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Challenges, Applications and Future of Wireless Sensors in Internet of Things: A Review

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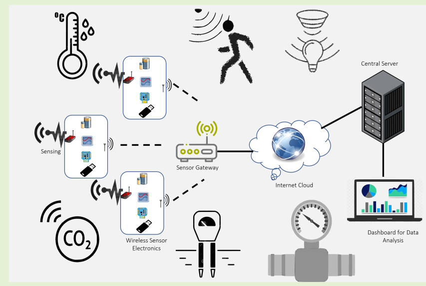
***Abstract*—The addition of massive machine type communication (mMTC) as a category of Fifth Generation (5G) of mobile communication, have increased the popularity of Internet of Things (IoT). The sensors are one of the critical component of any IoT device. Although the sensors posses a well-known historical existence, but their integration in wireless technologies and increased demand in IoT applications have increased their importance and the challenges in terms of design, integration, etc. This survey presents a holistic (historical as well as architectural) overview of wireless sensor (WS) nodes, providing a classical definition, in-depth analysis of different modules involved in the design of a WS node, and the ways in which they can be used to measure a system performance. Using the definition and analysis of a WS node, a more comprehensive classification of WS nodes is provided. Moreover, the need to form a wireless sensor network (WSN), their deployment, and communication protocols is explained. The applications of WS nodes in various use cases have been discussed. Additionally, an overlook of challenges and constraints that these WS nodes face in various environments and during the manufacturing process, are discussed. Their main existing developments which are expected to augment the WS nodes, to meet the requirements of the emerging systems, are also presented.**



***Index Terms*—Future Wireless Communication, Internet of Things (IoT), Sensor Electronics, Wireless Sensor (WS), Wireless Sensor Network (WSN).**

I. INTRODUCTION

SENSORS are capable of accurately estimating the environmental changes, and are known to guide humans since Han dynasty [1]. The seismometer is a sensor developed in 2nd century by Zhang Heng (a Chinese astronomer and mathematician), used to sense earthquakes [2], and the auxanometer and the crescograph are the senors used to measure the growth in plants [3] [4]. Whereas, the galvanometer developed by Hans Christian Ørsted in 1820 (a Danish chemist and physicist) is used to measure the flow of electric current [5]. Moreover, the actinometer developed in 1825 by Sir John Frederick William Herschel (an English astronomer and mathematician) is used to measure thermal power and radiations [6]. Based on the applications, scenarios, and the environment, the sensor(s) can be of different types. For instance, to measure sound/noise levels in a given environment, the acoustic sensors, e.g., hydrophone, microphone, etc., are used [7]. Similarly, thermometer is a popular sensor, used to measure the temperature [8]. To the best of authors' knowledge and information available in the literature, different sensor types are presented in Fig. 1.

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Nowadays, the sensors are playing a vital role in our daily routine tasks, e.g., tactile sensors used in elevators, lamps that are brighten or dim by a touch of hand, fire alarms, motion detectors etc., are a few examples. The advancements in micromachinery have enhanced the expansion of sensors beyond their traditional types as indicated in Fig. 1. The magnetic, angular rate, and gravity, known as MARG, is one of the classic examples of such type of expansion, which is used to estimate the altitude of an aircraft [9]. The Microelectromechanical Systems (MEMS) technology has enabled the manufacturing of these sensors on a microscopic scale [10]. The microsensors developed using different microscopic approaches are comparatively more accurate and faster than the older sensors. Due to the increased demand for rapid, reliable and affordable data access, the lost-cost and easy to use disposable sensors have gain more importance [11].

With the evolution of telecommunication technology, especially, with the advent of wireless communication, more efforts have been put to integrate the sensors with the wireless antennas, that are capable of transmitting sensing information over large distances. The integration of wireless communication technology with the sensors has enabled the humans to gain useful information from hard to reach areas. In current era of Fifth Generation (5G) of mobile communication and beyond, and the addition of massive Machine Type Communication (mMTC) and Ultra-reliable Low Latency Communications (URLLC) use cases have increased the connectivity and reliability of Internet of Things (IoT) devices [12], [13]. It is envisioned that the number of IoT devices will reach 75 billion by 2025, which is significantly going to increase the popularity of sensors in wireless communication domain [14]. This increase in the popularity of IoT devices, will arise a plethora of challenges to meet the end-user requirements. In order to tackle with such challenges, firstly, there is a need to understand the physics behind these sensors, which will result in a more fruitful integration with the wireless domain and in return provide a meaningful platform to address these challenges effectively.

A. Related Work

To the best of authors' knowledge, there is no in-depth survey, covering all aspects (design, applications, and research gaps) of sensors, their integration with wireless infrastructure, and the challenges associated with these Wireless Sensor (WS)s by integrating them with future wireless communication technologies. Nevertheless, there is some work available in the literature that discuss few aspects of WSs briefly. In [15], the authors provide a survey on some applications of WSs and Wireless Sensor Network (WSN)s. Application of WSNs in railway industry has been surveyed in [16]. These two surveys lack the design and integration challenges, as well as a historical perspective of WSs. In [17], a detailed survey on WS is performed, while considering the challenges faced by these WSs in various applications. Although the work on [17] is a state-of-the-art on sensors, it lacks the challenges from the wireless communication (including 5G and beyond technologies) and sensors' electronics perspective. The work of [17], also neglects the environmental constraints that the WS may face. Similarly, the works of [18] and [19] only covers the communication aspect of WSs. There are some other studies as well, that briefly surveys on various aspects of WSs [20]–[24].

There are several Key Performance Indicator (KPI)s that define the efficiency and performance of a WS node as well as its ability to work in a networked environment. In this regard, the work in [25] highlights different methodologies that can be employed to increase the throughput of WSN. The energy efficiency is one of the critical and challenging aspect in a WS node as well as WSN. In [26], a survey on data aggregation and privacy preservation have been carried out to overcome the communication overheads, which in return helps in optimizing the energy budget. Similarly, in [27], tree based techniques have been surveyed for data aggregation in WSs to enhance the battery life of WS nodes. Moreover, in [28], the authors look into various optimization algorithms that can enhance the lifetime of each WS node(s) as well as WSN.

Though there are a number of studies available in the literature that discuss various aspects of WSs as well as WSN, a holistic overview is missing. This significant gap can result in misinterpretation of various design and technical aspects of WS nodes. The aim of this paper is to fill knowledge gaps and provide an updated state-of-the-art survey on WS nodes. In this study, we are aiming to provide a holistic overview of WSs, types and classification of WSs, electronics involved in the design of a WS node, collaboration of WSs to form a WSN, integration of WSs in future communication systems, KPIs, highlighting key research challenges associated with a WS node and some possible solutions. This comprehensive overview will help better understand physics behind a WS providing important insights for a better integration with future communication systems.

B. Contributions

This paper covers various technical and non-technical aspects of sensors, their integration with wireless technologies, and the collaboration of different WSs to form a WSN. It provides an architectural overview of WSs, how they can be used in wireless networks, environmental constraints, their usefulness in modern day applications, and the design challenges that they encounter. We also discuss fundamental KPIs necessary to determine the performance of these WS nodes. The contributions of this paper are summarized as follows:

- We provide a holistic overview of WSs, including various architectural aspects. A modified generic classification of WSs is also provided.
- We provide an in-detail explanation on how numerous WSs can collaborate to form a WSN. The deployment scenarios and communication protocols of a WSN are also covered.
- We explore different applications of WSs, and how the WSs are benefiting and actively playing a key role in various domains.
- We provide a complete list of KPIs that are used to define the performance of any WS nodes. This lead us to identify some of the research challenges and promising research directions, that can be used to optimize and enhance the performance of WSs. We also provide some suggestions and some solutions, that might be used to minimize these issues.

C. Paper Outline

The remainder of the paper is organized as follow: Section II provides a holistic overview of WS nodes. A comprehensive definition and an in-detail architectural overview is also covered in this section. Section III, provides an updated and wholly integrated classification of WS nodes. Section IV, provides an explanation related to the collaboration of numerous WS nodes to form a WSN. Section V discusses some of the applications of WSs by identifying the key areas, in which these WS nodes are actively participating. Section VI, explains the vital performance parameters and how they effect the working of WSs. This section also discusses some of the challenges and open research statements and suggests some possible solution that might be useful to overcome these challenges. Finally, we conclude the paper in Section VII.

II. Wireless Sensors: Definition and Architecture

A modern day sensor/sensor node is a device capable of gathering changes in its vicinity, sometimes capable of pre-processing those changes and then transmitting it to other

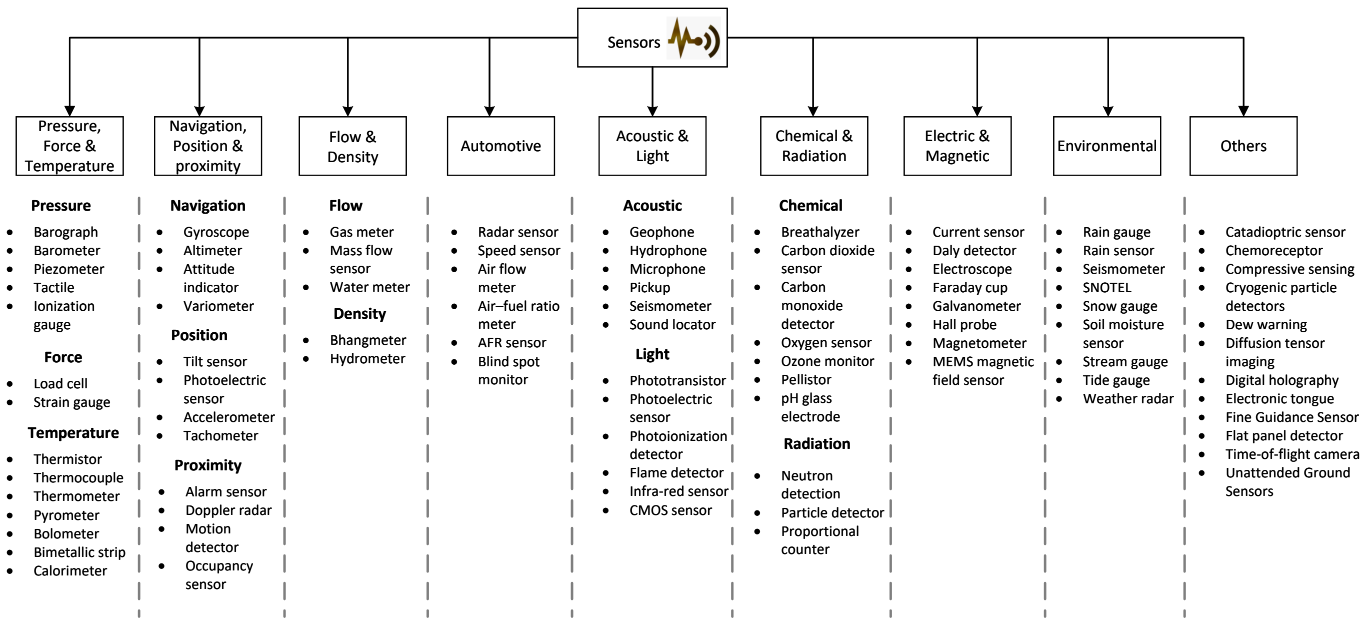

Fig. 1. Types of sensors.

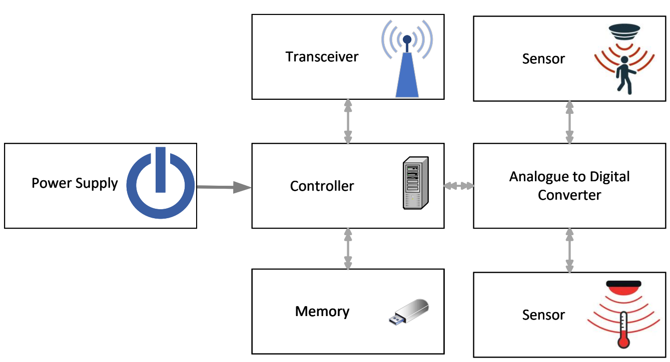

Fig. 2. A classical wireless sensor node architecture.

nodes or directly to the gateway node [29]. A sensor node can also be termed as a mote, and a mote can be a node but a node is not always a mote [30]. The transmitting medium, over which a sensor node transmits its sensing information, can be a wired or a wireless channel [31], and for the scope of this paper, we only focus on the wireless medium.

A. Wireless Sensor Node Architecture

A classical architecture of a WS node is shown in Fig. 2 where a WS node constitutes of five fixed modules and one adjustable module. The fixed modules consist of a fixed power supply, which can also be a battery, with or without rechargeable capabilities. A controller controls the functionality of a WS node by processing the data and performing operational and maintenance activities. A memory module is often added to a WS node, based on the application requirements and to perform programming (algorithms implementation) tasks. A transceiver is used for communicating with other WS nodes and to transmit the sensory information. The analogue to digital converter is used to convert the analogue signal produced by the sensors into a digital form, to make it understandable for the controller. The adjustable module in a WS node is sensor(s), which are entirely application specific. The detailed description of each of these modules is provided in the following.

- **Power Supply**: The power supply is a critical component of any WS node, and can be termed as the heart of it. There are some applications, where these WS nodes can be equipped with a continuous power supply, like for instance, in measuring the thermal heat in data centers etc., [32]. Mostly, the WS nodes are deployed in hard-to-reach locations and are equipped with removable and rechargeable batteries. The lifetime of these batteries is a critical aspect for any WS node. In the development phase of a WS node, it is needed to be ensured that there is enough power supply for a wireless mote to perform the intended sensing operation(s), as it is really hard and costly to replace them very often. Hence, making the energy efficiency as one of the critical and open research statement for WS nodes. There are following three main operations performed by a WS node, that consumes power:
  - Sensing.
  - Communicating.
  - Data processing.

  Among these three operations, the processing of data transmission requires a significant amount of battery power. The cost of energy required in transmitting 1 kb of data at approximately a distance of 330 ft is similar to an execution of 3 million instructions per second [33]. The batteries used by these sensors are classified based on the material used for manufacturing, e.g., lithium-ion, nickel-cadmium, nickel-metal hydride, etc., [34]. Some new WS nodes are also capable to harvest energy from

TABLE I
COMPARISON OF DIFFERENT OPERATING SYSTEMS USED IN WIRELESS SENSORS

Attribute	**TinyOS**	**LiteOS**	**RIOT**	**Contiki**	**PreonVM**
Software language	nesC	C/LiteC++	C/C++/Rust	nesC	C,Java
Execution model	Event driven	Multithreading	Multithreading	Protothread	Multithreading
Kernel	Monolithic	Modular	Microkernel	Modular	-
Real-time support	✗	Partial	✓	Partial	-
Platforms	3ARM7, PXA271	ARM,RISC-V	ARM Cortex	MSP430	ARM Cortex-M3
Low power support	✓	✓	✓	✓	✓
Scheduling	Preemptive	Priority	Multithreading	Preemptive	Multithreading
Network stack	BLIP	-	✓	✓	✓
Communication security	✓	✓	✓	✓	✓
Simulation support	TinySEC	✓	✓	Cooja	✓

various sources, such as, Radio Frequency (RF), solar, vibrations, etc., but require additional electronics [35].

- **Controller**: The controller is referred to as the brain of any WS node, as it controls the functionality of the wireless mote. Commonly, a microcontroller serves the purpose of a controller, but there are other alternatives as well, e.g., Field Programmable Gate Arrays (FPGAs), Digital Signal Processors (DSP), microprocessors, etc., but generally, a microcontroller is preferred because of its lower cost and lower power consumption [36].
- **Memory**: The memory module present on a WS node servers two purposes, one storing sensing data and the other is for programming the device. Generally, the memory requirements are set based on the applications. Mostly, a microcontroller equipped with an on-board memory chip serves as the memory module. In particular, the flash memory is preferred because of their lower cost and more storage [37].
- **Transceiver**: WS nodes equipped with wireless transceiver (ability to both uplink and downlink data) possess the capability of transmitting the sensing information over the wireless channel. The WS nodes, usually transmit their sensing data in Industrial, Scientific and Medical (ISM) band. The transceiver associated with WS nodes usually operates in four states, i.e., receive, transmit, idle and sleep. The modern day transceivers are generally equipped with state machines, that are able to perform some of these operation automatically. It is noted that the power consumption in idle mode is equal to power consumption in receiving mode, and requires some innovative techniques to have a sheer difference between the two states. Similarly, a significant amount of power is consumed while switching between different modes [38].
- **Analogue to Digital Converter**: The sensors produce analogue signals, which need to be converted into a digital form so that it can be readable by a controller. Analogue to digital converter usually acts as an interpreter between controller and the sensor(s) [18].
- **Sensors**: The sensor module is basically the front-end of a WS node and directly interacts with the environment. Based on the intended applications, the sensors can be of various types as shown in Fig. 1.

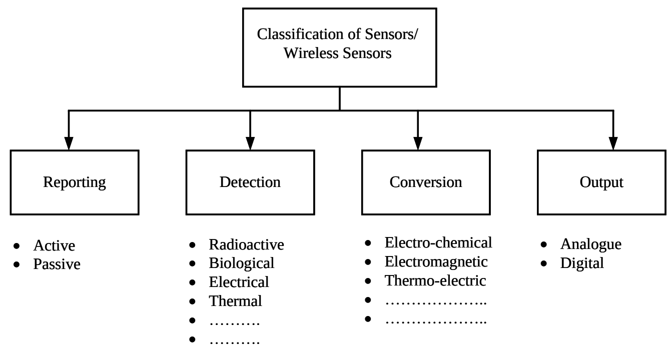

Fig. 3. Classification of wireless sensors.

B. Operating Systems

Similar to a general purpose computer, an operating system with less complexity is usually required for WS nodes. The operating system for WS nodes closely resembles an embedded system and the operating systems such as Embedded Configurable Operating System (eCos), microcontroller operating systems, etc., can serve the application specific needs of WSN [39], [40]. The first ever WSN specific operating system, TinyOS was developed collaboratively by University of California, Intel Research, and Crossbow Technology [41]. Instead of multithreading, TinyOS uses event driven programming model, where a signal is triggered based on the occurrence of an external event [42]. The Lightweight Operating System (LiteOS), developed by Huawei, is fairly a new operating system for WSNs and supports C programming language [43]. RIOT, Contiki and PreonVM are some other examples of operating systems developed specifically for IoT based WS nodes [44]–[46]. A comparison of various attributes of well-known operating systems for WS nodes is shown in Table I.

III. CLASSIFICATION OF WIRELESS SENSORS

WSs can be classified in a variety of ways. Mostly, the work available in the literature have classified the WSs based on their applications [19], [47]–[50]. In [17], the authors classify the WSs based on different factors, such as, deployment, reporting, and monitoring making it purely application specific. Similarly, in [49], six different categories have been identified to classify WSs, which include operational environment, type of sensor node, network, etc., again restricting the classification to intended application. Moreover, the works of [51], [52], classify the WS based on different protocols that each WS node strictly follows to perform intended sensing and data transmission operations.

In this survey, we have provided a simple yet comprehensive classification of WSs as shown in Fig. 3. This simple approach classifies the WSs into four main types listed below:

- Reporting method.
- Detection.
- Conversion.
- Output.

The WSs based on their reporting method can be classified into two groups, i.e., active and passive. Active sensors are periodic, as they continuously transmit the data after meeting a certain threshold, whereas, passive sensors generally transmit the data upon receiving an acknowledgement signal from the sink node/gateway. The sonar and radar are excellent examples of active sensors that require a continuous amount of power supply [53]. The passive sensors can be further subdivide into omnidirectional sensors (no well-defined direction for measurement), and narrow-beam sensors (having a well-defined direction for measurement) [54], [55]. The detection based classification of WSs depends upon the means by which a sensor detects a change in its sensing area. Some classical examples of detection are radioactive, biological, electrical, etc. The classification based on the conversion phenomenon requires a different output in comparison to an input [56]. Electro-chemical, electromagnetic, thermo-electric, etc., are some of the examples of this type of classification [56]. The classification based on the output is divided into two types, i.e., analogue and digital. The analogue sensors produce a continuous signal as an output, whereas the digital signal is produced as outputs by a digital sensor.

IV. Wireless Sensor Networks

The WS nodes are restricted in terms of their transmit power, size, and the coverage area where the physical attributes are needed to be measured. The collaborative use of WS nodes to overcome such limitations and to broaden their sensing horizon lay down the foundation of a WSN. A typical WSN can be defined as a network of spatially distributed WS nodes, which are assigned to measure some specific physical characteristics of an environment or an object, and then forward them to a central/gateway node or to another WS node [57]. Illustration of a typical WSN is shown in Fig. 4 where each WS node gathers their sensing data and transmit the data directly towards the gateway node or to towards the neighbouring WS nodes. Finally, all the sensing data must be received at the gateway node to be gathered at the central server using the internet cloud.

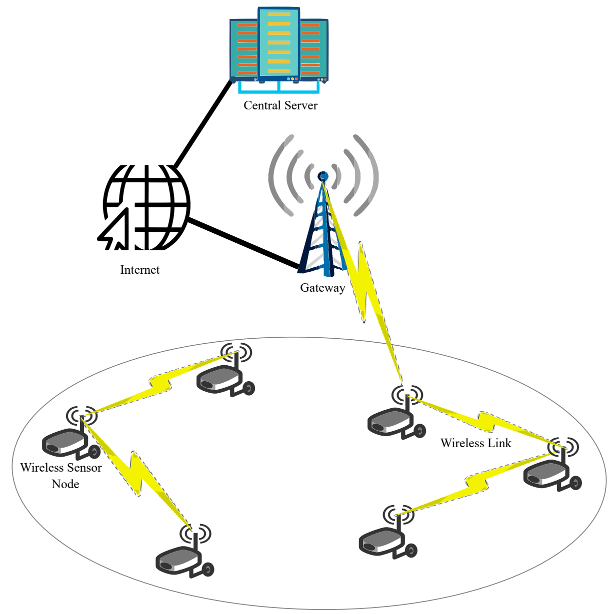

Fig. 4. An illustration of a wireless sensor network.

A. Wireless Sensor Network Topology

The ways in which these WS nodes are deployed in a WSN are termed as WSN topologies. There are numerous ways in which these WS nodes can be deployed within a WSN. Among all the parameters listed previously, the energy efficiency plays a critical role in deciding the topology of a WSN. Based on energy efficiency constraint the toplogies of the WSN can be divided into the following three main types [29], [58]:

- Star.
- Mesh.
- Hybrid.

The star topology follows a layered architecture, where each WS node directly communicate with the gateway and are restricted to perform a cooperative communication (are not allowed to communicate with each other). In star topology, all the WS nodes, must be within the communication range of the gateway. The star topology is helpful in minimizing the power consumption of each WS node, but is permissible for large scale network [59]. In mesh topology, the WS nodes are allowed to communicate with each other and the gateway node as well, if they are within their communication range. The mesh topology is suitable for large scale network and are highly reliable, but are less energy efficient, as compared to star topology [59]. The hybrid topology is a combination of star and mesh topology and usually employed to overcome the limitations of star and mesh topology. In hybrid topology, a WS node having a minimum power level (below a predefined threshold) does not forward data packets of other nodes, hence optimizing the energy efficiency of WSN. The other toplogies proposed in the literature are the evolved version of these three basic topologies. For instance, the digimesh [60] and zigbimesh [61] are the advanced version of a mesh topology. The topologies directly impact the routing of data from a WS node to the gateway node as well as the scheduling of data at each WS node.

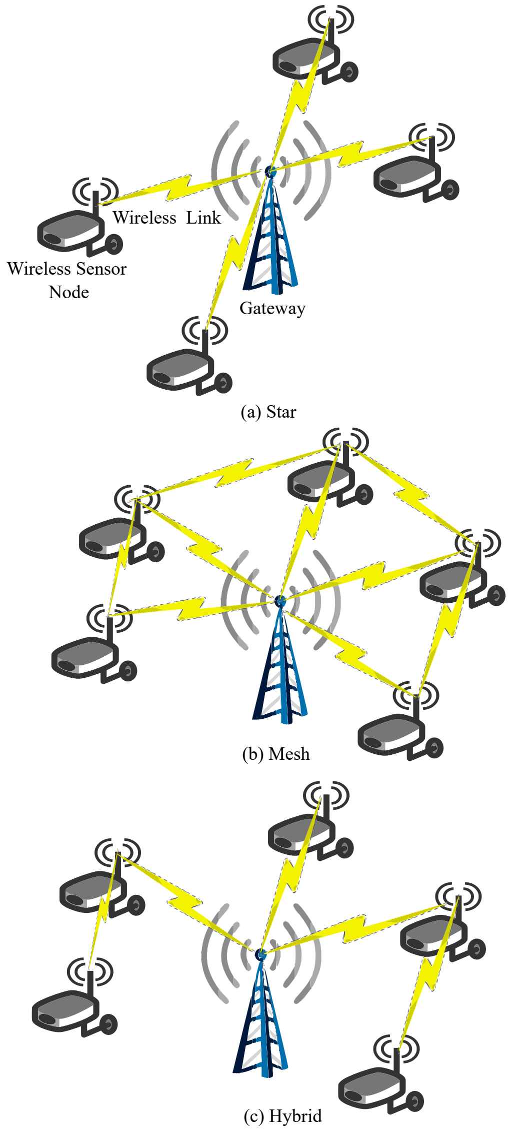

Fig. 5. An illustration of a wireless sensor network topology (a) star, (b) mesh, and (c) hybrid.

B. Communication Protocols

The way in which the WS nodes communicate with each other as well as with the gateway by using a wireless channel, require some wireless standards. These standards are usually defined by IEEE 802.15.4 working group [62]. Zigbee protocol is a wireless network stack of IEEE 802.15.4 that connects WS nodes transmitting data at 2.4 GHz and is usually suited for applications requiring transmission of information over short distances [63]. Thread is fairly a new protocol. It is similar to Zigbee protocol (thread also transmits at 2.4 GHz) and also uses the wireless network stack of IEEE 802.15.4 [64]. The key difference between Zigbee and Thread is the use of Internet Protocol (IP) addressing, i.e., Thread uses IPv6 over Low Power Wireless Personal Area Networks (6LoWPAN) [65] and is encrypted using Advanced Encryption Standard (AES) [66], whereas, Zigbee is built entirely on physical and data link layers [62]. Since, Zigbee and Thread are preferred for short range communication, there are other standards for long range communication. For instance, the Z-wave is usually used for long range communication at 915 MHz, but results in a very low data rate [67]. Low-power Wide-area Network (LPWAN) is yet another technology which provides long range and low power communication between WS nodes and the gateway [68]. Recently, the Narrowband IoT (NB-IoT) and Long Term Evolution for Machines (LTE-M) have emerged as promising technologies for low power IoT devices and can provide connectivity to million of WS nodes by relying on cellular technology [69], [70].

V. Application of Wireless Sensors

The use of WSs is rapidly evolving, and nowadays they are considered as an integral part in performing routine tasks. With the addition of mMTC as a use case in 5G, the popularity and feasibility of using WSs in IoT domain have gain a lot of interest, and it is predicted that the number of connected IoT devices would reach 125 billion by 2030 [82]. There are numerous applications, in which the WSs are actively playing or can play an active role in making the human life more secure, increasing industrial production efficiency, helping towards global warming, etc. Based on the literature, some of the key areas in which WSs are actively participating are listed below:

- Industrial automation.
- Environmental monitoring.
- Healthcare and patient monitoring.
- Livestock & wildlife monitoring.
- Military applications.

Although the WSs are known for decades, here their applications in the above areas are briefly explained. In various industrial verticals, the WSs are proving to be cost effective, as it is estimated that a continuous WS monitoring setup can save energy consumption up to 18%, in comparison to traditional manual periodic checkups [83]. The real time monitoring is made possible by using WSs, which has played a major role in automating various industrial processes. For instance, the inventory can be managed effectively by using the WSs, and can eliminate the fear of over-stocking, replenishing the required products on time, removes burden on productions, etc., [84]. Ocado, one of the leading online supermarkets in United Kingdom, is effectively exploiting the IoT based WSN in increasing the efficiency of their warehouses [85]. To measure the health and efficiency of machinery in real time, the industries are actively employing WSNs [86]. Similarly, a WSN can be used to measure the environmental parameters in any industrial area, such as, raising an alarm for evacuation on detection of any gas leakage, liquid and other harmful stuff, hence saving human life [71].

Modern day equipment, along with bringing an ease to human life, have also brought some byproducts, which are being added to our environment, hence, creating adverse effects. The global warming is one of the byproducts of these luxuries. To prevent human health from these adverse effects, the environmental monitoring is becoming a fundamental thing and is being made possible because of WSs [87]. In an urban environment, a study have been proposed in [72] for measuring

TABLE II
COMPARISON OF LITERATURE USING VARIOUS ATTRIBUTES OF WIRELESS SENSORS & WIRELESS SENSOR NETWORKS

Citation	Operating System	Application	Network Topology	Communication	Energy Harvesting
[71]	-	Industrial	Hybrid	Zigbee	-
[72]	-	Environmental	Star	LTE-M	✓
[73]	-	Healthcare	Star	ZigBee	✗
[74]	-	Healthcare	Star	-	✗
[75]	✓	Livestock	Star	-	-
[76]	✓	Livestock	Hybrid	✓	-
[77]	-	Livestock	Star	ZigBee	✗
[78]	Contiki	Wildlife	Hybrid	RFID & 802.15	✗
[79]	✓	Environmental	Hybrid	✓	✗
[80]	✓	Industrial	✓	✓	✓
[81]	✓	Military	Hybrid	✓	-

the different noise levels in real time using the WS nodes. Similarly, Breathe London is a project which uses WS nodes to measure the quality of air in different parts of London [88]. The impact of deforestation, have also risen the need to measure the growth of trees, plants, etc., in real time as they directly impact the level of oxygen in the environment. In [89], a fast bacteria detection method in olive tree is presented by using WS nodes that can be adaptive to other kinds of trees as well. Moreover, a company, Nature 4.0 is purely dedicated to develop innovative IoT products to save environment from various adverse effects [90]. The TreeTalker (TT +) is one of their products that measure the water consumption, biomass growth, etc., in a tree.

In healthcare sector, the WS nodes are also actively saving human lives. In medical domain, the WS nodes can be implanted inside the human body, can be worn over a specified area of the human body, and they can be embedded in an environment for patient monitoring. In orthopedic, the implantable WS nodes are used to monitor the physical conditions of bones in real time. In [91], an extensive literature survey on implantable WS nodes have been carried out, which identifies the advantages and challenges related to the use of implantable WSs. An example of a body worn WS to treat Cardiovascular patients effectively has been proposed in [73]. It is estimated that in United States, every year, 3 million elderly people are brought to Accidents & Emergency (A&E) for fall-related injuries [92]. Here, the use of WS nodes have been proven to be an effective approach in reducing such injuries [93]. The environment-embedded WSs also play a key role in monitoring the health of patients. In [74] the environment-embedded WS nodes are employed to monitor the health of elderly, in mobile as well as static conditions.

WS nodes are also facilitating the farmers with the real time monitoring of their livestock. To study the animal's activities and behaviour, Commonwealth Scientific and Industrial Research Organisation (CSIRO) have developed a platform using the WS nodes [75]. Similarly, in [76], the authors uses wireless temperature sensors to predict the pregnancy in cows. Moreover, in [94] a livestock health monitoring system is proposed by using the WS nodes, and in [77], an electronic nose (e-nose) is developed using WSs to measure the odors in and around livestock farms. Apart from livestock, WSs are also used to monitor wildlife, to balance and stabilize the ecosystem [78]. In [95], the authors proposes a mechanism based on WS nodes to gather information related to different wildlife species, which in return helps to undertake necessary steps to protect wildlife. Furthermore, the WSs are also being used in various military domains [96]. Military graded unmanned ground vehicles and drones are some of the popular military based applications where WS nodes are playing a key role [97], [98]. In [99], a method of integrating WSs and drones is proposed to effectively perform rescue related operations. In [100], an energy efficient WSN has been proposed to effectively monitor various military related verticals. A comprehensive comparison of literature on WSs/WSNs using various attributes in shown in Table II.

VI. PERFORMANCE INDICATOR, RESEARCH CHALLENGES & FUTURE OF WIRELESS SENSORS

The addition of mMTC as a use case of 5G, have increased the use of IoT devices in industrial as well as user-specific applications. The increased usage of WSs associated with IoT devices have increased the challenges in fulfilling the end-user demands. Standardizing technology, energy efficiency, handling heterogeneous traffic, reducing cost in the design of WS nodes, securing user information, etc., are some of the challenges that are being faced by WSs [101]. In our recent Newsletter, we have showed that the combined use of Multiple-Input-Multiple-Output (MIMO) and Intelligent Reflecting Surfaces (IRS) (see Fig. 6), can be a solution to enhance the energy efficiency and provide privacy to users of WSs, but requires some innovative algorithms and novel hardware designs. Although the challenges related to WSs have been well-addressed in the literature, yet their incorporation in the 5G and beyond have added new challenges. The following are the four important parameters that are used to measure the performance of WS nodes:

- **Interoperability:** The interoperability is the extent to which the WS nodes can communicate with different types of WS devices. This performance parameter impacts the scalability, self-organization, and routing capability of WS nodes.
- **Energy Efficiency:** The energy efficiency directly impacts the lifetime of WS nodes. This parameter indicates how long a sensor can live and successfully performs the intended operation.

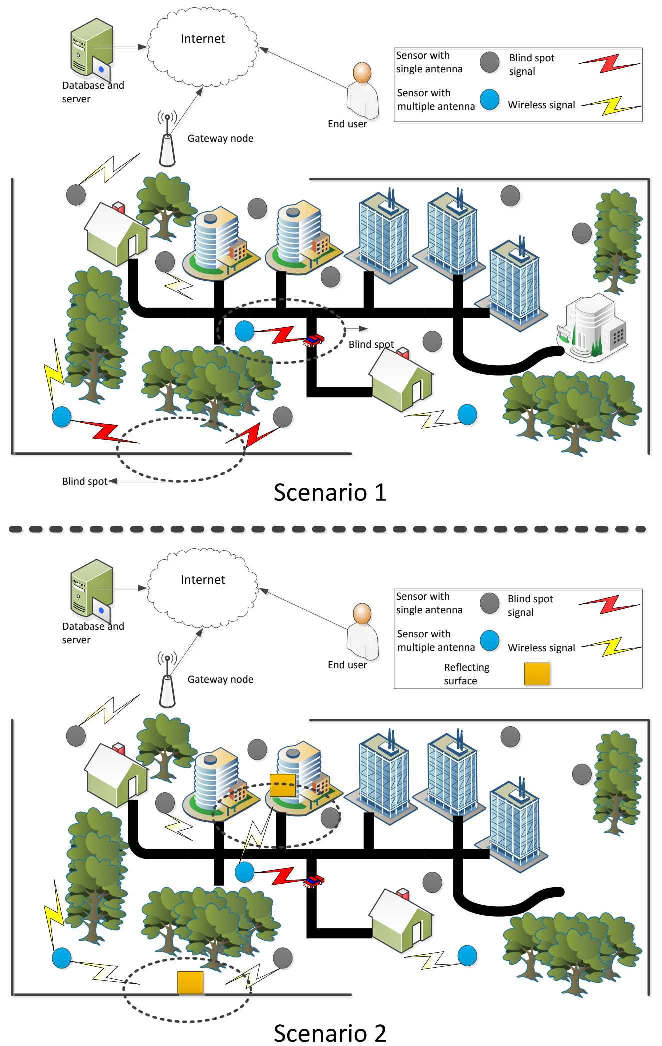

Fig. 6. An Illustration of the combined use of MIMO and IRS to overcome blind spots for WSN [12].

- **Security and Privacy:** This parameter tells the extent to which a WS node can perceive the end-user information and how securely it can transmit sensing information.
- **Coverage:** The coverage capability of a WS node is to sense information in its surrounding radius. The coverage directly impact the energy consumption of a WS node.

Based on these KPIs, the challenges associated with the WS nodes, with some possible solutions are discussed as follows.

A. Interoperability

The rapid increase in the popularity of WSs with the rise of the IoT devices, have significantly increased the level of heterogeneous traffic [102]. Currently, there are more than three hundred different types of IoT platforms available in the market, and each of the platform is working under a closed-ecosystem [103]. This definitely going to increase the issues related to interoperability. The absence of interopearbility is highlighted as an economic threat and it is stated that, solely, the presence of interopearbility between different IoT platforms can increase the potential benefits of IoT devices by 40% [104]. Nevertheless, the need for the solutions to tackle the interoperability is growing. Recently, a multi-layer trust based mechanism has been proposed in [105] to overcome interoperability issues in WSNs. Similarly, in [106], a centralized trust management based approach has been utilized to overcome interoperability. In literature, the use of trust management is considered as an effective way to overcome interoperability, but it adds an additional trust computational burden on resource-constrained WS nodes. In [107], a block-chain based trust management scheme is proposed, that reduces the trust computational load of WS nodes. The use of semantic graph representation approach is yet another way to mitigate the issues related to interoperability in WSNs [108]. The absence of interoperability reduces the scalability of WS nodes. Although, a plethora of research work is available in the literature to deal with the interoperability [109], [110], yet they are unable to overcome it completely. There is a need to work towards the standardization of IoT based WS nodes [111].

B. Energy Efficiency

Sustainability in the design of WS nodes is a challenging task. It is expected that the WS nodes can perform the intended operations for long periods by just relying on a limited power supply. However, replacement of batteries for each WS node is cost-prohibitive or even for some hostile environment applications, it is impossible. The energy consumption requirements of WS nodes varies from application-to-application and each of the WS node in a WSN is designed accordingly [112]. The size of a WS node is yet another factor that limits the use of large batteries. With the increase in the demand for IoT applications, achieving the required amount of energy efficiency is becoming a challenging task. A significant amount of research work have been carried to enhance the energy efficiency of WS nodes by varying various hardware and software parameters. The use of energy efficient scheduling, routing, and clustering algorithms are one of the simplest, yet effective ways to increase the lifetime of WS nodes [113]–[116]. Energy harvesting is another popular way to enhance the lifetime of WS nodes, but requires additional electronics, hence, increases the cost and size of the WS nodes [117]. In [118], the use of compressed sensing have shown to be much effective in prolonging the lifetime of WS nodes, but works effectively for smaller coverage area. The research work available in the literature mostly focuses on software-based algorithms, such as, data-aggregation [119]. However, there exits a significant gap from the hardware perspective. Nowadays, the WS nodes are manufactured to perform numerous tasks, which increases the compromise over power consumption. Therefore, a strong urge in developing WS nodes with net-zero-energy is required.

C. Security and Privacy

The popularity of WS nodes is also raising concerns related to the privacy and security of end-users data. In the context of security and privacy of WS devices, there exists a large gap, due to the lack of security standards [120]. Numerous efforts are being made to solve the security and privacy issues in WS nodes. Radio Frequency Identification (RFID) and new 5G standards are aiming to solve the privacy concerns at hardware level [121], [122]. Whereas, at software level blockchain and key management systems are proving to be effective solutions against security threats [123], [124]. The energy constraints also limits the use of more powerful security protocols is WSs. In [125], a lightweight security algorithm based on intrusion detection is used to provide energy efficient security and privacy in WSs. Similarly, in [126], an energy efficient hybrid intrusion detection based lightweight security and privacy preservation scheme is proposed. The trust-based schemes are also useful in securing the user data in WS nodes, but consumes more energy, in comparison to lightweight algorithm. To address the issues in trust-based security schemes, in [127], the authors propose a new energy efficient trust evaluation scheme. The new technologies, such as blockchain, have also proven to be much effective [128], [129]. Nevertheless, there still exist challenges in achieving the optimal performance in terms of security and privacy and to gain trust of end-users, which imposes a significant impact on the economical growth of IoT-based WSs.

D. Coverage

Covering a sensing region optimally is one of the critical challenge faced by a WS node. Coverage plays a critical role in keeping the energy consumption within the required limits, to maintain the Quality of Service (QoS), and to enhance the lifetime of WS nodes [130]. The physical coverage area of a WS node is defined by the capability of a WS node to sense information in its surrounding radius [131]–[133]. Whereas, in [134], the authors propose a new and more useful definition of coverage based on the cooperation and information received from neighbouring WS nodes. A notable amount of work is available in the literature to solve the coverage related problems of WS nodes. In [135], the authors surveys various strategies to solve the coverage problem of WS nodes. Virtual force, voronoi-based, vector-based, etc., are some of the classical examples of algorithms used to optimize the coverage of a WS node [136]–[138]. A Bee protocol is proposed in [139], to improve the coverage of a WS node, which in return, improves the energy efficiency of WSN. The topology by which each of WS node is deployed in a WSN is also an effective method to improve the coverage of each WS node [140]. However, the increase in the use of WSs in delay-tolerant applications, such as, healthcare, livestock monitoring, etc., have significantly increased the challenges associated in achieving the optimal coverage. Therefore, it is difficult to achieve optimal coverage and energy efficiency at a given instant, and requires some new and innovative techniques.

VII. Conclusion

This paper provides a holistic overview of WS nodes. It starts by providing architectural background of sensors, their types, and how they are integrated with wireless technologies. Afterwards, a generic definition and architecture (exploring both hardware and software domains), of a WS node is explored. A generalized classification of WSs have been provided. Moreover, the collaboration of numerous WS nodes to form a WSN is explained. Furthermore, the applications of WSs in various domains have been discussed. It also highlights some KPIs to measure the performance of a WS node. Finally, based on the KPIs, this survey provides some research problems that are currently being faced by WS nodes. This indeed provides possible future research directions to the research community working on WS nodes. Overall, the aim of this survey is to provide a comprehensive guideline on WS nodes.

References

[1] J. Needham, "Science and civilization in china. volume i," introductory orientations"," *Philosophy*, vol. 30, no. 115, 1955.
[2] A. W. Sleeswyk and N. Sivin, "Dragons and toads. the chinese seismoscope of ad 132," *Chinese Science*, pp. 1–19, 1983.
[3] C. M. Olymbios, "Physiological studies on the growth and development of the carrot, daucus carota l." 1973.
[4] J. C. Bose and G. Das, "Researches on growth and movement in plants by means of the high magnification crescograph," *Proceedings of the Royal Society of London. Series B, Containing Papers of a Biological Character*, vol. 90, no. 631, pp. 364–400, 1919.
[5] J. F. Keithley, *The story of electrical and magnetic measurements: from 500 BC to the 1940s*. John Wiley & Sons, 1999.
[6] M. Gouy and Rigollot, "On an electrochemical actinometer," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 27, no. 166, pp. 288–288, 1889.
[7] G. Sessler, "Acoustic sensors," *Sensors and Actuators A: Physical*, vol. 26, no. 1-3, pp. 323–330, 1991.
[8] V. K. Rai, "Temperature sensors and optical sensors," *Applied Physics B*, vol. 88, no. 2, pp. 297–303, 2007.
[9] J. L. Cookson, "A method for testing the dynamic accuracy of micro-electro-mechanical systems (mems) magnetic, angular rate, and gravity (marg) sensors for inertial navigation systems (ins) and human motion tracking applications," NAVAL POSTGRADUATE SCHOOL MONTEREY CA, Tech. Rep., 2010.
[10] K. Gabriel, J. Jarvis, and W. Trimmer, "Small machines, large opportunities: a report on the emerging field of microdynamics," *National Science Foundation, AT&T Bell Laboratories, Murray Hill, New Jersey, USA*, 1988.
[11] C. Dincer, R. Bruch, E. Costa-Rama, M. T. Fernández-Abedul, A. Merkoçi, A. Manz, G. A. Urban, and F. Güder, "Disposable sensors in diagnostics, food, and environmental monitoring," *Advanced Materials*, vol. 31, no. 30, p. 1806739, 2019.
[12] M. A. Jamshed and M. U. Rehman, "Mimo and irs: Enablers for energy efficient wireless sensor networks," *IEEE IoT Newsletter*, 2021.
[13] S. R. Pokhrel, J. Ding, J. Park, O.-S. Park, and J. Choi, "Towards enabling critical mmtc: A review of urllc within mmtc," *IEEE Access*, vol. 8, pp. 131 796–131 813, 2020.
[14] I. Statista, "Internet of things (iot) connected devices installed base worldwide from 2015 to 2025 (in billions)," *URL: https://www. statista. com/statistics/471264/iot-number-of-connected-devicesworldwide/(Consulté 17/05/2020)*, 2018.
[15] T. Arampatzis, J. Lygeros, and S. Manesis, "A survey of applications of wireless sensors and wireless sensor networks," in *Proceedings of the 2005 IEEE International Symposium on, Mediterrean Conference on Control and Automation Intelligent Control, 2005.* IEEE, 2005, pp. 719–724.
[16] V. J. Hodge, S. O'Keefe, M. Weeks, and A. Moulds, "Wireless sensor networks for condition monitoring in the railway industry: A survey," *IEEE Transactions on intelligent transportation systems*, vol. 16, no. 3, pp. 1088–1106, 2014.
[17] M. Ayaz, M. Ammad-Uddin, I. Baig *et al.*, "Wireless sensor's civil applications, prototypes, and future integration possibilities: A review," *IEEE Sensors Journal*, vol. 18, no. 1, pp. 4–30, 2017.
[18] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," *IEEE Communications magazine*, vol. 40, no. 8, pp. 102–114, 2002.
[19] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," *Computer networks*, vol. 52, no. 12, pp. 2292–2330, 2008.

[20] M. Ali, A. Böhm, and M. Jonsson, “Wireless sensor networks for surveillance applications-a comparative survey of mac protocols,” in *2008 The Fourth International Conference on Wireless and Mobile Communications*. IEEE, 2008, pp. 399–403.

[21] L. Zhaohua and G. Mingjun, “Survey on network lifetime research for wireless sensor networks,” in *2009 2nd IEEE International Conference on Broadband Network & Multimedia Technology*. IEEE, 2009, pp. 899–902.

[22] C. Wang, K. Sohraby, B. Li, M. Daneshmand, and Y. Hu, “A survey of transport protocols for wireless sensor networks,” *IEEE network*, vol. 20, no. 3, pp. 34–40, 2006.

[23] V. Kumar and V. K. Sinha, “Underwater wireless sensor network routing protocols: The survey,” in *2020 2nd International Conference on Advances in Computing, Communication Control and Networking (ICACCCN)*. IEEE, 2020, pp. 359–362.

[24] N. Khalid, R. Mirzavand, and A. K. Iyer, “A survey on battery-less rfid-based wireless sensors,” *Micromachines*, vol. 12, no. 7, p. 819, 2021.

[25] P. Deshpande and M. S. Madankar, “Techniques improving throughput of wireless sensor network: A survey,” in *2015 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2015]*. IEEE, 2015, pp. 1–5.

[26] J. Xu, G. Yang, Z. Chen, and Q. Wang, “A survey on the privacy-preserving data aggregation in wireless sensor networks,” *China Communications*, vol. 12, no. 5, pp. 162–180, 2015.

[27] N. John and A. Jyotsna, “A survey on energy efficient tree-based data aggregation techniques in wireless sensor networks,” in *2018 International Conference on Inventive Research in Computing Applications (ICIRCA)*. IEEE, 2018, pp. 461–465.

[28] R. M. Curry and J. C. Smith, “A survey of optimization algorithms for wireless sensor network lifetime maximization,” *Computers & Industrial Engineering*, vol. 101, pp. 145–166, 2016.

[29] J. S. Wilson, *Sensor technology handbook*. Elsevier, 2004.

[30] K. Malasri and L. Wang, “Design and implementation of a securewireless mote-based medical sensor network,” *Sensors*, vol. 9, no. 8, pp. 6273–6297, 2009.

[31] H. M. A. Fahmy, *Concepts, applications, experimentation and analysis of wireless sensor networks*. Springer Nature, 2020.

[32] X. Wang, X. Wang, G. Xing, J. Chen, C.-X. Lin, and Y. Chen, “Intelligent sensor placement for hot server detection in data centers,” *IEEE Transactions on parallel and distributed systems*, vol. 24, no. 8, pp. 1577–1588, 2012.

[33] A. Rice and S. Hay, “Measuring mobile phone energy consumption for 802.11 wireless networking,” *Pervasive and Mobile Computing*, vol. 6, no. 6, pp. 593–606, 2010.

[34] S. Yasin, T. Ali, U. Draz, A. Shaf, and M. Ayaz, “A parametric performance evaluation of batteries in wireless sensor networks,” in *Recent trends and advances in wireless and IoT-enabled networks*. Springer, 2019, pp. 187–196.

[35] M. Whitaker, “Energy harvester produces power from local environment, eliminating batteries in wireless sensors,” *J. Analog Innov*, vol. 20, pp. 1–36, 2010.

[36] A. Di Nisio, T. Di Noia, C. G. C. Carducci, and M. Spadavecchia, “High dynamic range power consumption measurement in microcontroller-based applications,” *IEEE Transactions on Instrumentation and Measurement*, vol. 65, no. 9, pp. 1968–1976, 2016.

[37] E. Pruteanu and P. Gabriel, “Intelligent measuring system using network wireless sensors for structural diagnostics,” in *2019 22nd International Conference on Control Systems and Computer Science (CSCS)*. IEEE, 2019, pp. 492–495.

[38] M. A. Matin and M. Islam, “Overview of wireless sensor network,” *Wireless sensor networks-technology and protocols*, pp. 1–3, 2012.

[39] G. Thomas, “Ecos: An operating system for embedded systems.” *Dr. Dobb’s Journal: Software Tools for the Professional Programmer*, vol. 25, no. 1, pp. 66–72, 2000.

[40] T. N. B. Anh and S.-L. Tan, “Real-time operating systems for small microcontrollers,” *IEEE micro*, vol. 29, no. 5, pp. 30–45, 2009.

[41] P. Levis and D. Gay, *TinyOS programming*. Cambridge University Press, 2009.

[42] P. Levis, S. Madden, J. Polastre, R. Szewczyk, K. Whitehouse, A. Woo, D. Gay, J. Hill, M. Welsh, E. Brewer *et al.*, “Tinyos: An operating system for sensor networks,” in *Ambient intelligence*. Springer, 2005, pp. 115–148.

[43] X. Wang, “Analysis of thread schedulability in huawei liteos,” in *MATEC Web of Conferences*, vol. 336. EDP Sciences, 2021, p. 05031.

[44] E. Baccelli, C. Gündoğan, O. Hahm, P. Kietzmann, M. S. Lenders, H. Petersen, K. Schleiser, T. C. Schmidt, and M. Wählisch, “Riot: An open source operating system for low-end embedded devices in the iot,” *IEEE Internet of Things Journal*, vol. 5, no. 6, pp. 4428–4440, 2018.

[45] A. Dunkels, B. Gronvall, and T. Voigt, “Contiki-a lightweight and flexible operating system for tiny networked sensors,” in *29th annual IEEE international conference on local computer networks*. IEEE, 2004, pp. 455–462.

[46] “Operating software ”PreonVM” for Preon32 series,” https://web.archive.org/web/20171111094628/ https://www.virtenio.com/en/preonvm-virtual-maschine.html, accessed: 2021-09-15.

[47] E. P. K. Gilbert, B. Kaliaperumal, and E. B. Rajsingh, “Research issues in wireless sensor networkapplications: a survey,” *International Journal of information and electronics engineering*, vol. 2, no. 5, p. 702, 2012.

[48] B. Rashid and M. H. Rehmani, “Applications of wireless sensor networks for urban areas: A survey,” *Journal of network and computer applications*, vol. 60, pp. 192–219, 2016.

[49] L. M. Borges, F. J. Velez, and A. S. Lebres, “Survey on the characterization and classification of wireless sensor network applications,” *IEEE Communications Surveys & Tutorials*, vol. 16, no. 4, pp. 1860–1890, 2014.

[50] Y. Li and M. T. Thai, *Wireless sensor networks and applications*. Springer Science & Business Media, 2008.

[51] S. K. Singh, M. Singh, D. K. Singh *et al.*, “Routing protocols in wireless sensor networks–a survey,” *International Journal of Computer Science & Engineering Survey (IJCSES)*, vol. 1, no. 2, pp. 63–83, 2010.

[52] P. Huang, L. Xiao, S. Soltani, M. W. Mutka, and N. Xi, “The evolution of mac protocols in wireless sensor networks: A survey,” *IEEE communications surveys & tutorials*, vol. 15, no. 1, pp. 101–120, 2012.

[53] J. Minkoff, “Signals, noise, and active sensors- radar, sonar, laser radar((book)),” *New York, John Wiley & Sons, Inc., 1992, 256*, 1992.

[54] Y. Yagi, “Omnidirectional sensing and its applications,” *IEICE transactions on information and systems*, vol. 82, no. 3, pp. 568–579, 1999.

[55] Y. B. Gianchandani and K. Najafi, “Bent-beam strain sensors,” *Journal of Microelectromechanical Systems*, vol. 5, no. 1, pp. 52–58, 1996.

[56] J. Fraden and J. Fraden, *Handbook of modern sensors: physics, designs, and applications*. Springer, 2004, vol. 3.

[57] S. L. Ullo and G. Sinha, “Advances in smart environment monitoring systems using iot and sensors,” *Sensors*, vol. 20, no. 11, p. 3113, 2020.

[58] R. Bogue, “Sensor technology handbook,” *Sensor Review*, 2005.

[59] J. Soparia and N. Bhatt, “A survey on comparative study of wireless sensor network topologies,” *International Journal of Computer Applications*, vol. 87, no. 1, 2014.

[60] M. Y. Fathany and T. Adiono, “Wireless protocol design for smart home on mesh wireless sensor network,” in *2015 International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS)*. IEEE, 2015, pp. 462–467.

[61] H. Salah, S. Alouneh, A. Al-Assaf, K. Darabkh *et al.*, “Performance evaluation of digimesh and zigbee wireless mesh networks,” in *2018 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)*. IEEE, 2018, pp. 1–6.

[62] A. F. Molisch, K. Balakrishnan, C.-C. Chong, S. Emami, A. Fort, J. Karedal, J. Kunisch, H. Schantz, U. Schuster, and K. Siwiak, “Ieee 802.15. 4a channel model-final report,” *IEEE P802*, vol. 15, no. 04, p. 0662, 2004.

[63] T. de Almeida Oliveira and E. P. Godoy, “Zigbee wireless dynamic sensor networks: feasibility analysis and implementation guide,” *IEEE Sensors Journal*, vol. 16, no. 11, pp. 4614–4621, 2016.

[64] H.-S. Kim, S. Kumar, and D. E. Culler, “Thread/openthread: A compromise in low-power wireless multihop network architecture for the internet of things,” *IEEE Communications Magazine*, vol. 57, no. 7, pp. 55–61, 2019.

[65] Z. Shelby and C. Bormann, *6LoWPAN: The wireless embedded Internet*. John Wiley & Sons, 2011, vol. 43.

[66] V. Rijmen and J. Daemen, “Advanced encryption standard,” *Proceedings of Federal Information Processing Standards Publications, National Institute of Standards and Technology*, pp. 19–22, 2001.

[67] I. Unwala and J. Lu, “Iot protocols: Z-wave and thread,” *International Journal on Future Revolution in Computer Science & Communication Engineering*, vol. 3, no. 11, pp. 355–359, 2017.

[68] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, “A comparative study of lpwan technologies for large-scale iot deployment,” *ICT express*, vol. 5, no. 1, pp. 1–7, 2019.

[69] R. Ratasuk, B. Vejlgaard, N. Mangalvedhe, and A. Ghosh, "Nb-iot system for m2m communication," in *2016 IEEE wireless communications and networking conference*. IEEE, 2016, pp. 1–5.

[70] R. Ratasuk, N. Mangalvedhe, D. Bhatoolaul, and A. Ghosh, "Lte-m evolution towards 5g massive mtc," in *2017 IEEE Globecom Workshops (GC Wkshps)*. IEEE, 2017, pp. 1–6.

[71] S. Shinde, S. Patil, and A. Patil, "Development of movable gas tanker leakage detection using wireless sensor network based on embedded system," *International Journal of Engineering Research and Application (IJTERA)*, vol. 2, no. 6, pp. 1180–1183, 2012.

[72] L. Luo, H. Qin, X. Song, M. Wang, H. Qiu, and Z. Zhou, "Wireless sensor networks for noise measurement and acoustic event recognitions in urban environments," *Sensors*, vol. 20, no. 7, p. 2093, 2020.

[73] U. Gogate and J. Bakal, "Healthcare monitoring system based on wireless sensor network for cardiac patients," *Biomedical & Pharmacology Journal*, vol. 11, no. 3, p. 1681, 2018.

[74] V. Vaidehi, M. Vardhini, H. Yogeshwaran, G. Inbasagar, R. Bhargavi, and C. S. Hemalatha, "Agent based health monitoring of elderly people in indoor environments using wireless sensor networks," *Procedia Computer Science*, vol. 19, pp. 64–71, 2013.

[75] Y. Guo, P. Corke, G. Poulton, T. Wark, G. Bishop-Hurley, and D. Swain, "Animal behaviour understanding using wireless sensor networks," in *Proceedings. 2006 31st IEEE Conference on Local Computer Networks*. IEEE, 2006, pp. 607–614.

[76] A. H. H. Nograles and F. S. Caluyo, "Wireless system for pregnancy detection in cows by monitoring temperature changes in body," in *2013 IEEE 9th International Colloquium on Signal Processing and its Applications*. IEEE, 2013, pp. 11–16.

[77] L. Pan and S. X. Yang, "An electronic nose network system for online monitoring of livestock farm odors," *IEEE/ASME Transactions on mechatronics*, vol. 14, no. 3, pp. 371–376, 2009.

[78] V. Dyo, S. A. Ellwood, D. W. Macdonald, A. Markham, N. Trigoni, R. Wohlers, C. Mascolo, B. Pásztor, S. Scellato, and K. Yousef, "Wildsensing: Design and deployment of a sustainable sensor network for wildlife monitoring," *ACM Transactions on Sensor Networks (TOSN)*, vol. 8, no. 4, pp. 1–33, 2012.

[79] Y. Wei, H. Wang, K. F. Tsang, Y. Liu, C. K. Wu, H. Zhu, Y.-T. Chow, and F. H. Hung, "Proximity environmental feature based tree health assessment scheme using internet of things and machine learning algorithm," *Sensors*, vol. 19, no. 14, p. 3115, 2019.

[80] Y.-Y. Chen and Y.-H. Lin, "A smart autonomous time-and frequency-domain analysis current sensor-based power meter prototype developed over fog-cloud analytics for demand-side management," *Sensors*, vol. 19, no. 20, p. 4443, 2019.

[81] S. H. Lee, S. Lee, H. Song, and H. S. Lee, "Wireless sensor network design for tactical military applications: Remote large-scale environments," in *MILCOM 2009-2009 IEEE Military communications conference*. IEEE, 2009, pp. 1–7.

[82] I. Markit, "The internet of things: a movement, not a market," *Critical IoT Insights*, pp. 1–9, 2017.

[83] D.-S. Kim and H. Tran-Dang, "Wireless sensor networks for industrial applications," in *Industrial Sensors and Controls in Communication Networks*. Springer, 2019, pp. 127–140.

[84] V. C. Gungor, "Industrial wireless sensor networks," *Industrial Communication Systems*, 2016.

[85] "Ocado testing transformative IoT warehouse solution," https://internetofbusiness.com/ocado-testing-transformative-iot-warehouse-solution/, accessed: 2021-09-16.

[86] D. Puccinelli and M. Haenggi, "Wireless sensor networks: applications and challenges of ubiquitous sensing," *IEEE Circuits and systems magazine*, vol. 5, no. 3, pp. 19–31, 2005.

[87] A. Lanzolla and M. Spadavecchia, "Wireless sensor networks for environmental monitoring," 2021.

[88] "Breathe London," https://www.breathelondon.org/, accessed: 2021-09-16.

[89] A. Di Nisio, F. Adamo, G. Acciani, and F. Attivissimo, "Fast detection of olive trees affected by xylella fastidiosa from uavs using multispectral imaging," *Sensors*, vol. 20, no. 17, p. 4915, 2020.

[90] N. Friess, J. Bendix, M. Brändle, R. Brandl, S. Dahlke, N. Farwig, B. Freisleben, H. Holzmann, H. Meyer, T. Müller *et al.*, "Introducing nature 4.0: A sensor network for environmental monitoring in the marburg open forest." *Biodiversity Information Science and Standards*, no. 2, 2019.

[91] S. S. Karipott, B. D. Nelson, R. E. Guldberg, and K. G. Ong, "Clinical potential of implantable wireless sensors for orthopedic treatments," *Expert review of medical devices*, vol. 15, no. 4, pp. 255–264, 2018.

[92] "Ocado testing transformative IoT warehouse solution," https://www.cdc.gov/homeandrecreationalsafety/falls/adultfalls.html, accessed: 2021-09-17.

[93] E. Casilari, J. A. Santoyo-Ramón, and J. M. Cano-García, "Analysis of a smartphone-based architecture with multiple mobility sensors for fall detection," *PLoS one*, vol. 11, no. 12, p. e0168069, 2016.

[94] L. T. Beng, P. B. Kiat, L. N. Meng, and P. N. Cheng, "Field testing of iot devices for livestock monitoring using wireless sensor network, near field communication and wireless power transfer," in *2016 IEEE Conference on Technologies for Sustainability (SusTech)*. IEEE, 2016, pp. 169–173.

[95] J. Zhang, X. Luo, C. Chen, Z. Liu, and S. Cao, "A wildlife monitoring system based on wireless image sensor networks," *Sensors & Transducers*, vol. 180, no. 10, p. 104, 2014.

[96] M. P. Ðurišić, Z. Tafa, G. Dimić, and V. Milutinović, "A survey of military applications of wireless sensor networks," in *2012 Mediterranean conference on embedded computing (MECO)*. IEEE, 2012, pp. 196–199.

[97] T. Czapla and J. Wrona, "Technology development of military applications of unmanned ground vehicles," in *Vision Based Systemsfor UAV Applications*. Springer, 2013, pp. 293–309.

[98] P. J. Springer, *Military robots and drones: a reference handbook*. ABC-CLIO, 2013.

[99] H. Kim and K. Choi, "A modular wireless sensor network for architecture of autonomous uav using dual platform for assisting rescue operation," in *2016 IEEE SENSORS*. IEEE, 2016, pp. 1–3.

[100] I. Bekmezci and F. Alagöz, "Energy efficient, delay sensitive, fault tolerant wireless sensor network for military monitoring," *International journal of Distributed Sensor networks*, vol. 5, no. 6, pp. 729–747, 2009.

[101] M. A. Imran, A. Zoha, L. Zhang, and Q. H. Abbasi, "Grand challenges in iot and sensor networks," *Frontiers in Communications and Networks*, vol. 1, p. 7, 2020.

[102] M. Noura, M. Atiquzzaman, and M. Gaedke, "Interoperability in internet of things: Taxonomies and open challenges," *Mobile Networks and Applications*, vol. 24, no. 3, pp. 796–809, 2019.

[103] A. Gluhak, O. Vermesan, R. Bahr, F. Clari, T. Maria, T. Delgado, A. Hoeer, F. Bösenberg, M. Senigalliesi, and V. Barchett, "Bdeliverable d03. 01 report on iot platform activities-unify-iot," 2016.

[104] M. James, M. Chui, P. Bisson, J. Woetzel, R. Dobbs, J. Bughin, and D. Aharon, "The internet of things: Mapping the value beyond the hype," *McKinsey Global Institute*, vol. 3, 2015.

[105] M. A. Abbasi, Z. A. Memon, N. M. Durrani, W. Haider, K. Laeeq, and G. A. Mallah, "A multi-layer trust-based middleware framework for handling interoperability issues in heterogeneous iots," *Cluster Computing*, pp. 1–28, 2021.

[106] M. D. Alshehri and F. K. Hussain, "A centralized trust management mechanism for the internet of things (ctm-iot)," in *International conference on broadband and wireless computing, communication and applications*. Springer, 2017, pp. 533–543.

[107] X. Wu and J. Liang, "A blockchain-based trust management method for internet of things," *Pervasive and Mobile Computing*, vol. 72, p. 101330, 2021.

[108] B. Di Martino and A. Esposito, "Semantic techniques to support iot interoperability," *Semantic IoT: Theory and Applications: Interoperability, Provenance and Beyond*, p. 229, 2021.

[109] Z. Pan, S. Hariri, and J. Pacheco, "Context aware intrusion detection for building automation systems," *Computers & Security*, vol. 85, pp. 181–201, 2019.

[110] C. Fernandez-Gago, F. Moyano, and J. Lopez, "Modelling trust dynamics in the internet of things," *Information Sciences*, vol. 396, pp. 72–82, 2017.

[111] N. Chen, Y. Yang, J. Li, and T. Zhang, "A fog-based service enablement architecture for cross-domain iot applications," in *2017 IEEE Fog World Congress (FWC)*. IEEE, 2017, pp. 1–6.

[112] T. Rault, A. Bouabdallah, and Y. Challal, "Energy efficiency in wireless sensor networks: A top-down survey," *Computer networks*, vol. 67, pp. 104–122, 2014.

[113] M. A. Jamshed, O. Amjad, and E. Zeydan, "Multicore energy efficient scheduling with energy harvesting for wireless multimedia sensor networks," in *2017 International Multi-topic Conference (INMIC)*. IEEE, 2017, pp. 1–5.

[114] D. Kandris, P. Tsioumas, A. Tzes, G. Nikolakopoulos, and D. D. Vergados, "Power conservation through energy efficient routing in wireless sensor networks," *Sensors*, vol. 9, no. 9, pp. 7320–7342, 2009.

[115] H. Luo, J. Luo, Y. Liu, and S. K. Das, "Adaptive data fusion for energy efficient routing in wireless sensor networks," *IEEE Transactions on computers*, vol. 55, no. 10, pp. 1286–1299, 2006.

[116] S. E. Khediri, N. Nasri, A. Wei, and A. Kachouri, "A new approach for clustering in wireless sensors networks based on leach," *Procedia Computer Science*, vol. 32, pp. 1180–1185, 2014.

[117] N. Bizon, N. M. Tabatabaei, F. Blaabjerg, and E. Kurt, "Energy harvesting and energy efficiency," in *Technology, Methods, and Applications, vol. 37 of Lecture Notes in Energy*. Springer, 2017.

[118] C. Karakus, A. C. Gurbuz, and B. Tavli, "Analysis of energy efficiency of compressive sensing in wireless sensor networks," *IEEE Sensors Journal*, vol. 13, no. 5, pp. 1999–2008, 2013.

[119] S. Bhushan, M. Kumar, P. Kumar, T. Stephan, A. Shankar, and P. Liu, "Fajit: a fuzzy-based data aggregation technique for energy efficiency in wireless sensor network," *Complex & Intelligent Systems*, vol. 7, no. 2, pp. 997–1007, 2021.

[120] H. Shafagh, L. Burkhalter, A. Hithnawi, and S. Duquennoy, "Towards blockchain-based auditable storage and sharing of iot data," in *Proceedings of the 2017 on cloud computing security workshop*, 2017, pp. 45–50.

[121] A. Kumar, A. K. Jain, and M. Dua, "A comprehensive taxonomy of security and privacy issues in rfid," *Complex & Intelligent Systems*, vol. 7, no. 3, pp. 1327–1347, 2021.

[122] M. Liyanage, I. Ahmad, A. B. Abro, A. Gurtov, and M. Ylianttila, *A comprehensive guide to 5G security*. John Wiley & Sons, 2018.

[123] N. M. Kumar and P. K. Mallick, "Blockchain technology for security issues and challenges in iot," *Procedia Computer Science*, vol. 132, pp. 1815–1823, 2018.

[124] V. Kumar, N. Malik, G. Dhiman, and T. K. Lohani, "Scalable and storage efficient dynamic key management scheme for wireless sensor network," *Wireless Communications and Mobile Computing*, vol. 2021, 2021.

[125] C.-F. Hsieh, Y.-F. Huang, and R.-C. Chen, "A light-weight ranger intrusion detection system on wireless sensor networks," in *2011 Fifth International Conference on Genetic and Evolutionary Computing*. IEEE, 2011, pp. 49–52.

[126] R. Kishore, A. C. Pappa *et al.*, "Light weight security architecture for cluster based wireless sensor networks," in *2015 IEEE International Conference on Ubiquitous Wireless Broadband (ICUWB)*. IEEE, 2015, pp. 1–5.

[127] R. Rani, S. Kumar, and U. Dohare, "Trust evaluation for light weight security in sensor enabled internet of things: Game theory oriented approach," *IEEE Internet of Things Journal*, vol. 6, no. 5, pp. 8421–8432, 2019.

[128] M. A. Ferrag, L. Shu, X. Yang, A. Derhab, and L. Maglaras, "Security and privacy for green iot-based agriculture: Review, blockchain solutions, and challenges," *IEEE access*, vol. 8, pp. 32 031–32 053, 2020.

[129] A. Dorri, M. Steger, S. S. Kanhere, and R. Jurdak, "Blockchain: A distributed solution to automotive security and privacy," *IEEE Communications Magazine*, vol. 55, no. 12, pp. 119–125, 2017.

[130] C. Zhu, C. Zheng, L. Shu, and G. Han, "A survey on coverage and connectivity issues in wireless sensor networks," *Journal of Network and Computer Applications*, vol. 35, no. 2, pp. 619–632, 2012.

[131] C.-F. Huang and Y.-C. Tseng, "The coverage problem in a wireless sensor network," *Mobile networks and Applications*, vol. 10, no. 4, pp. 519–528, 2005.

[132] S. Meguerdichian, F. Koushanfar, M. Potkonjak, and M. B. Srivastava, "Coverage problems in wireless ad-hoc sensor networks," in *Proceedings IEEE INFOCOM 2001. Conference on computer communications. Twentieth annual joint conference of the IEEE computer and communications society (Cat. No. 01CH37213)*, vol. 3. IEEE, 2001, pp. 1380–1387.

[133] X. Wang, G. Xing, Y. Zhang, C. Lu, R. Pless, and C. Gill, "Integrated coverage and connectivity configuration in wireless sensor networks," in *Proceedings of the 1st international conference on Embedded networked sensor systems*, 2003, pp. 28–39.

[134] B. Wang, W. Wang, V. Srinivasan, and K. C. Chua, "Information coverage for wireless sensor networks," *IEEE Communications Letters*, vol. 9, no. 11, pp. 967–969, 2005.

[135] N. A. A. Aziz, K. A. Aziz, W. Z. W. Ismail *et al.*, "Coverage strategies for wireless sensor networks," *World academy of science, Engineering and technology*, vol. 50, pp. 145–150, 2009.

[136] Y. Zou and K. Chakrabarty, "Sensor deployment and target localization based on virtual forces," in *IEEE INFOCOM 2003. Twenty-second Annual Joint Conference of the IEEE Computer and Communications Societies (IEEE Cat. No. 03CH37428)*, vol. 2. IEEE, 2003, pp. 1293–1303.

[137] T.-W. Sung and C.-S. Yang, "Voronoi-based coverage improvement approach for wireless directional sensor networks," *Journal of Network and Computer Applications*, vol. 39, pp. 202–213, 2014.

[138] J.-P. Sheu, P.-C. Chen, and C.-S. Hsu, "A distributed localization scheme for wireless sensor networks with improved grid-scan and vector-based refinement," *IEEE transactions on mobile computing*, vol. 7, no. 9, pp. 1110–1123, 2008.

[139] O. I. Khalaf, G. M. Abdulsahib, and B. M. Sabbar, "Optimization of wireless sensor network coverage using the bee algorithm." *J. Inf. Sci. Eng.*, vol. 36, no. 2, pp. 377–386, 2020.

[140] M. Farsi, M. A. Elhosseini, M. Badawy, H. A. Ali, and H. Z. Eldin, "Deployment techniques in wireless sensor networks, coverage and connectivity: A survey," *IEEE Access*, vol. 7, pp. 28 940–28 954, 2019.