization problem formulation.
- Several challenges, recommendations, and future prospects are discussed.

The organization of this paper is structured as follows. A detailed discussion on concepts and an overview of water quality monitoring is provided in Section II. Section III gives insight into the classification of key energy-efficient solution models in WSNs. An insight in the incorporation of energy solution models is considered in Section IV. Section V gives an account of relevant and powerful optimization tools for seeking solutions to energy problems in WSNs for monitoring water quality. Section VI describes challenges, recommendations, and future prospects. The conclusion of this work is presented in Section VII.

II. CONCEPT DISCUSSION AND OVERVIEW OF WATER QUALITY MONITORING

A. *Water Quality Monitoring*

WQM has attracted the research community in recent years in an attempt to develop novel monitoring devices for measuring WQ parameters such as pH values and bacterial load (E-coli is often used as indicator organism), in a timely manner [38]. The aforementioned parameters are important chemical and microbiological properties for WQM [39], [40]. The reason why the research community is seeking efficient and reliable monitoring systems for WQM is because of the increase in the influx of environmental and water pollutants [41] such as organic and inorganic contaminants, through anthropogenic activities and natural processes [42].

The surge in anthropogenic events has had negative effects on the environment, contributing to a state of poor quality water in the context of chemical, microbiological and physical properties. Water-related diseases prosper globally due to people’s lack of access to clean water. As a result of the poor state of water quality, ingested water is harmful to public health due to the presence of micro-organisms and metal ions such as mercury (Hg) and lead (Pb). The micro-organisms cause water-related diseases. The diseases are responsible for a significant percentage of illnesses and deaths around the world, especially in developing countries. For example, according to the World Health Organization (WHO), over 3.4 million human deaths are caused by water-related diseases every year [43]. Moreover, the metal ions are also environmental contaminants that create several health issues such as cancer, organ damage, acute hepatic and renal failure, epigastric pain, and diarrhoea [44], [45], as well as other environmental concerns due to their highly toxic characteristics [46] - [48]. However, these great tragedies can be circumvented through the help of simple and low-cost measures. Hence the need for simple, low-cost, fast response time and energy-efficient WQM systems in order to guarantee clean water provision.

Uncontaminated (or clean) water is paramount not only for the survival of humans, but also their good state of health, as well as that of animals and plants, and the whole natural environment [49]. It is typically used in agriculture, in industry, and for drinking [50], [51]. Clean water is an indispensable resource that needs to be monitored and maintained through efficient WQM systems. To address this technologically, a number of laboratory-based WQM methods have been explored and exploited, such as inductive-coupled plasma-mass spectrometry (ICP-MS), pH-metric determination, optical-infrared spectroscopy, and optical spectroscopy [52], [53]. The traditional laboratory-based methods typically involve three basic phases, namely water sample collection, laboratory testing of the water sample, and biological and chemical analysis of the water sample for contaminants [54]. In determining the quality of water using the traditional methods, water sampling is crucial. Sampling involves the collection of water samples from a water body, transporting the water samples to the laboratory, and developing a sampling plan, for analytical purposes in the context of microbes and chemicals [54], [55]. The laboratory testing is concerned with checking of the water sample for contaminants using the standard laboratory methods, while the biological and the chemical analysis phases are performed by specialist laboratory personnel, which include measurement and analytical scientists [54] for necessary decision making. The taxonomy of a typical laboratory-based system for WQM is provided in Fig. 1.

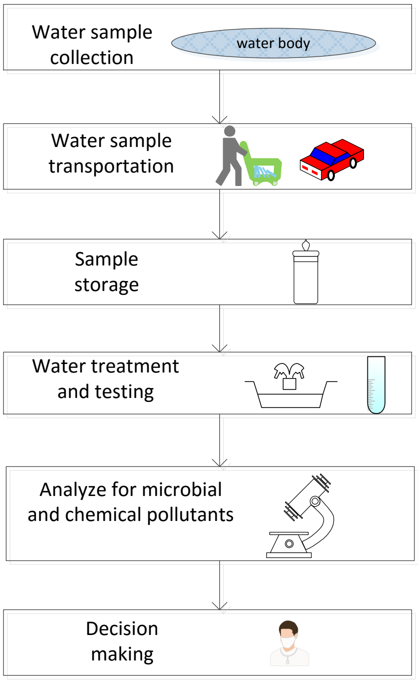

Fig. 1: Taxonomy of a typical laboratory-based method for WQM

The traditional methods waste a lot of time since it requires sending the water samples taken at water sources to laboratories that may be far away. In many cases, there might be need to wait for days for a response since the laboratory analytical measurements do not commence immediately upon sample arrival, as samples are often stored first so as to develop a sampling plan to meet the intended purpose for the measurement [54], [56], [57]. The traditional methods might not be a reliable technique for the monitoring of key chemical parameters of water such as pH, dissolved oxygen, and temperature, as they can only be reliably measured at the on-site for accurate results [54], [58], [59]. The off-site analysis of the aforementioned parameters does not guarantee reliable results as they are affected by the transportation process to the laboratory [58]. The laboratory-based methods are confronted by other problems which are regarded as open research issues such as high cost, large size, difficulty in operating and deployment, and interference from operators [60].

An efficient WQM system should be cheap, portable, ubiquitous, and fast in response time [51], [61]. As a result, research efforts are ongoing to propose efficient methods for WQM [38], [62]. In order to meet WHO, United States Environmental Protection Agency (USEPA), European Union (EU) guidelines [49], as well as the South African Blue Drop [63] and Green Drop requirements [64] of safe water provisioning in a timely manner to society, it is necessary to monitor and analyze water obtained from different sources which include reservoirs, groundwater, and rivers, for contaminants at various WQ stations, using WQNs [65]. To achieve the requirements of efficient WQM, and to circumvent the shortcomings of the laboratory-based method, WSN technology has been proposed through research efforts as a promising economical method [3], [4], [34], [37]. In this case, WQNs are deployed at a water station to measure, process, and transmit WQ information through the help of a communication network, to a local WQM station and as well to remote WQM centers for necessary decision making, in a timely fashion. The taxonomy of a typical WSN-based system for WQM is provided in Fig. 2. For instance, when there is an issue of contamination in the course of data analysis, an urgent emergency warning is communicated to prevent such water from distribution by the water networks. Examples of WQM systems that have employed WSN technology can be found in references [50], [66], [67]. For example, in [50], the authors applied WSN technology to WQM to develop a low-cost solution for drinking WQ systems. In [66], the authors employed WSN technology to develop a monitoring system for water environment. The authors in [67] have considered the optimization of WQNs placement in a WSN-based WQM system developed for detecting contaminants in water. Furthermore, examples of WSN systems implementations and where they have been deployed are presented in references [59], [66], and [68]. The works in [59], [66], and [68] are deployed in Australia, China, and Portugal, respectively.

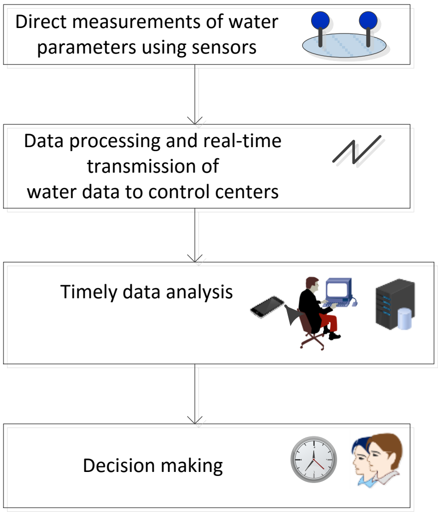

Fig. 2: Taxonomy of a typical WSN-based method for WQM

In summary, the comparison of the laboratory based approach and the WSN based approach in presented in Table 1 in terms of deployment cost, size, analysis type, strength, and limitation.

TABLE I
COMPARISON OF LABORATORY- AND WSN-BASED MONITORING APPROACHES

Water monitoring approach	Size	Deployment cost	Analysis type	Strength	Limitation
Laboratory-based monitoring	Large / bulky	Expensive	Off-site	It is a widely used method due to its recognized establishment.	• It may not provide a reliable measurement since some key parameters are best monitored on-site. Such parameters are pH, dissolved oxygen, temperature, organic compounds, and E.coli. • Interference from operators. • Waste time because of the numerous stages involved in sampling plans. • Requires human intervention. • Maintenance problem. • Difficult to operate.
WSN-based monitoring	Portable	Low cost	In-site (or on-site)	• Fast response time. • Reliable measurements, but multiple sensors are encouraged when dealing with multiple parameters. • Easy to deploy. • Easy to maintain	• It may the hindered by the energy problems in WSNs. • It may be limited with respect to long distance communication when long range communication radios are not in place.

B. Examples of Water Quality Parameters and Sensors

Briefly, water consumption is an important salient issue in WQM framework. The consideration of consumption helps to meet different intended purposes, while ensuring WQ. The quality of water provided for various uses is highly crucial because of its great influence on the quality of life and industry [68]. However, water is a scarce resource. The scarceness of water resources is due to reasons that include industrialization and urbanization, accompanied by population growth. These issues, among others, affect the quality of water, and contribute to the increase in water consumption as a result of the growth in population and the utilization of products that are water intensive in industries and urban locations. Unfortunately, most of the available water is not fit for consumption without monitoring and treatment. Consequently, to address the water consumption issue for meeting the needs of various users and taking the factor of quality into account, the optimal utilization of water resources and a reliable monitoring of WQ are important. It is essential to underline that if consumption and water quality issues are not well addressed, there may be water shortage crisis.

WQ is simply described by three key evaluation parameters. The key parameters are the physical, the chemical, and the microbiological characteristics of water. These characteristics are important metrics used to determine the fitness of a particular water source for various purposes which may include irrigation, drinking, fishing, recreation, and industrial supply [53].

The physical quality of water is concerned with the monitoring of the physical properties of water. It affects the aesthetic quality of water in the context of appearance, color, taste, foam, smell, conductivity, turbidity, total dissolved solid, and temperature. The physical quality of WQ involves the application of the human sensory organs for necessary observations and deductions. Such organs include the eyes, the nose, and the tongue. The eyes are used to observe the appearance of the water, the composition of the water, the flow of the water, and the depth of the water. The nose is a crucial organ used for odor observation, while the tongue may be used to taste the water for necessary deduction.

The chemical quality of water is used to determine the concentration of the dissolved chemicals, including inorganic and organic chemicals such as heavy metals [69], [70]. Examples of heavy metals are arsenic, cadmium, potassium, and zinc [71] - [73]. The monitoring of the chemical quality of water helps to investigate key parameters such as pH, dissolved metal ions, dissolved oxygen, inorganic and organic compounds [51], [74] in the context of measurement, while chemical parameters that include industrial pollutants, agrochemicals (such as fertilizers and pesticides) and mining pollutants can be detected. The chemical analysis of water is crucial in order to ascertain the health and the fitness of water. It is important to emphasize that different types of WQN have been designed for necessary measurements and detections, while choices are made depending on the application requirements.

The microbiological quality of water describes the occurrence of invisible organisms in water such as bacteria, protozoa, and viruses. Water-borne diseases are the major consequence of the aforementioned microbes. The microbes are contaminants that cause devastating effects to the health of humans when the water containing these microbes is ingested. The microbiological analysis of water can be carried out through the application of WQN and WSN technology. Often, E.coli is considered as an indicator organism for faecal contamination in microbiological analysis of water [39], [69], [70]. Other micro-organisms that can be in water include other coliforms and faecal streptococci.

Examples of some of the sensors utilized in existing WQNs include pH sensors, electrical conductivity sensors, turbidity sensors, temperature sensors, E.coli sensors, dissolved metal ions sensors, dissolved oxygen sensors, heavy metals sensors, inorganic and organic compounds, and so on. Much research, that is outside the scope of this review, is ongoing to reduce the power consumption of sensors, including many water monitoring sensors, including less prevailing ones such as those for organic compounds, biological contamination, and heavy metals. Nevertheless, due to the inherent energy scarcity issue in WSN systems for WQM, taking the energy requirements of different WQNs in WQM sensor networks into consideration will be advantageous for optimizing the energy consumption of a network since some sensors are energy consumers as the energy requirement of a particular sensor varies from another due to their intended measuring tasks. Typically, the energy requirements of WQNs are in the range of μW and mW. As a result of the possible disparity in energy requirements in terms of energy dissipation among different WQNs, activating energy consumer WQNs concurrently with other lesser energy dissipating WQNs without energy-efficient strategies being put in place may results in network inefficiency.

C. Sensor Node Architecture for Monitoring Water Quality

The application of WQNs to the field of WQM has greatly revolutionized the process of monitoring the quality of water. To support this fact, the market of WQNs has experienced a surge in growth in recent times. For instance, the market has been estimated to worth \$2.95 billion, in USD, in 2016 [75]. Similarly, the market is envisioned to increase to about \$4.6 billion by 2022. The growth is envisaged at an annual compound growth rate of 6.6% [76]. This shows that WQN utilization in WQM has enjoyed a global wider acceptance. WQM is an active field of research as water is a crucial resource to human survival. For example, in WQM applications, several issues are put into consideration for effective monitoring of the quality of water. Such issues include the consideration of the right WQNs to be employed, consideration of alternative power solutions (such as energy harvesting) for an enhanced network lifetime, consideration of energy optimization techniques for efficient resource allocation and a sustainable network operation, choice of communication technology to be utilized for data communication, the consideration of the application environment (or water sampling location(s) selection), strategies on how to extract data, development of low-cost, low-power and portable WQN, and simplicity in setting up (or configuring) the application. Other issues that are important for the deployment of WQM networks are sampling frequency rate of water quality measurements and the number of WQNs required in WSN-WQM deployments for optimum coverage, taking energy problems and cost into consideration. As the number of WQNs considered for deployment influences the total energy consumption of the WSN-WQM system then the number of WQNs should be smaller owing to limited energy resources, and be optimally placed for optimum coverage of water body.

The WQN in WSN-WQM is composed of four basic modules as described in Fig. 3, namely a sensor module, a micro-processor module, an RF transceiver module, and a power source [77], [78], [79], [80]. Fig. 3 describes the general architecture of a wireless sensor node.

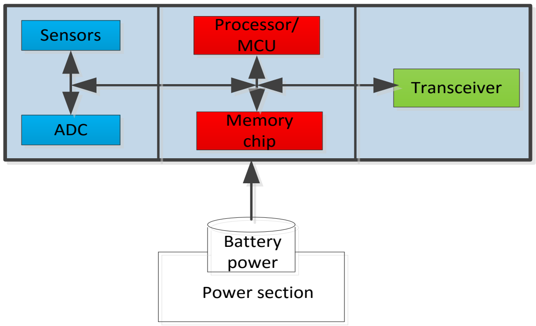

Fig. 3: Typical WQN architecture

Examples of commonly used sensors are described in Section C, while typical other modules for WQN may be based on a micro-controller (such as the Texas Instruments (TI) such as TI MSP430F1611 and TI 8051), and an RF transceiver (such as TI CC2420), and a battery for storage. The sensor module usually consists of two sub-units, namely an analog-to-digital converter (ADC) and the sensor [77]. The sensors are used to measure WQ data as an analog signal, while the ADC operates on the analog signal generated by the sensors based on the observed parameters. Thereafter, the ADC converts the analog signals into digital signals, and forwards them to the processing unit for onward processing [70]. The processing unit generally consists of two sub-units, namely a processor and a memory device [80]. The processing unit is responsible for managing the processes that integrates the sensor module with other modules in order to execute instructions that relates to WQ measurements, gathering of WQ measured data from the sensor module, storage of the obtained WQ data from the sensor module, and transmission of the stored WQ data via the transceiver to a base station. It is also responsible for the management of hardware component functions, and data processing [81]. The processing unit uses the memory device for storing program instructions, as well as the measured WQ data. The memory device consists of the microcontroller random access memory (RAM) program, in-chip flash memory, and data memory [81], [82]. The transceiver unit is responsible for data transmission (*Tx*) and reception (*Rx*). In the context of WQM, the transceiver can be described as a low-power, low-cost, and low-rate compliant chip [83]. The transceiver unit contains the antenna and a radio, two crucial components used for communication purposes. The transceiver radio is employed to establish communication with the neighboring WQN wirelessly, as well as with a base station. It is important to mention that the transceiver radio works with RF compliant communication technologies such as IEEE 802.11, IEEE 802.15.4 radio and ZigBee radio. These are common communication technologies employed for local data networking or connectivity, and operate on the 915 MHz or the 2.4 GHz bands of the free industrial, scientific and medical (ISM) frequency allocation [77], [84].

The current solutions typically employ ISM radio bands to provide wireless communications to wireless devices such as WSNs [85], [86]. Table 2 describes the available frequency bands for ISM applications according to the International Telecommunication Union (ITU) standards.

TABLE 2
AVAILABLE RADIO BANDS FOR ISM BASED WIRELESS SYSTEMS

S/N	Radio band	Hertz	Channel bandwidth	Hertz	Center Frequency	Hertz
1	6.765 – 6.795	MHz	30	kHz	6.78	MHz
2	13.553 – 13.567		14		13.56	
3	26.957 – 27.283		326		27.12	
4	40.66 – 40.7		40		40.68	
5	433.05 – 434.79		1.84	MHz	433.92	
6	902 – 928		26		915	
7	2400 - 2500		100		2450	
8	5725 - 5875		150		5800	
9	24 – 24.25	GHz	250		24.125	GHz
10	61 – 61.5		500		61.25	
11	122 - 123		1	GHz	122.5	
12	244 - 246		2		245	

Despite the advances in wireless technologies, wired communication solutions such as universal asynchronous receiver transmitter (UART) are still sometimes employed to directly connect a sensor node to a BS, while Ethernet is used to connect the BS to an application system. A few examples of communication technologies that can be employed for remote data networking are GPRS network, GSM network, and 3G networks.

Moreover, in recent times, new radio technologies that target WSN and IoT systems have been proposed for reliable delivery of information. Examples of such radio technologies are the long range (LoRa) radio [87], the narrowband-IoT (NB-IoT) radio [88], and the sigfox radio [4], [89]. These radio solutions are envisaged to advance WSN-IoT solutions for WQM applications based on their long communication range and low energy consumption capabilities, for example, in situations that require the transmission of WQ information over long distances. The issues of communication range and energy consumption are crucial challenges that currently confront WSN solutions for WQM. The IoT architectures of the presented communication solutions can be implemented for WQM applications as described in Figs. 4 to 6. To achieve this, the WQNs in both LoRa and sigfox architecture are equipped with LoRa module and sigfox module respectively, and they are connected to remote water control stations through their proprietary gateways (that is LoRa gateway and sigfox gateway) which could be connected to a network server using an Ethernet solution or one combined with cellular network solutions (such as LTE / 3G) to access the internet cloud through which WQ information is pushed to the application server of the remote WQ analysts. Different from the discussed IoT architectures, in the case of NB-IoT architecture, where the technology is a cellular-based solution and supports the existing cellular network infrastructures, the WQNs may be connected to remote water monitoring stations using the existing cellular network masts, thus circumventing the need for a proprietary gateway. Consequently, the NB-IoT base station (i.e. NB-IoT BS) at the core network is employed to forward WQ measurements to the application server of the remote control centres where the WQ personnel resides.

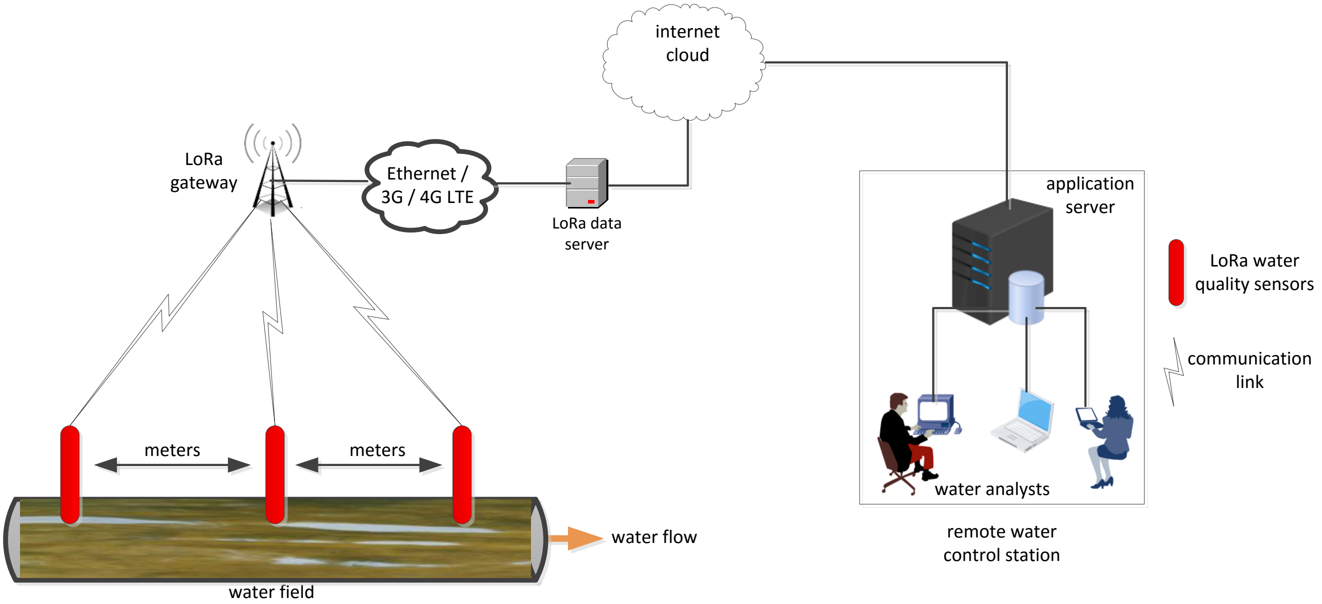

Fig. 4: LoRa architecture for WQM application

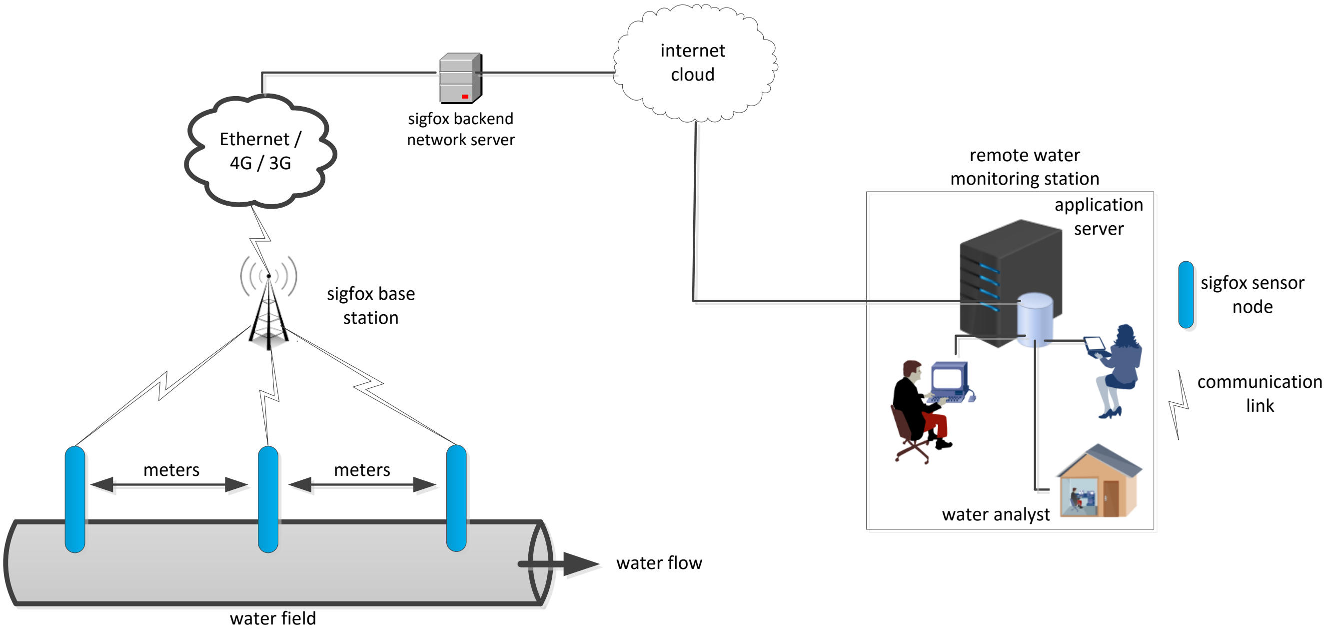

Fig. 5: Sigfox architecture for WQM application

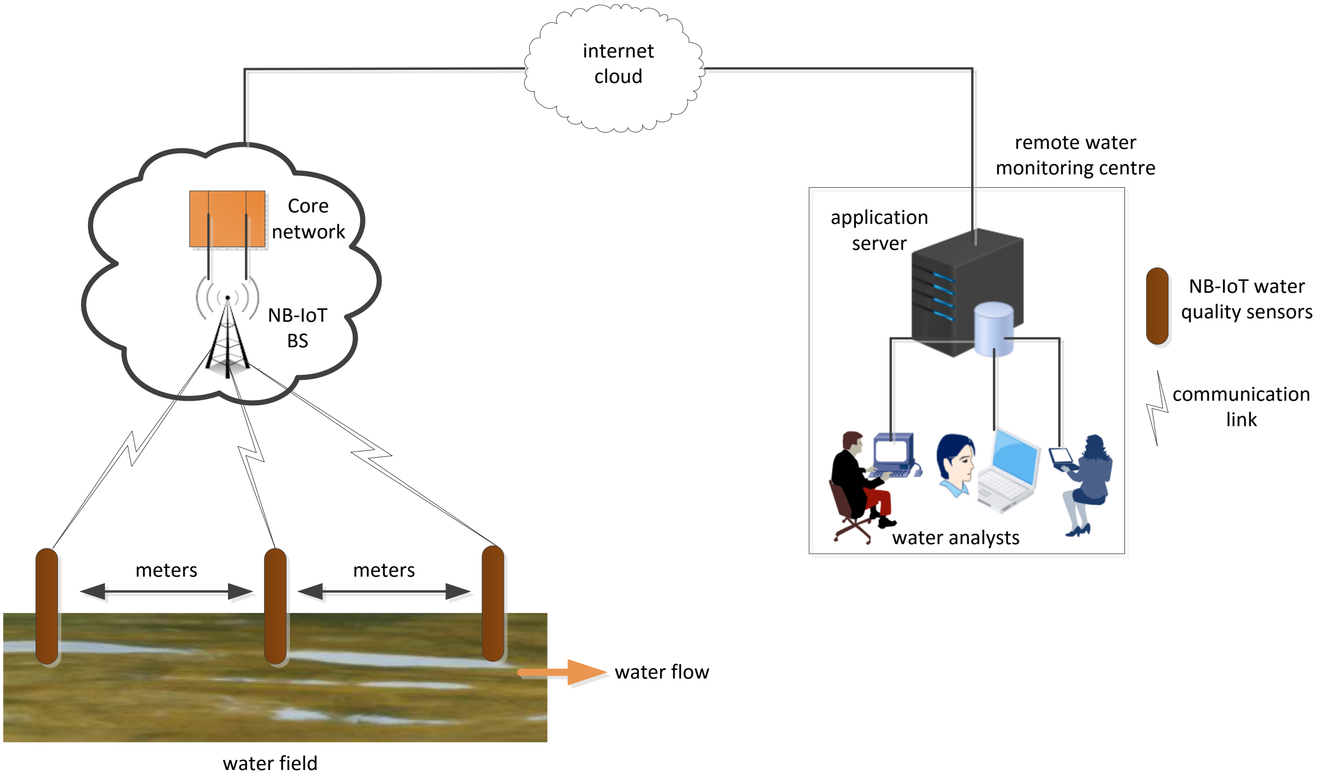

Fig. 6: NB-IoT architecture for WQM application

A summary of examples of local and remote communication technologies, including where they have been employed for WQ data networking, and the parameters monitored, is provided in Table 3.

No published examples of the use of the presented IoT technologies in WQM have been found.

TABLE 3
SOME EXAMPLES OF COMMUNICATION TECHNOLOGY FOR LOCAL AND REMOTE WQ DATA NETWORKING

Consideration of local data networking	Consideration of remote data networking	Used radio for local data networking	Used radio for remote data networking	Parameters monitored	References
√	√	ZigBee	Ethernet / GPRS / 3G	pH. E.coli, turbidity	[50]
√	√	Wi-Fi module	Wi-Fi access point	pH, turbidity, conductivity	[90]
√	√	ZigBee	GPRS / GSM	pH, dissolved oxygen, turbidity and temperature	[66],[91],[92], [93], [94]
√	√	IEEE 802.15.4	3G / GSM / GPRS	pH, temperature, conductivity, dissolved oxygen	[95], [96]
√	X	IEEE 802.15.4	X	pH, dissolved oxygen, turbidity	[97]
√	X	ZigBee	X	pH, temperature, turbidity	[98],[99]
√	√	UART	GPRS / 3G	pH, turbidity, temperature	[100], [101]
√	√	UART	Ethernet	pH and temperature	[61]

√: Considered X: Not considered

In summary, the power source is responsible for making the required energy available to the various modules in the WQN architecture and this makes it an important component to the survival of a WSN application [77]. Thus, energy is a crucial resource in a WSN-WQM as it is employed to run the modules of the WQN.

D. Sensor Network in WQM

WSNs are valuable tools used in WQM application to collect, process, and disseminate WQ data to WQ centers [77], [102], [103]. A WSN-WQM integrates several wireless WQNs deployed in a WQ field to measure the microbial and the chemical characteristics of water [104]. The WQNs carry out necessary signal processing on the measured WQ data either at the local level or at the cluster level, and transmit the processed data via a wireless link and an internet connection to a WQ (or control) center for onward analysis [81]. Fig. 7 shows a typical scenario of a WSN topology for WQM and data transmissions to various data centers. The WQN can be connected using two fundamental routing techniques to form a wireless network for WQ data transmission to the base station. The methods are single-hop routing and multi-hop routing. In a single-hop data transmission approach, each WQN is connected directly to a base station and each of them sends their individual WQ data to the base station. A single-hop communication can be implemented by employing a star network topology.

In multi-hop settings, WQN are connected to each other, and this type of routing technique can be implemented through the application of either tree, cluster tree or mesh topologies. Based on the connecting links created between the WQNs, a WQN sends its data through the neighboring WQN(s) to a destination sensor node. The sensor node from which the information originates is referred to as the source node, while the destination node is the one that receives the information from the sensor node(s) in a network. The destination sensor node is typically close to the base station and is responsible for delivering the gathered WQ information from the WQN to the base station in an aggregated or individual fashion. The destination sensor node may be a cluster head, provided a cluster tree network is incorporated in the multi-hop routing. If cluster tree is considered as depicted in Fig. 8 then the WQNs are referred to as local clusters. Typically, multi-hop routing saves energy consumed by the WQNs, since their individual WQ data is transferred over multiple short distances, unlike in direct communication with the base station. As a consequence, the multi-hop data transmission approach in WSN-WQM is an energy-efficient approach compared to a single-hop approach. However, the multi-hop data transmission method is confronted by a problem referred to as an energy hole. This is a situation whereby the cluster head or the destination sensor(s) quickly drains up their energy since more energy is consumed by them to transfer the huge aggregated WQ data to the base station. Another problem is the high complexity of the routing protocols used in implementing the technique, while a single-hop routing technique employs routing protocols that are simple and easy to implement.

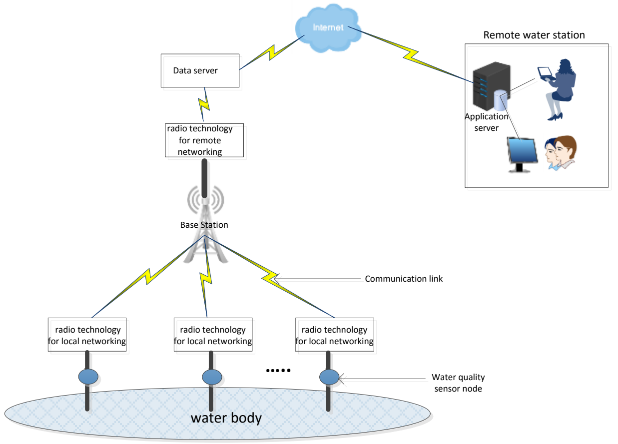

Fig. 7 : Scenario of a WSN deployment at a water site using single-hop data networking

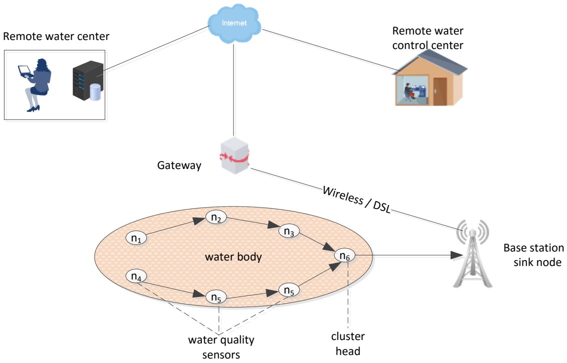

Fig. 8: Scenario of a WSN deployment at a water site using multi-hop data networking

III. COMMON ENERGY SOLUTION MODELS IN WSNs

Considering the energy problems that are associated with WSN systems that are powered by batteries, it is crucial to explore alternative energy sources for the realization of sustainable data communication and a reliable network. Thus, this section presents a review of some alternative energy solutions that could be harnessed to power the WQN in WSN systems. Alternative energy solutions could be utilized to complement the usage of batteries. The alternative solutions can be classified into two basic categories based on ambient energy solutions, and intended energy solutions. These techniques are envisioned to mitigate the energy crisis in wireless systems [105], [106], [107], [108], [109]. For the purpose of clarity, a typical taxonomy of the energy harvesting solutions that are based on ambient and intended sources is given in Fig. 9.

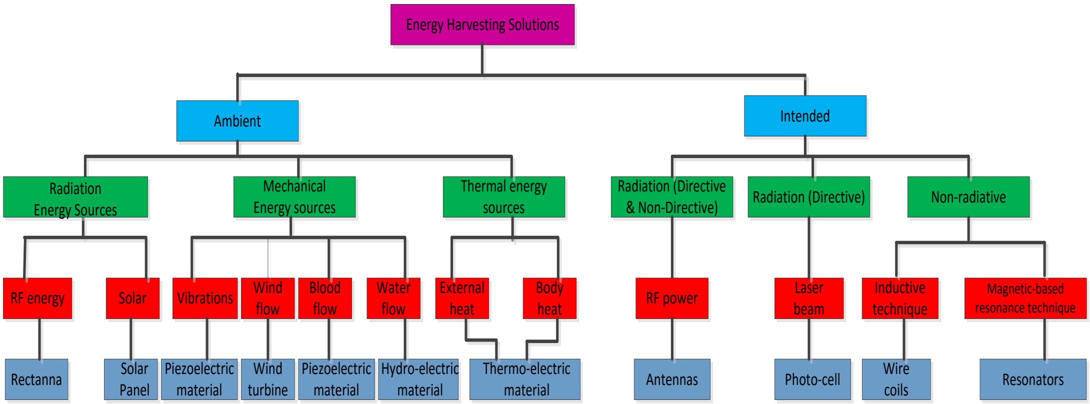

Fig. 9: Taxonomy of a typical energy harvesting solutions based on ambient and intended sources

A. *Classification Based on Ambient Energy Solutions*

In this subsection, we present a brief overview of energy harvesting (EH) solutions in WSNs that are based on ambient sources. Energy harvesting is concerned with the scavenging of energy from renewable energy sources. These types of energy are naturally occurring energy in the environment, and they are therefore freely available. Energy from these sources is green and likewise gives birth to green communication in wireless networks. To exploit the numerous benefits of renewable energy sources, energy harvesting systems are employed. It is worth clarifying that some energy harvesters operate as an AC source, while others are modelled as a DC source. The block diagrams of AC and DC energy harvesters are depicted in Figs. 10 and 11, respectively. It is important to mention that the energy harvested through the reviewed EH techniques cannot be employed directly to power a sensor node, or to store energy directly in a battery device. As a consequence, they are subjected to power conditioning processes that involve AC rectification, and a DC-DC conversion.

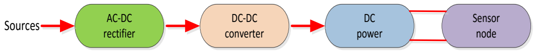

Fig. 10: Energy harvester for AC source

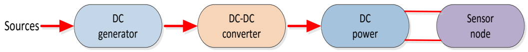

Fig. 11: Energy harvester for DC source

An energy harvesting system can be described as an embedded system in WSNs, employed to address energy problems such as energy scarcity. It is composed of three basic components, namely an energy harvester, energy storage, and an energy management unit [84]. The energy harvester is employed to harvest energy from energy harvesting sources, and converts it into an electrical energy suitable for powering the sensor node components (sensing unit, processing unit, transceiver unit). Thereafter, the generated electrical energy is delivered to the energy management unit for further actions [80].

Several WSN solutions have been proposed using various types of EH techniques to harvest energy from different renewable energy sources. Energy harvesting sources can be classified into three basic categories, namely, radiation energy sources (RF waves, solar), mechanical energy sources (vibrations, wind, water flow, blood flow), and thermal energy sources (external heat, body heat). Examples of EH techniques are solar EH, thermal EH, vibration EH, and radio frequency (RF) EH. A short overview of some of the EH techniques is presented below.

1) Vibrations energy harvesting

Energy can be generated from the vibrations produced by mechanical devices. These vibrations are sources of mechanical energy [110]. By employing a piezoelectric method, the mechanical energy obtained from vibrations can be converted into electrical energy [111], [112]. Vibrations EH are based on AC source as illustrated in Fig. 10. A small number of vibration energy harvesters have been developed. Some examples of vibration harvesting systems for powering WSNs, and where they have been deployed, may be found in references [113], [114], [115], [116] , and [117].

This technique may be applied to WSNs devoted to the monitoring of WQ for powering the sensors in a network. For instance, the authors in [117] adopted a piezoelectric technique to harvest from a vibrational energy source to power a WSN system devoted to the monitoring of WQ. Due to the materials employed, the method has high energy efficiency of about 60% [118]. However, this method is confronted with an issue of charge leakage [119], which may be due to piezoelectric material deterioration. Fig. 12 describes the block diagram of vibration EH.

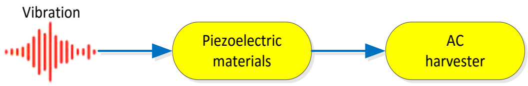

Fig. 12: Diagrammatic representation of vibration EH

2) Solar energy harvesting

Energy can be harvested from light produced by artificial means or by natural means. An example of an artificial light source is a man-made light, such as a torch, while an example of natural light is sunlight (solar). Using a photovoltaic method, the light obtained from the identified sources can be converted into electrical energy [110]. Solar energy harvesting solution models have been developed in [110], [120], [121]. For example, the authors in [91], [94], [122] have considered solar energy for powering WSN systems for monitoring WQ. In the cited references, different harvesting systems have been developed to harvest energy for light environments, either indoor or outdoor. This technique may be applied to WSNs devoted to the monitoring of WQ, to enhance the system viability. The efficiency of this method depends on the efficiency of the photovoltaic (or solar) cell type employed. Some examples of photovoltaic cells are thin-film, mono-crystalline, and poly-silicon. Note that the mono-crystalline type is commonly employed because of its high energy conversion efficiency which is typically less than 25%. Consequently, it is key to underline that this method has a low efficiency [123]. Furthermore, this method is limited when light is not available and also suffer from quick depletion [124]. Solar EH may support both AC and DC sources as illustrated in Figs. 10 and 11 depending on the source of light. As an example, in the case of sunlight, an AC source is applicable, while a DC source is employed in the case of an artificial indoor light that is based on rechargeable cells. Figs. 13 and 14 depict the block diagrams of solar EH from both natural and artificial EH.

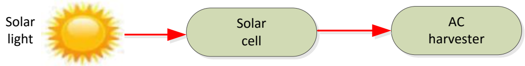

Fig. 13: Diagrammatic representation of solar EH from natural light

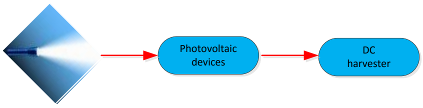

Fig. 14: Diagrammatic representation of solar EH from artificial light

3) Thermal energy harvesting

This technique provides the opportunity to harvest energy from waste heat from sources that include friction, heaters, and furnaces. By exploiting thermal EH, energy can be harvested from thermal gradients, otherwise known as a temperature difference. Using a thermoelectric generator, thermal gradients can be converted into an electrical energy. This method is capable of harvesting thermal energy once a temperature difference is established, and is based on an AC source as illustrated in Fig. 10. Conversely, this method is limited by the failure to maintain a temperature difference between two different metals, which also act as the conductive electrodes in the transducers. This technique is not a suitable candidate for powering WQN, due to the low efficiency of the thermoelectric generators employed for harvesting thermal energy. The efficiency of the thermoelectric generators which is typically less than 11% is a function of the performance of the thermoelectric materials within them [125]. Technically, the efficiency of the thermoelectric generators can be enhanced to improve the output power and the voltage levels of the thermal EH system, by putting multiple thermo-electric materials in place. However, doing so would incur high cost, as well as increasing the size of the EH system. This renders the method only suitable for large scale applications [117]. Some good examples of thermal energy harvesting systems can be found in references [126], [127]. For example, the authors in [127] exploited thermal energy harvesting method to harvest the waste heat from a thermoelectric system. Fig. 15 describes the block diagram of a thermal EH.

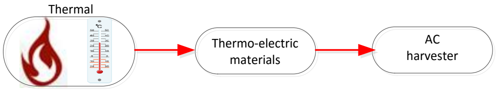

Fig. 15: Diagrammatic representation of thermal EH

4) Water flow energy harvesting

This technique may be explored to harvest a small amount of energy from the flow of water. In this technique, kinetic energy is harvested from the water flowing through a pipe by integrating a hydro-electric (or a water turbine) system that is connected to a DC power generator such as a permanent magnet DC generator. Water EH is based on a DC source as depicted in Fig. 11. This technique has been applied to WSNs for aquaculture and metering applications [128], [129]. Typically, it is more useful and employed in large scale applications, for example hydro-electric dams, where there is continuity in the re-circulation of the water flowing in water pipes. Otherwise, this technique suffers from uncontrollable energy generation when applied to WSN systems, like in the case of solar EH [128], [129]. For instance, EH from water is not possible when the flow of water is zero. Consequently, other techniques are required to make a WSN system operational. Without the integration with multiple methods that may include solar and wind, it will not be functional for powering the sensors in a network. For example, in [130], the authors considered harvesting from multiple energy sources that include water flow, solar, and wind for powering the sensors in their system. Due to some possible intermittent flow in water, the amount of energy harvested at a time may not measure up with the energy requirement of a particular WSN. Also, EH from water requires bulky systems and is complex [131]. Consequently, this technique is still impractical to power WQN in WSN application. Furthermore, it is characterized by low energy efficiency of about 8% due to the low conversion efficiency of the generators used to exploit energy from the flow of water [125]. The block diagram of water EH is illustrated in Fig. 16.

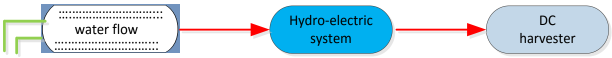

Fig. 13: Diagrammatic representation of water EH

5) Wind energy harvesting

Wind is also a potential source of energy that can be generated in large amounts in coastal areas. Energy can be harvested from the waves produced by wind or air. This involves the utilization of a wind EH system, otherwise known as a wind turbine. A wind EH system employs energy generators such as piezoelectric. Using a piezoelectric generator, a linear motion can be exploited from the blow or flow of wind, which is thereafter converted into electrical energy. Other generators employed for exploiting wind are triboelectric nano-generator, permanent magnet DC generator, series wound DC generator, and shunt wound DC generator [132]. The piezoelectric- and triboelectric nano-generators are based on an AC source, while the permanent magnet DC generator, series wound DC generator, and shunt wound DC generator are based on a DC source. A wind turbine for harvesting energy from wind may either exploit an AC source block or a DC source block as described in Figs. 10 and 11 depending on the adopted generator. This technique may be combined with other methods and applied to WSNs dedicated to the monitoring of WQ, to enhance the lifetime of the system. Unfortunately, wind energy harvesting is limited by fluctuations in the strength of the wind, low flow rates, low energy efficiency of about 38.28% [133], as the generators commonly employed in the exploitation of wind energy suffers from low conversion efficiency [125], and the unpredictable nature of flow sources [110]. Some examples and where they have been developed are found in references [134], [135]. For example, in [134], a wind energy conversion system was developed to power WSN applications. Fig. 17 describes the block diagram of a wind EH.

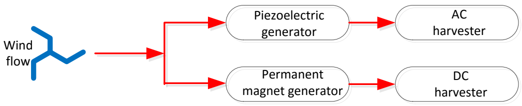

Fig. 17: Diagrammatic representation of wind EH.

6) Radio frequency energy harvesting

RF energy can be described as the radiation of electromagnetic (EM) waves. An electromagnetic wave or radio frequency (RF) energy can be radiated in a frequency range of 3 kHz to about 300 GHz [124]. RF energy harvesting describes the process of scavenging energy from electromagnetic (RF) wave radiations. To achieve this, a rectifying antenna (rectenna) is employed to acquire and convert the RF waves from RF sources into electrical energy as described in Fig. 18, while the AC block in in Fig. 10 is employed for necessary rectification for necessary rectification. However, when little beam shaping is applied, this method experiences low efficiency when the RF wave spreads omnidirectionally from the source.

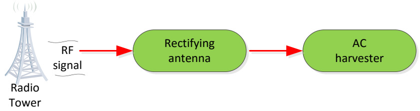

Fig. 18: Diagrammatic representation of RF EH process

RF energy sources can be categorized into two groups [136], namely ambient RF energy sources, and dedicated RF energy sources. Ambient-based RF sources are not primarily dedicated to the transfer of RF energy, but they are freely available for harvesting to EH devices such as EH WQN. Consequently, their availability is not predictable. Also, the ambient-based method has low energy efficiency with an increasing transmission distance. Examples of ambient RF energy sources include television towers, radio towers, microwaves, WiFi routers, and cell phones [110]. Dedicated RF energy sources are often employed for RF energy transfer in WQN, where a predictable supply of energy is required. With dedicated RF energy sources, the sources are deployed and committed to the supply of RF energy to the WQN at a pre-defined rate and frequency [136]. Furthermore, a dedicated RF energy source can transfer RF energy to the WQN through the reserved ISM frequency bands. Thus, RF energy sources are controllable, and offer suitable QoS performance for WSN applications [136]. Some good examples of dedicated RF energy sources include the Powercaster transmitter [137], the Cota transmitter [138], and Isotropic RF transmitters [139]. In comparing a dedicated RF energy source with other energy sources that include ambient RF, wind, solar, water and vibrational sources, it has a number of advantageous characteristics [136], such as stable and predictable energy harvesting over a fixed distance.

In summary, various EH sources and techniques have been identified, and their strengths and drawbacks are highlighted. In order to make a WSN application sustainable, a suitable energy source should be considered along with the area of deployment of the WSN application. This simply implies that, as part of the design, the EH WQN should be deployed in areas where the chosen energy source is densely available. Also, to meet the needs of a specific WSN application, two or more energy sources could be hybridized or combined to generate more – and more consistent - energy [84]. Furthermore, some of the EH sources are uncontrollable [124]. Based on their uncontrollable characteristics, they can be classified into various perspectives. Such classifications include [140] uncontrollable and unpredictable, uncontrollable but predictable, partially controllable, and fully controllable. Uncontrollable and unpredictable energy sources are energy sources that cannot be controlled or predicted to generate energy when desired. Uncontrollable but predictable energy sources are energy sources that cannot be harvested when desired, but their behavior can be modelled to determine when energy can be harvested. Partially controllable energy sources can be partially harvested at a desired time. Fully controllable energy sources can be harvested at any desired time. The behavior of this type of energy source is human-controlled. For comparison, a summary of the important reviewed methods is given in Table 4, containing solution approaches, harvesting technique, power density, efficiency, strength, drawbacks, and examples of application systems. The formulated table would assist in making an optimal choice among the identified EH methods.

TABLE 4
EH SOLUTIONS TO ENERGY ISSUES IN WSN

	Energy source	Solution approaches	Harvesting technique	Power Density	Strengths	Drawbacks	Applications	Refs
1.	Vibration	Electric energy is generated through piezoelectric material straining	Piezoelectric	Industrial: 100 µW/cm^2 (1m at 5 Hz) Human: 4 µW/cm^2 (0.5m at 1 Hz)	Predictable High efficiency	Stability issues, Uncontrollable, Unpredictable, Charge leakage	Train route tracking Event monitoring (sabotage activities) Train monitoring	[116] [141] [142] [143]
2.	Solar	Natural light (sunlight) or artificial light (touch light) is converted into electrical energy	Photovoltaic	Indoor: 0.01 W/cm^2, 100 µW/cm^3 Outdoor: 10 mW/cm^2, 100 mW/cm^3	Fully controllable (artificial light) Uncontrollable, but predictable (sunlight)	Intermittent Costly Bulky Light-dependent Low efficiency	Biomedical Wildlife	[84] [104] [121] [144]

3.	Thermal	Temperature gradients are converted into electrical energy	Thermoelectric	Industrial: 10 mW/cm^2 Human: 25 µW/cm^2	Predictable	Uncontrollable Low efficiency	Industry (waste heat energy recovery), Micro-scale application	[126] [127] [145]
4.	Water	Water flow is exploited through a hydro-electric (or a turbine) system that is connected to a DC power generator	Hydro-electric system Permanent magnet DC generator	At a flow velocity of 2 m/s: 16.2 µW/cm^3	Available for harvesting when there is continuity in water flow	Unpredictable Low efficiency May not be useful for some WSN and IoT systems	Metering Aquaculture	[129] [130]
5.	Wind	Wind wave linear motion is exploited and converted into electrical energy	Piezo-turbine Triboelectric	At a wind speed of 5 m/s: 380 µW/cm^3	Available at all times for harvesting no matter how little the flow could be	Uncontrollable Unpredictable Low efficiency May not be useful for some WSN and IoT systems	Water treatment Agriculture	[132] [135] [146]
6.	RF	Electromagnetic waves (RF) are converted into electrical energy	Rectifying antenna/ rectenna	Wi-Fi router: 0.01 µW/cm^2 (2.4 GHz), AM Radio: At 5 Km, 0.02 µW/cm^2 Cell phone: 0.1 µW/cm^2 (900/1800 MHz)	Fully controllable (Dedicated RF energy), Available at all times, Densely available in urban areas	Partially controllable (Ambient RF energy sources) Less available in rural areas, Decrease in efficiency over a long distance (range), resulting in low efficiency	Smart home Aircraft systems Medical Aerospace	[147] [148] [149] [150]

B. Classification Based on Intended Energy Solutions

In this subsection, we present a brief overview of energy transfer (or EH) solutions in WSN that are based on intended sources. An energy transfer technique is an alternative method to harvesting energy at the sensor node. Energy transfer in WSN can also be referred to as a wireless energy recharging technique. This technique is employed to wirelessly transfer energy from a dedicated energy source to an energy harvester or energy receiver at the sensor node. Energy transfer in WSN can be done in two ways [124], namely wired recharging and wireless recharging. Wired recharging is a direct contact approach that involves the use of wires for interconnection of devices for the purpose of energy transfer. This technique would forfeit the essence of wireless network. Wireless recharging is the process of transferring energy to the sensor nodes in a WSN wirelessly. This approach is appropriate for energy transfer in WSN. Examples of EH systems in WSNs that have employed energy recharging through wireless energy transfer techniques can be found in references [102], [151], [152]. In [102], a power beacon was employed to transfer energy to the WQN in a cognitive radio sensor network. The power beacon harvested RF energy from ambient RF energy sources, and delivered the energy harvested through an in-band wireless energy transfer technique. In [151], a cognitive WQN employed a wireless energy transfer technique to receive RF energy from a set of randomly deployed RF energy sources, here referred to as power beacons. In [152], the authors employed an in-band energy transfer technique to transfer the RF energy harvested by a power beacon (energy source) to the cognitive WQN in a cognitive radio sensor network.

To support the operation of WSN applications with various QoS constraints, several energy transfer techniques have been developed. Examples of such techniques include radio frequency energy transfer, energy transfer through laser beam, and coupling-based energy transfer [124], [136], [153]. In what follows, a brief review of the aforementioned techniques is offered.

1) RF energy transfer (or electromagnetic radiation)

RF energy transfer can simply be described as the transmission of RF energy through RF wave radiations from an RF transmitter [154], [155], [106]. Consequently, RF wave radiations serve as a vehicle (or medium) for the delivery of energy. It is important to emphasize that RF energy radiation can be achieved in two ways, namely directive and non-directive. In the case of directive radiation, directed antennas, which may include beamforming techniques, are employed. Non-directive radiation may be implemented by employing omnidirectional antennas.

Since electromagnetic radiation covers a frequency bands of 3 kHz to 300 GHz [124], [136] in the electromagnetic spectrum, RF energy can be harvested or transferred in the specified frequency bands through a far-field wireless transmission method [136]. For example, for WSN applications the radio spectrum of unlicensed ISM such as 902 to 928 MHz (915 MHz center frequency) and 2400 to 2500 MHz (2450 MHz z center frequency) can be used to realize the broadcasting of RF energy. RF energy transfer employs a dedicated RF energy source to transfer RF energy to an energy receiver in an EH sensor node. Dedicated RF energy sources are powerful devices with power transmission capability. In practice, they could be powered either through batteries with higher power or alternating current (AC) input sources. Examples of commercialized dedicated RF energy sources include the Powercaster transmitter, isotropic RF transmitter, and the Cota transmitter [102], [136], [156]. In a similar vein, examples of commercialized RF energy harvesters are the Powercaster receiver [137] and the Cota receiver [136]. As an example, according to [157], [158], [159], it is possible to harvest power that is up to 1.5 mW at a distance of 0.5 m from an RF energy source. Similarly, a 1 μW and a 3.5 mW power have been reported to be harvested at distances of 11 m and 0.6 m respectively based on the Powercaster energy solution at a frequency of 915 MHz [160]. Taking the efficiency of this method into account, an energy charging efficiency of about 75% may be achieved over a short distance in meters, but a decline in efficiency may be experienced over larger distances due to signal attenuation. Note that the efficiency of this method may be enhanced through the exploitation of highly efficient rectennas and energy beamforming strategies [137]. To harvest RF energy from a dedicated RF energy source, an RF energy harvester sends a low-power omnidirectional signal to an RF energy source. Then, the RF energy source transfers the energy requested to the RF energy harvester. Examples of studies where RF energy transfer have been applied are references [3], [4], [102], [151], [152]. For example, this technique has been employed in references [3], [4] to power a WSN system for monitoring of WQ at water sites.

In RF energy transfer, there is no need for any line of sight between the RF source antenna and the RF energy harvester antenna [124], [136]. Energy transfer is done in an omnidirectional manner by the omnidirectional antennas. Consequently, concurrent energy transfer to several WQN in the network is possible [136]. However, there is a decrease in the transmitted energy efficiency as the distance between the RF energy source and the RF energy harvester increases. Furthermore, the RF energy received by each sensor node differs a little due to the distance of each RF energy harvester to the RF energy source. This situation is due to the doubly near-far problem [154].

There are several circuit structures for RF EH and information transmission. They can be classified into four basic categories [136], namely the time switching structure, the power splitting structure, the separated receiver structure, and the integrated receiver structure. Typically, the type of structure employed by a harvesting node determines the operation of such a node in the context of RF EH and information communication. However, it is important to emphasize that there is a trade-off in efficiency between RF EH and information transfer, as each of the processes use different circuits with different sensitivities in terms of signal power [161]. In practice, the circuit structures are employed in a line of research known as wireless powered sensor network (WPSN), where the sensor nodes in such network are powered wirelessly by the harvested RF energy. The building of a WPSN system involves two fundamental blocks. Such blocks may involve a separated architecture or a co-located architecture. Briefly, in a separated architecture, an energy source (or transmitter) and a BS (or data gathering node) are differently located, while an energy source and a BS are combined in a co-located architecture. Due to the integration of an energy source and a BS in the case of a co-located architecture, the two components are mostly called a hybrid access point (or HAP), for the sake of convenience [162].

To demonstrate the transfer of RF energy and RF EH using any of the aforementioned circuit structures, a single dedicated RF energy source, a set of WQNs, and a BS are presented in Fig. 19, while a single HAP and a set of WQNs are considered in Fig. 20. In both cases, the flow of energy and information are represented with a broken line and an unbroken line, respectively. In Fig. 19, a separated architecture is employed to differently deploy a dedicated RF energy source and a BS, such that the deployed dedicated power source operates as a separate entity to wirelessly transfer RF energy to the WQN in a sensing field in the downlink (DL). The WQNs used their harvested energy to transfer the measured information to the BS in a single-hop manner in the uplink (UL), in this case. In Fig. 20, a co-located architecture is adopted to combine a dedicated RF energy source and a BS into a single element, defined as HAP. The HAP performs a dual function, as it transfer RF energy to the sensor nodes in the network in the DL, as well as gathering information from the sensor nodes in the UL. An optional antenna switching system is incorporated in the structures of both Figs. 19 and 20. The consideration of an antenna switching system depends on the used structure (such as time switching structure and power splitting structure). For example, in both time switching structure and power splitting structure, a single antenna may be used, while an antenna switching system is incorporated to control the switching between the energy harvesting system and the data communication system. In a separated receiver structure, each of the energy harvesting and data communication systems has a separate antenna [154].

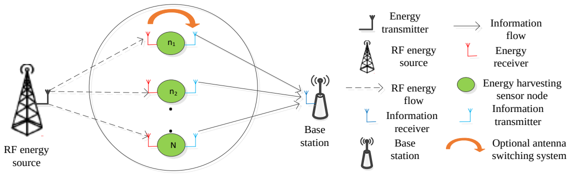

Fig. 19: RF energy transfer and information transmission based on a separated architecture

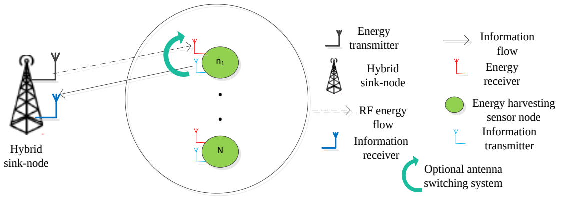

Fig. 20: RF energy transfer and information transmission based on a co-located architecture

2) Energy transfer through laser beam

This approach falls in the category of directed radiation and transfers energy in the form of light through a laser beam, usually by exploiting lasers based on solid-state technology. Laser energy is transferred to an EH sensor node through a high intensity laser beam as shown in Fig. 21. The transferred laser energy is received by a set of photovoltaic (PV) or solar cells embedded in a panel. Thereafter, the received laser energy is converted into an electrical energy by the PV cell. In the electromagnetic spectrum, laser light covers frequency bands of 30 THz to as high as 3 PHz [124]. So, any frequency bands within the aforementioned range of the electromagnetic spectrum can be employed for transmitting laser energy from the laser energy source to the PV cells of the energy harvester. An example of energy transfer through laser beam can be found in [163] where laser was used to transfer light to the working field of a WSN application. The laser beam energy transfer technique can be employed to transfer energy over a long distance. Also note that the charging efficiency of this method depends on the distance between the transmitting station and the receiving node. As a result, this method may achieve up to 98% charging efficiency over a distance of 50m [124]. The reason for the high charging efficiency of this method can be attributed to the narrow beam and high intensity of a laser beam, unlike other sources of lights such as infrared, fluorescent, torch, and solar. However, the amount of harvestable energy by the harvesting node is a function of the conversion efficiency of the PV cell type that is embedded in the harvesting node. Also, laser energy transfer through a laser beam is limited by line of sight (LOS). Furthermore, laser energy transfer through a laser beam is potentially harmful to humans. Some of the light in the frequency region of Terahertz and Petahertz can penetrate living organisms and cause severely negative impact.

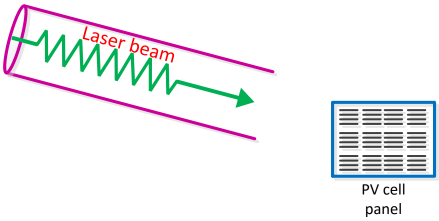

Fig. 21: Laser energy transfer scenario

3) Energy transfer through coupling techniques

Coupling techniques are non-radiation based solutions used for transferring energy from a device to another device by exploiting the magnetic fields that exist between the coils of two devices. This technique has been widely explored in wireless and mobile devices to transfer energy and data. Energy transfer using the coupling method can be classified into two major perspectives, namely inductive coupling and magnetic-resonance coupling, and are discussed in the following subsections.

3.1) Energy transfer through inductive coupling

Inductive coupling can be described as a means by which electrical energy is produced and exchanged based on the principle of electromagnetic induction [164]. This technique is employed often in coil based wireless mobile devices and is easy to implement. Inductive coupling obeys the principles of a conventional transformer, whereby the primary side and the secondary side of the transformer are separated and inductively coupled together to transfer energy [164]. The transmission of energy using inductive coupling is achieved when the primary side of a transmitter coil is used to induce a voltage across a receiver's secondary coil placed in the magnetic field region of the transmitter coil. The magnetic fields between the transmitter coil and the receiver coil is used to transfer energy [124]. A descriptive diagram of wireless energy transfer using inductive coupling is given in Fig. 22.

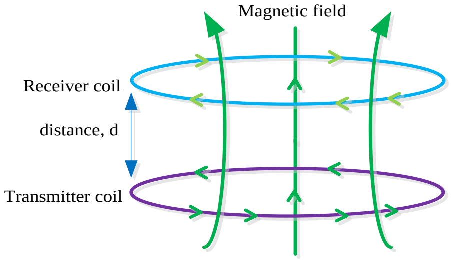

Fig. 22: Transmission of energy in inductive coupling

The inductive energy transfer technique is characterized by non-radiative behavior [164]. Energy transmission based on inductive coupling is limited by a near-field wireless transmission property, and energy transfer is achieved within few millimeters and few centimeters (typically less than one meter) [136], [165]. In inductive coupling, the efficiency of the energy transferred is determined by the distance between the coils. Thus, this method requires a close coil spacing and alignment for efficient energy transfer. Also, it is important to mention that the two coils must maintain the same orientation for this technique to be operational [166], [167]. As a result, for effective energy transfer from the transmitting coil to the receiving coil, a typical short distance of about 3 cm is required for efficiency. Taking such distance into account, it is possible to achieve an efficiency of about 70% [124]. Unfortunately, as the mentioned distance is exceeded, the charging efficiency begins to depreciate. These drawbacks make this technique unsuitable for energy transfer to remote WQN, thereby, limiting its application areas to mobile devices such as medical electronic devices and in smart home applications. In addition, it is not a suitable candidate for powering WQN because of the strict requirements.

3.2) Energy transfer through magnetic-resonance coupling

Magnetic resonance coupling is an interesting means by which energy is wirelessly transferred between two systems, and is characterized by a near-field non-radiative pattern or behavior [168]. Depending on the transmission medium type [164], electric-based or magnetic-based energy transfer may be employed. In the case of electric-based energy transfer, wireless energy transfer is achieved through electric fields, while wireless energy transfer is achieved through magnetic fields in the case of magnetic-based energy transfer. The energy transmission propagation mode of this technique in either case is omnidirectional [164], [166], and in transferring energy between resonant coils, line of sight is not required [168], [169].

With the magnetic resonance technique, wireless energy transfer is achieved when electromagnetic coupling is prominent at a shared resonant frequency [124]. For example in references [170] and [171], when two conductors such as coils couple energy when they are tuned to a resonant frequency of 6.5 MHz and 9.9 MHz, respectively. One of the conductors can be regarded as a transmitting coil, while the other can be regarded as a receiving coil. Different from the inductive coupling technique that requires placing the coils within a close range, with resonance energy transfer can be effectively achieved at a longer distance - within a few centimeters and a few meters. A descriptive diagram of wireless energy transfer using magnetic resonance coupling is given in Fig. 23.

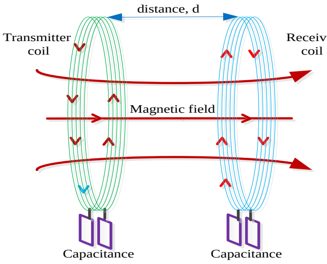

Fig. 23: Example of energy transfer in magnetic resonance coupling

The concept of magnetic resonance technique was employed in [169] to transfer energy to the WQN in a WSN. The authors developed a wireless charging vehicle that travels periodically in the WSN working environment and wirelessly deliver energy to the WQN. In [171], the authors investigated the transfer of energy from a source coil to a receiver coil wirelessly through a non-radiative electromagnetic field. Moreover, examples of commercial solutions based on magnetic coupling techniques can be found in [172], [173], [174].

Regardless of its improved wireless transmission property compared to inductive coupling, an effective wireless transmission can only be achieved for relatively small distances, and a charging efficiency of about 60% may be realized at a charging distance around 2 m [170]. Furthermore, a magnetic-resonance coupling based system is complex to implement. All these limitations make this technique unsuitable for transferring energy to remote WQN, thereby typically limiting its application to mobile devices such as medical equipment.

In summary, the WQN in wireless sensor network applications are energy-hungry devices, which is exacerbated on a system level by the limited energy budget of the batteries which are traditionally employed to power them. As a consequence, the wide-spread deployment of WSNs has been limited in practice. To address this problem, EH from ambient sources has been proposed as an alternative solution to powering the WQN in a network. Unfortunately, this technique is associated with several constraints, which may not contribute to the advancement of WSN application in the context of wide acceptability. Such constraints include the intermittent and unpredictable characteristics of EH solutions that are based on ambient sources, for example in the cases of wind and solar energy sources. With these characteristics, it may be difficult to guarantee the reliability and sustainability of networks that are based on this technique. Due to the limitations of EH solutions that are based on ambient sources, energy solutions that are based on intended sources have been proposed as a promising solution to ending the energy problems in WSN systems. The new technique is based on energy transfer and has attracted much attention in recent years. Some of the key advantages of the EH technique based on the intended sources over the EH technique based on the ambient sources include deterministic and controllable energy supply [138]. Among the energy solutions that are based on the intended sources are methods such as magnetic-resonance and inductive coupling which are characterized by a near-field property, which limits their transmission coverage and application. As well, they are associated with problems that include energy transmitter's coils alignment and energy receiver's cols alignment [175]. Because of these problems, they cannot be employed for remote energy transmission. Furthermore, energy transmission in an intended laser beam can be obstructed, and it is not considered safe for humans due to its operating regions. RF energy transfer technology is more suitable and promising to advance the successful deployment of WSNs. One of the reasons for this can be attributed to its far-field characteristic, which makes it possible to conveniently power a sizeable number of WQ nodes in a network using this technique. A summary of the considered techniques is given in Table 5.

TABLE 5
SUMMARY OF ENERGY TRANSFER TECHNIQUES

	Energy transfer techniques	Approach	Mode and field region	Propagation characteristics	Strengths	Weaknesses	Applications/ Solutions	Refs.
1.	RF energy transfer	Transfers energy through radio frequency waves using antennas such as antenna array	Radiative mode: Far-field / long distance range	Omnidirectional	No line-of-sight, covers a long distance, High efficiency, for example 1.5 m	The energy decreased over a long distance, health and safety challenges	Cognitive radio sensor networks, IoT, Wireless sensor networks, aircraft charging.	[151] [152]
2.	Laser beam energy transfer	Transfers energy in the form of light through either a laser beam or a photocell	Radiative mode: Far-field / long distance range	Directional	It covers a long distance, High efficiency, for example 50 m	It is prone to scattering due to atmospheric conditions that include rain, fog, and cloud, Not safe for humans due to its operation regions, it requires line-of-sight	Wireless sensor networks, Satellite solar power, Unmanned aerial vehicles, Elevation climbers in space	[163]
3.	Inductive coupling	Transfers energy through magnetic fields using wire coils	Non-radiative mode: Near-field / short distance range	Semi-directional/it requires alignment	Ease of operation, High efficiency, for example 3cm	It requires close coil spacing and alignment, Short transmission range	Smart home, Medical implants, Industrial applications	[176] [177]
4.	Magnetic-resonance coupling	Transfers energy through magnetic fields using either resonators or tuned wire coils	Non-radiative mode: Near-field / long distance range	Omnidirectional	It does not require line-of-sight, Short transmission range, Safe,	It is complex to implement	Biomedical implants, Industrial applications, Medical equipment, Implantable devices,	[173] [178] [179]

					High efficiency, for example 2 m		Smart cards	

IV. EQUIPPING WQN WITH ALTERNATIVE ENERGY SOLUTION MODELS

Energy is a scarce resource in WSNs. EH technology has recently emerged as a promising approach to the energy-scarcity problem in WSNs [105], [106], [107], [108], [109]. EH is a process that involves scavenging energy from either ambient energy or intended energy sources, or from both, in a sensor node’s environment through EH systems and schemes [180]. The harvested energy is converted into electrical energy and is thereafter stored in an energy buffer (or energy storage device) such as super-capacitors or batteries, based on a pre-defined random operation and the used components, such as transceivers or microprocessor with respect to a specified mode of operation [181]. The stored energy is used by a sensor node to power its components. To optimally utilize the harvested energy, energy optimization is necessary. Energy optimization is aimed at maximizing the energy efficiency of a sensor node. It is therefore important to study energy harvesting and energy optimization jointly. Energy optimization is essential because the basic operations of a WSN, such as data sensing, processing, and communication, are energy-intensive. EH wireless WQN are better replacements to the traditional battery driven wireless WQN such that the stored energy in an EH sensor node rechargeable battery is repeatedly replenished through energy harvesting, while the limited energy available in a non-rechargeable battery-powered wireless sensor node depletes with time [182].

Unlike a traditional sensor node without EH capability, a conventional sensor node is empowered with EH capability. To achieve this, the hardware of a conventional sensor node presented in Fig. 3 is equipped with EH technology. As a consequence, the power unit of an EH-based sensor node is extended by incorporating an EH system to the power unit [101]. A crucial circuit in an RF EH system is a rectifying antenna [183]. The rectifying antenna helps to convert RF energy into DC power. Technically, the efficiency of an EH system is determined by the sensitivity of the signal power transducer. For example, the sensitivity of an EH system is typically around -30 dBm [184]. As a result of the advances in energy harvesting approaches in wireless networks, an EH unit, which is also referred to as a recharging unit, can be integrated to an energy management system in the power unit, as shown in Fig. 24 [180].

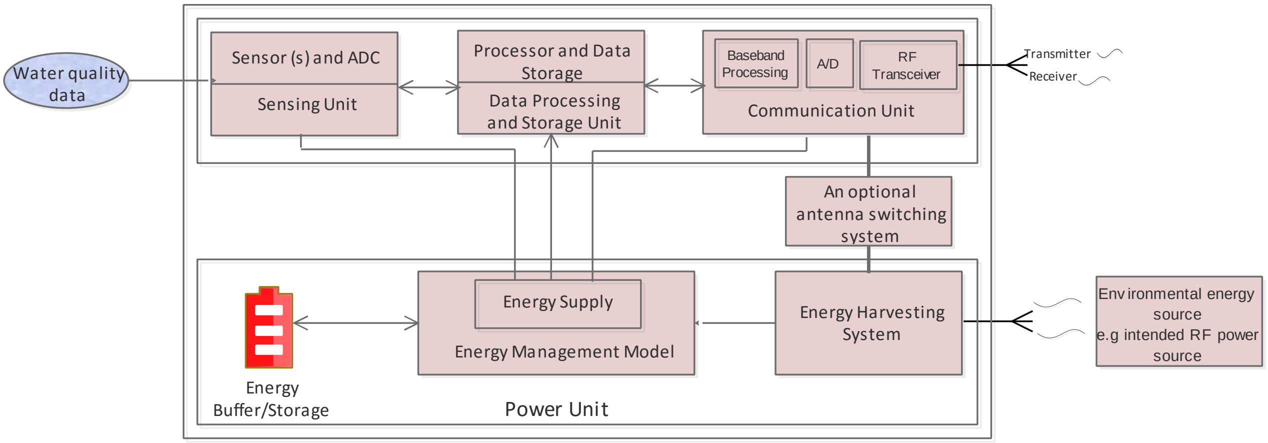

Fig. 24: Structure of a sensor node equipped with energy harvesting technology

V. COMMON OPTIMIZATION TOOLS USED FOR SOLVING ENERGY MINIMIZATION PROBLEMS IN WSNS

In this subsection, we present an overview of optimization in WSNs. Presently, the problem of high energy consumption in WSNs is one of the major focus areas of the WSN research community, since this line of research permeates all aspects of a sensor network. Considering the energy problems in WSNs, and taking into account the unique requirements of WSN-WQM applications that include timely delivery of WQ information, reliable QoS (such as throughput rate), sustainable network communications, and the peculiar features of WQM networks in comparison to other types of WSNs in terms of sampling frequency rate of water quality measurements, processing of the measured data, and communication of measurements in relation to energy cost, it may be difficult to satisfy the requirements of WSN-WQM applications. Also, it is important to take into account the energy requirements of different WQNs in WQM sensor networks for optimizing the total energy consumption of a network as a result of the disparity in energy dissipation among WQNs due to their intended measuring tasks. To address the problem of high energy consumption through optimal utilization of energy resources, energy optimization techniques are crucial. For example, in WSNs, the component that dissipates the most energy in WQNs is the RF transceiver. The RF transceiver of the sensor nodes in a WSN can be controlled by optimizing the rate of power transmission. Importantly, optimization techniques are powerful resource allocation tools that can be applied to WSNs to address the problem of energy scarcity among the WQN in a network by minimizing the energy consumption of a WQN in an efficient manner. This implies that optimization techniques can be employed to control the allocation of power in an optimal manner to solve energy problems such as excessive energy consumption [185]. To address energy consumption problems in WSNs, the physical (PHY) layer and the medium access control (MAC) of the WSN protocol stack model can be optimized [79], [186]. As an example, in a sensor node, the choice of decisions at the PHY layer will influence the whole of the sensor node energy consumption and other protocols.

The impact of the PHY layer in WSN, and on the energy consumption of sensor nodes cannot be overemphasized. Briefly, the PHY layer detects signals (or data streams) and carries out data stream conversion (or data encryption) into suitable signals for transmission over the wireless communication channel. It defines the type of transceiver employed, selection of frequency band, generation of centre frequency, communication medium (such as air), and also includes definition of parameters such as transmission power, modulation scheme, data transmission rate, and data transmission distance (or hop distance). These parameters can be optimized by a network designer to reduce energy consumption.

The MAC layer is responsible for data stream multiplexing, that is, combining multiple signals into one signal. It is also responsible for the detection of the data frame. The MAC layer defines the control of the communication channel (or medium), including error control. These processes are controlled by protocols, which dissipate much of the battery power in WSNs in the absence of robust energy-efficient optimization strategies.

Energy optimization problems in WSNs can be classified into two basic perspectives, namely the linear optimization problem and the non-linear optimization problem [185], and they are determined by three basic parameters which are; the objective function, the constraints, and the decision variables. In optimization, the objective function could be a minimization or maximization function, which is a single expression. An important characteristic of a minimization problem is convexity, while the characteristic of a maximization problem is concavity. The constraints may contain several equalities and inequalities, while there could be one or more decision variable(s).

For a better understanding of the structure of optimization problems, a quick review of the general formulation is provided to illustrate the formulation of energy minimization problem in WSNs. Suppose we have an energy function $f(c,d)$ and we are interested in determining the value for the decision variables c and d that minimizes the energy function $f(c,d)$, where the requirements to be satisfied by c and d are defined by constraints $0 \le p_u(c,d) \le P_u$, $\forall\, u = 1,2,..,v$, $c_a \ge 0, \forall\, a = 1,2,..,\mathrm{A}$, and $d_b \ge 0, \forall\, b = 1,2,..,\mathrm{B}$. Based on the optimization requirements, the optimization problem can then be formulated as:

$$\min_{c,d} \; f(c,d) \tag{1}$$

subject to:

$$0 \le p_u(c,d) \le P_u \,, \forall\, u = 1,2,..,v \tag{2}$$

$$c_a \ge 0, \forall\, a = 1,2,..,\mathrm{A} \tag{3}$$

$$d_b \ge 0, \forall\, b = 1,2,..,\mathrm{B} \tag{4}$$

From the above mathematical model, (1) is the objective function, which is a minimization problem. Technically, the objective function (1) is the design problem, which is to be minimized in the context of this optimization problem. (2) to (4) are the constraints, while the decision variables are c and d. It is important to mention that the decision variable(s) is/are typically used to give an insight into the type of the decision(s) to make in an optimization problem. (3) and (4) are the non-negative constraints for the decision variables. (2) gives a power constraint defined for sensors u, where the maximum allowable transmission power of each sensor u has been bounded (or restricted) by P_u. For simplicity, (2) can be written as:

$$p(c,d) = \begin{bmatrix} p_1(c,d) \\ p_2(c,d) \\ p_3(c,d) \\ \vdots \\ p_v(c,d) \end{bmatrix},$$

and $P = [P_1, P_2, P_3, \dots, P_v]^T$ is a vector for power allocation.

An optimization problem is said to be a linear optimization problem by establishing the linearity of the objective function and all its constraint(s), while an optimization problem becomes a non-linear problem once either the objective function or any of the constraints is not linear. Therefore, the linearity or non-linearity of an optimization problem can only be established based on the objective function and the constraints. A WSN optimization problem is solved by an optimization method in the class of optimization (linear or non-linear) into which such optimization problem falls. Several optimization methods have been developed to seek solutions to various energy problems in WSNs. The major ones among them are considered in this paper. Examples of such include linear programming (or classical optimization), meta-heuristics, heuristics, solution based on problem structure exploration, solution based on soft computing, solutions through dynamic programming, and solutions through geometric programming. The reason why several types of optimization techniques are reviewed in this work is that a single optimization algorithm capable of solving all problems does not exist, so an insight into various optimization techniques is essential to solving various energy problems.

1) Obtaining solutions using linear programming methods

WSN energy optimization problems that fall into the class of linear programming (LP), or convex programming, are solved using classical methods. As an example, if functions $f(c,d)$ and $p_u(c,d)$ that represent the energy (or objective) function and the constraints in (1) and (2), respectively, could be shown to be a convex problem, then it can be solved using the classical methods. To establish that an optimization problem falls into the class of convex programming, two techniques are available, while any one of them can be employed. These techniques are Lagrangian and partial derivatives (either or both first and second). A developed optimization method for providing a solution to an optimization problem is referred to as an optimization problem solver [185]. There are two basic optimization methods for solving WSN LP problems, namely interior point algorithms and simplex methods. These methods are classical methods that employ well-developed tools used to seek optimal solutions to energy problems developed as an LP problem. Examples of both the interior point and the simplex methods, including studies where they were employed to obtain solutions to energy problems in WSNs, are the bisection method [187], [188], the Lagrangian duality method [187], [189], [190], the traveling salesman problem [191], [192], the gradient method [190], [193], the dual-decomposition method [189], [194], and the branch-and-bound method [195].

LP methods have a number of advantages, they can provide optimal solutions to optimization problems and they can also act as bounds for the algorithms obtained using other methods [196]. However, solutions provided through classical optimization methods often result in high complexities in terms of computational time and resources [196]. Because of their high complexities, they consume more resources in the context of energy and memory [197]. Solutions with high complexity are not considered optimal in a real-life or practical WSN scenarios. Moreover, in cases where the solutions provided through classical methods are unreachable or less optimal, non-linear solutions are considered [185], [198]. Thus, a suitable non-linear optimization method can be employed to seek solutions to such problems. More often, because of the structure of energy consumption minimization problems in WSNs, authors mostly resolve to seek optimization algorithms for non-convex problems.

2) Custom methods

Custom-based methods are optimization tools that adopt the concepts of naturally occurring conditions and logical ideas to seek solutions to several categories of optimization problems. They can be classified into two major categories, namely the meta-heuristic methods, and the heuristic methods.

2.1) Obtaining solutions using heuristic methods

Heuristics are algorithms developed by applying the concept of logical ideas. This method is well known for seeking solutions to specific optimization problems in WSN, and they are often sought to find solutions to hard problems. A reason why methods such as heuristics are sought when classical optimization methods could not solve a non-linear problem is because classical optimization methods only have the capabilities for local optimal solutions. A heuristic algorithm can be developed along with any of the well-developed methods for solving non-linear non-convex problems, specifically when a solution with reduced complexity in terms of time and space resources is desired. A heuristic is always developed for a specific problem. This means that a solution sought through a heuristic method to a specific energy problem is not transferrable to other problems. A good number of energy problems have been solved through the development of problem-specific solutions. Solutions are often sought through a heuristic method when other methods such as classical optimization methods could not solve an energy minimization problem, or when the solutions obtained have high complexities and failed to deliver an expected result within a reasonable period of time [196]. Examples of where heuristics solutions have been developed are in maximizing WSN lifetime with respect to energy [195], [199]. Due to the high-complexity issue associated with most classical optimization methods, a heuristic algorithm can be developed to reduce the computational complexity, thus, optimizing the usage of WSN resources in the context of time, energy and memory. Examples of well-developed heuristic methods and studies where they have been applied are water-filling heuristics [200], [201], greedy algorithm [202], [203], and iterative-based and/or recursive-based heuristics [190], [204].

2.2) Obtaining solutions using meta-heuristic methods

Meta-heuristics are algorithms developed by applying the concept of naturally occurring conditions. This method is often used to solve several optimization problems in WSNs. Typically, meta-heuristics are sought to overcome the limitation of a heuristic solution, which is problem-specific. Meta-heuristics have two fundamental properties that include randomization and best solutions selection. The randomization property of meta-heuristics enables solutions to reach a global optimal solution, instead of being restricted to a local optimal solution, as in the case of classical optimization methods. While the best solutions selection property enables meta-heuristic solutions to reach optimal solutions.

Examples of well-developed meta-heuristic methods are evolutionary algorithms. An evolutionary algorithm is a type of algorithm that simulates the evolution of individual structures by selecting, recombining and reproducing mutations, and thus produces better solutions [196]. Some examples of evolutionary algorithms and where they have been employed are krill herd algorithm (KHA) [207], particle swarm optimization (PSO) algorithm [208], [209], ant colony optimization (ACO) [210], [211], and genetic algorithm (GA) [195], [210], [211], to solve energy problems in WSN.

WSN non-linear optimization problems can be classified into two basic types, namely non-linear convex problem and non-linear non-convex problem. A non-linear convex problem is treated as an LP problem if its convexity can be established. Such a problem can be solved by employing the Lagrangian duality method with Karush-Kuhn-Tucker (KKT) conditions, while the solution to such problem is optimal [187]. However, when the convexity of a non-linear problem is not established, then the problem is regarded as a non-linear non-convex problem, which can be solved through other well-developed methods that include particle swarm optimization (PSO) algorithms [205], genetic algorithm (GA) [206], artificial bee colony, and other newly developed algorithms. Solutions obtained to non-linear non-convex problems are regarded as sub-optimal, near-optimal or close-to-optimal. Meta-heuristics are algorithms developed alongside many well-developed methods to solve a wide-range of optimization problems. Meta-heuristic solutions often work well for the problem studied, thereby limiting the chances of transferring the solution to a particular problem to another problem. This technique is often employed to seek solutions to energy problems that are computationally demanding. Furthermore, meta-heuristic algorithms are developed when there is need for globally optimal solutions.

In summary, meta-heuristics and heuristics are custom optimization tools developed when there is a need for a solution to a problem within a reasonable time frame. Meta-heuristics are developed to seek solutions to a range of optimization problems, while a heuristic solution is problem-specific. However, a meta-heuristic algorithm or a heuristic algorithm developed for a range of problems cannot be transferred to other problems. This is the main drawback of these techniques.

3) Obtaining solutions through problem structure exploration

Suppose an optimization problem does not fit into a well-researched and well-known category of optimization problem: different techniques are employed such as reformulating the problem, splitting the problem, or finding an approximation of a function. In most cases, the problems of energy minimization in WSN do not really fall directly into the class of a linear optimization problem. As a result, standard classical optimization methods cannot be directly applied to seek optimal solutions to such problems. In such situations, other methods have been exploited and employed to seek solutions. A very good example of such a method is studying the structure of the formulated energy optimization problem to determine if there are certain parameter(s) that can be modified in a way to turn the problem into a standard problem, and thus, solvable using LP methods. In this manner, the problem becomes easier to solve, and the solution obtained could either be a sub-optimal solution or an optimal solution. The type of solution obtained is determined by the closeness of the reformulated or restructured problem(s) to the initial main formulated problem. A few important approaches based on this technique are examined as follows.

3.1) Solution based on approximation method

An approximation method is one of the techniques that have been employed in studies to seek solutions to energy optimization problems. In some energy optimization problems, certain parameters in the objective functions or the constraints could render the problem non-linear non-convex, and as a result, such problems do not fit into a standard optimization model, thus making it difficult to solve. One of the efficient ways to solve such a problem is to see if there are approximate substitutes for the parameters that rendered the problem non-linear non-convex. Of course, the substituted approximate function should be close to the original parameter. Furthermore, due to the approximate substitute, the solution obtained to such problem may be regarded as either an optimal solution, or a sub-optimal solution. Solutions obtained through the approximation method are useful because the computational complexity and the time required to arrive at a solution are reduced as a result of the substituted approximate function. Solution by the approximation approach has been employed in various studies to solve energy optimization problems. Examples of studies where an approximation-based method has been applied are found in references [190], [212], [213], and [214]. For example, in [212], the authors improved their WSN system energy efficiency by jointly optimizing the transmit power and data bit allocation.

3.2) Solution based on reformulation method

This method is one of the techniques commonly employed in studies to seek solutions to hard non-polynomial (NP) energy optimization problems in WSN. Certain features, once identified in a formulated problem, can be exploited to derive a reformulation of the originally formulated problem, without affecting the overall details of the initial problem. The reformulated version of the original problem can then be solved by employing classical optimization methods. A reformulation method has been employed in studies to seek solutions to energy optimization problems. For instance, the authors in [187] and [188] have employed this method to reformulate their original formulated non-convex energy maximization problem into a convex problem in order to seek an optimal solution to their power allocation problem. The major setback of this approach is obtaining the exact structure of some energy problems.

3.3) Solution based on decomposition method

This method is concerned with studying the structure of a formulated energy optimization problem and determines if the problem can be split into sub-problems to make it simpler to solve, but without a negative impact on the problem solution. Each of the decomposed sub-problems is solved individually, and thereafter, the solutions obtained to each sub-problem are combined. A decomposition method has been employed in studies to seek solutions to energy optimization problems. For instance, the authors in [189] and [194] have employed decomposition methods to obtain solutions to their formulated energy maximization problems. The major limitation of this method is that it is not applicable to every energy problem, while this method can also cause some integral parts of the original problem to be omitted in the cause of decomposition.

3.4) Solution based on linearization method

This method could be applied to a non-linear optimization problem based on the structure of the problem, to seek possible linearization to such a problem. In most cases, energy minimization problems are in non-linear forms. For example, an energy optimization problem automatically becomes a non-linear problem once either the objective function or any of the constraints is not linear. In such a situation, linearization is a useful technique that can be exploited to carefully linearize the function(s) that contains non-linear terms. If the linearization process of the non-linear function(s) is successful, then it becomes quite easy to seek solutions to the optimization problem by employing any of the classical optimization methods, even though the solutions obtained to such problem may be sub-optimal due to the linearization of the original function. Consequently, the type of solution that is obtained to such problem is determined by the closeness of the linearized function to the original function. This method has been explored by the authors in [215] and [216] to convert their non-linear energy optimization problems to simpler ones by linearizing the functions that made the optimization problems non-linear.

4) Solution based on the soft computing method

Soft computing is a fairly recent method for seeking solutions to energy optimization problems in WSNs. The soft computing method involves computer-based software, which controls the resource allocation to the WQNs in a network. The software developed for resource allocation incorporates advanced learning and optimization programming techniques, to drive the software during optimization. Examples of such learning and optimization programming techniques resort in the artificial intelligence field, including stochastic algorithms (such as evolutionary strategy, simulated annealing, ant colony optimization, particle swarm optimization), machine learning strategies (such as Q-learning), fuzzy systems (such as fuzzy logic), and artificial neural networks (such as Bayesian network). For instance, a fuzzy logic strategy was employed by the author in [217] to minimize energy consumption in a wireless sensor network. In [218], a stochastic algorithm based on particle swarm optimization was sought to address the problem of energy consumption minimization in the developed wireless sensor network application. Examples of works where Q-learning methods have been explored for energy utilization control are references [219], [220], [221], [222], [223], [224]. For example, in [219] a Q-learning technique was exploited to optimize the transmit power of the WQN in a wireless sensor network in an attempt to minimize the overall network energy consumption. However, this method is difficult to develop, as well as complex to apply to real-life situations.

5*) Obtaining solutions through dynamic programming*

This technique is an important optimization algorithm that was put forward around 1950 by Richard Bellman to seek solutions to optimization problems [225]. In dynamic programming, an optimization problem is decomposed into stages (or sub-sub-problems) that are similar to the original problem, but small in size. The stages of the sub-problems are dependent on each other (or they overlap), unlike the case of a divide-and-conquer approach, where a problem is decomposed into sub-problems while each sub-problem is independent. The main reason for decomposing the original problem into stages of sub-problem is to make a decision that optimizes the design problem at each stage of sub-problem. The stages of the sub-problems are solved recursively in a sequential manner during an optimization. Consequently, the solutions obtained to each stage of the sub-problems are combined together using recursive equations to form a solution to the original problem. The solution obtained to the original problem in dynamic programming may be viewed as a consequence of a sequence of decisions, and the solution obtained may be an optimal one. It is important to mention that the term programming in dynamic programming does not translate to mean computer code, but simply a tabular structure designed to store the solutions to optimization simulations for later use. This makes dynamic programming a computationally efficient technique, as it eliminates the need to further re-compute already computed sub-sub-problems when encountered again. Dynamic programming tools have been exploited in references [186], [226], and [227] to seek solutions to energy problems. For instance, the design goals in [226] were defined to ensure fairness in energy consumption within the WQNs in a network, as well as the minimization of the overall network energy consumption, by investigating a network configuration problem in WSN in the context of topology control and sensor placement. The essence of the sensor placement problem was to find optimal positions to minimize energy consumption, and an optimization-based power control model was sought for the management of the network topology. To address the topology control and sensor placement problems in an energy-efficient fashion, a dynamic programming technique is employed and the problems are treated as sub-problems based on the optimization model. In [186], the energy consumption minimization problem in a wireless sensor network is considered. To seek a solution to the formulated energy problem, a dynamic programming technique is employed, while the energy minimization problem is decomposed into sub-problems. Through the application of the dynamic programming optimization algorithm, an optimal solution was obtained to the original problem. In [227], the authors employed a dynamic programming algorithm to optimize the transmission power of the WQNs in a wireless powered sensor network during information transmission in the uplink. The optimization of the power allocation is a critical design goal in wireless sensor networks in order to minimize the network overall energy consumption.

One of the advantages of this technique is computational efficiency. It stores its results in a tabular form, which is quickly searched whenever it encounters the same problems that have been previously solved, thus, making this technique a time-efficient approach. Some of the limitations of dynamic programming include its restriction to optimization problems with an overlapping sub-problems structure, and the need for more expertise, which makes this method difficult to develop.

6*) Obtaining solutions through geometric programming*

This method is an indispensable optimization tool for solving energy resource allocation problems in wireless networks for efficient utilization of energy resources. It was put forward around 1967 by Zener, Duffin, and Peterson [228], [229], [230]. Typically, a geometric programming (GP) tool is employed for minimizing energy consumption in WSNs by optimizing the transmission power of each sensor node in a network [231]. It is also useful for seeking solutions to maximization problems in WSNs as well. This requires finding the inverse of the maximization problem and recasting it as a minimization problem [232]. GP is a special type of non-linear programming problem, where the technique is used to cast a non-linear problem into a convex problem. To achieve this, a non-linear problem is converted into a geometric problem form as described by (5) – (7), by turning the objective function of the optimization problem into a linear problem, while the constraints are cast as non-linear functions. The general formulation of a geometric optimization problem is developed by representing an objective function in a posynomial form and minimizing it over monomial equality and posynomial inequality constraints, as described in (5) – (7).

$$min\ f(c) \tag{5}$$

subject to:

$$f_a(c) \leq 1, \forall\, a = 1, 2, .., \mathrm{q} \tag{6}$$

$$d_a(c) = 1,\ \forall\, a = 1, 2, .., j \tag{7}$$

From the above mathematical derivations, (5) and (6) are posynomial functions that results from the addition of the monomial functions $f, \dots, f_q$, $a = 0, 1, 2, .., \mathrm{q}$, while c_a are variables and should be positive numbers such that $c_a > 0$. It is important to note that a monomial means a single function. (7) represents monomial functions containing d_a, $a = 1, 2, .., j$ and is defined by $d\colon \Re_+^j \to \Re$. Examples of well-known computational techniques that can be applied to GP problems are primal methods (such as primal decomposition) and dual techniques (such as dual decomposition and Lagrangian duality). The GP technique has been employed by the works in references [233], [234] and [235] to seek solutions to energy minimization problems. For example, the authors in [233] and [234] did a double transformation in their work. First they transformed their formulated energy consumption minimization problem, which is a non-convex problem, into a GP problem. Thereafter, the GP problem was transformed in to a convex problem.

In summary, the critical optimization methods that are exploited and employed by researchers in literature to seek solutions to their formulated energy consumption problems have been examined and grouped, discussing their strengths and weaknesses. The synopsis of the optimization solution methods is presented in Table 6. Currently, a single optimization algorithm that is capable of solving all problems does not exist. So, choosing an algorithm to seek a solution to an optimization problem is a critical design decision. The reason for this is that the suitability of an optimization algorithm will determine the optimality of the type of solution obtained to a particular problem. Consequently, choosing an efficient algorithm to an optimization problem is essential. Moreover, due to the energy problems in WSNs, energy resource optimization is a crucial design objective for effective utilization in WSN applications. In addition, one of key requirements of WSN systems for WQM application is energy efficient information transmission [32]. To meet this requirement, optimization is an important tool to control the power allocation process in an efficient manner, thus, minimizing energy.

TABLE 6
OPTIMIZATION SOLUTION TECHNIQUES TO ENERGY PROBLEMS IN WSN

	Optimization techniques	Solution methods	Strengths	Weaknesses	Ref.
1.	Linear programming	Interior point methods and simplex methods. Examples of interior point methods are Lagrangian duality, bisection method, traveling salesman problem, etc. Examples of simplex methods are branch-and-bound method, dual-decomposition, etc.	It gives an optimal solution to energy problems. Furthermore, the solutions provided by this approach can act as a lower bound or an upper bound to other solution modes.	Solutions obtained through this approach often have high computational and time complexity. It is not all energy problems that fall into this category of standard optimization models.	[196] [197]
2.	Meta-heuristics	Particle swarm optimization, genetic algorithm, ant colony optimization, etc.	It is employed to solve a wide range of energy problems	Solutions obtained through this approach cannot be transferred to other energy problems	[187]
3.	Heuristics	Water-filling algorithm, greedy algorithm, iterative and recursive based algorithms, etc.	It has low computational and time complexity. It provides a quick solution to energy problems	It is problem-specific and it cannot be transferred to other energy problems.	[196]
4.	Solutions based on problem structure exploration	Approximation method, reformulation method, decomposition method, etc.	It gives a low computational and time complexity solution. It gives a near-optimal or optimal solution.	The restructured problem may not be the exact structure of the original problem, as the right form of certain parameters in the original problem may be difficult to obtain	[214]
5.	Soft computing	Fuzzy systems, stochastic algorithm, Q-learning	It is a computer based software that incorporates advanced learning and optimization programming techniques, to solve resource allocation problems.	It is difficult to develop, as well as complex to apply to real-life situations.	[220]
6.	Dynamic programming	Dynamic game algorithm	It has a low computational and time complexity. It gives an optimal solution	It can only be applied to optimization problems with overlapping sub-problems structure. It is different to develop because of the requirement for technical-know-how.	[225] [226]
7.	Geometric programming	Primal methods and dual techniques	It gives a low computational and time complexity. It gives a global optimal solution	It can only be employed if a problem is successfully transformed into a GP standard form.	[229] [230]

It is important to mention that two elements are paramount in achieving simple, low-cost, fast response time and energy-efficient WSN applications. The two key elements include energy supply from a suitable energy source through either energy harvesting techniques or energy transfer methods, and energy consumption minimization through energy optimization techniques. These issues have been discussed as part of the contributions of this work.

In outline, water contamination is an issue that has plagued the public with health issues, both in the developed and in the developing parts of the world. To address this problem, effective water quality monitoring is important to achieve good water quality. Due to the shortcomings of existing WQM analytical approaches and the risks environmental contaminants and water pollutants posed to human health, there is a need to develop energy-efficient wireless sensor systems to address the challenges of the existing WQM systems in a timely manner.

VI. CHALLENGES AND FUTURE PROSPECTS ON ENERGY-EFFICIENT STRATEGIES FOR WSNs IN WQM APPLICATIONS

This review has attempted to examine a wide range of energy-efficient strategies in WSNs for WQM applications. The techniques involve several energy-efficient solution models based on optimization techniques, EH techniques, and wireless energy transfer techniques. The observations made, along with suggestions for further directions on improving the examined energy-efficient solution models are discussed in the following sections.

A. Observations and Further Directions on EH Techniques in WSNs for WQM Applications

The energy harvesting concept simply has to do with energy scavenging from various energy sources. This is done with the help of an EH module in a sensor node. RF EH seems to be more promising for the realization of low-cost and low-power WQN, but the partially controllable nature for ambient sources is challenging. As a result, efficient prediction models should be investigated and developed for ambient RF EH. Furthermore, solar EH seems to have a high power value and is fully controllable, but it is confronted with a number of setbacks such as the inability to function in dark environments. Also, the size of solar panel determines the amount of harvestable energy, while its components are costly. This contradicts the design of a low-cost and portable WQN. Therefore, further research should concentrate on small panels that can address appropriate WSN node form factor. Low-cost solar panels should be investigated further to achieve the aim of low-cost WQN.

B. Observations on Research Issues on Wireless Energy Transfer in WSN for WQM Applications

Among the reviewed wireless energy transfer techniques, the RF energy technique seems to be a promising solution compared to other techniques. The following observations are made:

1) Most of the works on wireless energy transfer (WET) solution models assumes single-hop WET, which may not always be an ideal approach for energy provision and saving in WSN.
2) Wireless WQNs are energy-hungry devices due to the complexities in various computational schemes. Consequently, energy consumption is a major concern in WSN.
3) There is a need to investigate and develop more efficient methods for energy harvesting.
4) WSNs are often powered by intended RF sources, but there is large loss of energy during energy from intended RF power sources.
    a. In RF energy harvesting or transfer, the harvesting rate of RF energy depends on several factors such as the RF receiver antenna's direction, its gain, and the rectifying circuit.
    b. The performance of RF energy harvesters is limited due to a fixed amount of RF energy that can be supplied by practical sources, a low conversion efficiency of the receiver, as low receiver power gain.

Based on the above discussions, the following suggestions for further improvements can be made:

1) Multi-hop WET: further studies should investigate multi-hop WET to improve energy saving and efficiency of energy transfer.
2) Efforts should be intensified on developing improved RF energy harvesters, with more support for multiple frequency band harvesting.
    a. Beamforming antennas: consideration of antenna arrays for energy beamforming to enhance the energy transfer from an intended RF power source to the WQNs in a WSN, is a key future design strategy. The concept of multiple antenna beamforming may be useful since it has the potential to minimize the amount of energy loss during energy broadcasting compared to a single antenna method. It does not have the capability to only enhance the efficiency of energy, but also information transfer efficiency.
    b. High efficiency rectennas: the enhancement of rectenna efficiency should be considered for improved RF-to-DC power transformation.
    c. RF energy receiver circuits: the sensitivity of the RF energy harvester's circuity should be improved to allow conversion of low-power RF waves.
3) Low computational cost algorithms: more practical low-power consumption models should be further investigated.

C. Observations on Research Issues on Wireless Energy Transfer in WSN for WQM Applications

Optimization techniques are vital tools for seeking solutions to various energy problems in WSNs. Energy minimization problems that fall in the category of standard optimization models are easily solvable by employing classical optimization methods such as linear programming (LP) and convex optimization. It is observed that there is no particular standard for developing solutions to energy problems. Also, the developed solution models for energy problems seem to be disjointed. For similar problems, diverse approaches are used to formulate the objective functions, the decision variables, and the constraints. This makes it difficult to determine the focal point in several energy problem definitions.

Several energy models have not considered a number of factors that would have made energy problems more practical. For example, authors have not been paying much attention to the aspect of heterogeneity in WSNs in their problem development. The consideration of the concept will provide an opportunity for more practical cases in WSNs.

Such issues can be attributed to the following reasons:

1) Optimization as a vital tool employed in seeking solutions to energy problems is a dynamic tool with various interpretations. This makes it difficult to arrive at a generalized solution model to seek solutions to energy problems.
2) It is difficult to capture every detail of WSNs in a single model. Consequently, the development of a single energy model that addresses every important detail is not pragmatic.

Based on the above discussions, the following suggestions need further investigation in order to further enhance the productivity of energy models in WSN for WQM applications:

1) Energy consumption models in WSN: low energy consumption models should be further investigated to increase the network lifetime of WQN in WSN applications.
2) Development of efficient power management strategies: power management strategies with efficient dynamic policies that optimize a sensor node’s behaviour based on the energy available, should be further investigated. This is important when attempting to optimally make do with the available energy. To enhance the energy efficiency of a sensor node, efficient power management strategies are crucial. No matter how highly efficient the rectenna of a harvesting node is, without efficient power management strategies in place, such efforts may not guarantee a better performance.
3) Heterogeneous networks/WQNs: a resemblance of heterogeneity can occur in WSNs, and future studies should pay more attention to considering the possibilities of heterogeneity by making proper classification of energy problems in WSNs. By doing so, more practical energy models would be realized.
4) Development of energy-efficient physical layer schemes: in order to make the dream of wide-spread deployment of WSN applications a reality sooner, the development of energy-efficient schemes should be further investigated with the view of achieving low-power units.
5) Development of strategies for optimizing the overall network energy efficiency of WSN in WQM applications: the development of efficient strategies to optimize the overall network energy utilization of wirelessly powered WSN in WQM application. A suitable strategy in this direction is wireless powered sensor network (WPSN) system. WPSN is a new field of research that currently seeks energy efficient strategies, which are still open problems. The need for such strategies could be attributed to the varying energy consumption rates of the WQNs in a network as a result of factors that include the network topology (such as star and cluster), the transmit power, and sensor distances to the base station. Without putting efficient strategies in place, the overall energy consumption of such system is negatively impacted as more energy is consumed by the system when the aforementioned conditions are experienced in a network.
6) Development of efficient wireless powered sensor network systems: due to the inherent doubly near-far situation in WPSN applications - a practical issue in network designs that causes unfairness among the sensor nodes in a network in the context of the energy received, as well as the energy spent on data transmission to the base station - efficient resource allocation optimization schemes are required to realize energy efficient WPSN systems. This is currently an open research problem in practice.

VII. CONCLUSION

Several techniques to solve energy problems in WSN have been reviewed in this paper. The review has identified various challenges, strengths, and weaknesses associated with several energy-efficient techniques based on optimization techniques, EH techniques and wireless energy transfer techniques. Furthermore, a number of suggestions have been made on future directions to further improve on the identified issues. Also, this work is expected to advance the field of water quality monitoring using wireless sensor networks in the context of sustainable network operations. Based on this research, it is envisaged that the effective exploration and exploitation of wireless energy transfer and optimization promise to make sensors in a network devoted to water quality monitoring operational indefinitely.

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body area network", *in Proc. 2014 IEEE 79th Vehicular Technology Conf.*, 2014, pp. 1-6.

Segun O. Olatinwo received the B.Sc degree (Hons.) in computer engineering, and the M.Sc. degree in computer science. He is currently a PhD research scholar at the University of Pretoria, South Africa. He is a registered member of the Council for the Regulation of Engineering in Nigeria (COREN), and the Nigeria Society of Engineers (NSE). 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 communication.

Trudi-H. Joubert received both the B.Eng and M.Eng degrees in electronic engineering with distinction, and earned a Ph.D in electronic engineering from the University of Pretoria, South Africa, in 1996.

From 1987 to 2000, she advanced from Lecturer to Assistant Professor at the University of Pretoria. Between 2001 and 2013, she consulted to the microelectronics industry though 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. In 2013-4, she worked as senior research engineer at 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. Her most recent endeavour is printed electronics biosensors and networks, particularly for water quality monitoring. She has published 16 journal papers, and presented and co-authored 46 *Conf.* proceedings papers.

She is registered as a professional engineer with the Engineering Council of South Africa (ECSA), became a Member (M) of IEEE in 1996, and a Senior Member (SM) in 2015.