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Review Article

WSN Architectures for Environmental Monitoring Applications

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Wireless sensor networks (WSNs) have become ubiquitous, permeating every aspect of human life. In environmental monitoring applications (EMAs), WSNs are essential and provide a holistic view of the deployed environment. Physical sensor devices and actuators are connected across a network in environmental monitoring applications to sense vital environmental factors. EMAs bring together the intelligence and autonomy of autonomous systems to make intelligent decisions and communicate them using communication technologies. This paper discusses the various architectures developed for WSNs in environmental monitoring applications and the support for specific design goals, including machine learning in WSNs and its potential in environmental monitoring applications.

1. Introduction

Wireless sensor networks (WSNs) comprise spatially distributed sensor nodes that monitor and record physical environmental conditions [1]. As illustrated in Figure 1, WSNs have practical applications in various domains, including agriculture, water, animal tracking, oceanography, air quality, earthquake/landslide, forest fire, and flood detection. WSNs are self-configuring, infrastructure-free networks that monitor physical or environmental conditions [2]. WSNs can monitor various environmental conditions, including temperature, sound, vibration, acceleration, pressure, motion, humidity, and chemical or pollutant concentrations from the different application domains presented in Figure 1. When deployed in these conditions, WSNs cooperate to transmit data across the network to a central location or sink, from where it can be viewed and analyzed [3]. Wireless sensor nodes can withstand harsh environmental conditions and operate in their deployable environment without human intervention. Wireless sensor nodes can be deployed to cover large geographical areas, either fixed in place (static deployment) or mobile (dynamic deployment) [4].

EMAs have unique challenges that, if not considered in their deployments, may affect the service quality. For instance, deploying nodes in highly dynamic environments may affect the data collected even for environments with low spatiotemporal variations. Such changes may arise from sudden changes in the weather or close human activities [2, 5]. As such, real-time monitoring of the environment is necessary but without the cost and time needed to achieve even better results when compared to traditional monitoring systems. Conventional monitoring systems use sedimentation, electrostatic sampling, absorption, filtration, and condensation to scan and monitor the soil, air, and water.

Humans, animals, and nonliving things all require a habitat. Human and animal activities harm the environment, lowering people's quality of life. During the last decade, researchers have used wireless sensor devices to automate the monitoring of the environment, ensuring that accurate data is obtained for analysis [4, 6]. For example, sensor nodes monitor air quality to detect and estimate environmental

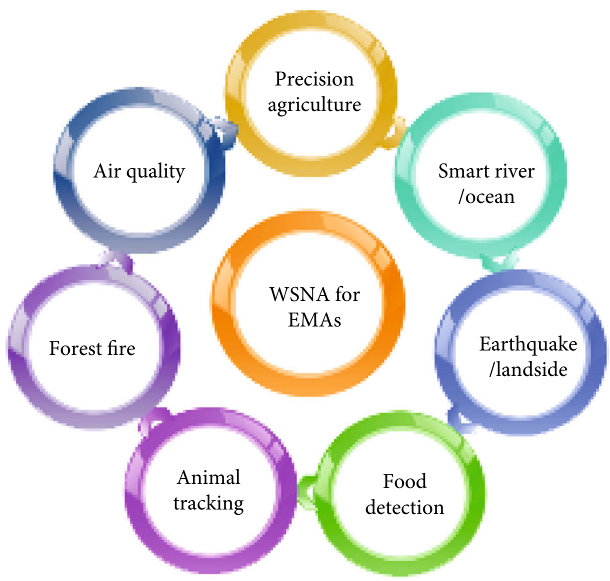

Figure 1: Wireless sensor network application domains.

pollution levels. When soil is observed, it is examined for threats such as biodiversity loss, acidity levels, erosion, and other forms of contamination [7].

Additionally, sensor nodes determine water quality by monitoring physical, chemical, and biological factors [8–10]. Due to WSNs, these monitoring techniques have become practical, simple, and exceptionally reliable. WSNs for EMAs aim to integrate autonomous systems' intelligence and autonomy to make intelligent decisions and communicate them via communication technologies. Hence, some challenges in their implementation include network and communication coverage, energy management and conservation, and data security [11]. Environmental automation allows substantial amounts of data to be collected and transmitted to a central repository via sensor nodes and communication technologies. Water quality monitoring ensures clean and safe water is available for domestic use [11] and clean water bodies for environmental sanitation, disposal, and storage of water [10]. The concept of smart cities powered by green technologies was one of the driving forces behind developing WSN-based EMAs. As a result, it is critical to examine the sensing, network communication, and analysis processes (SNcA). The SNcA operations rely on the underlying WSN architecture's ability to provide the necessary functions, services, and protocols to accomplish the design objectives of the relevant application (R. [12]).

The properties of EMAs that rely on WSNs are depicted in Figure 2. Figure 2 illustrates the communication, deployment, data collection, and energy consumption properties of EMAs. During the operational life of the sensor nodes, the communication group can be classified as broadcast or unicast. WSNs for EMA deployment can occur in either a mobile or static environment. These environments have various characteristics that affect the nodes' lifetime. The environmental data can be collected with high accuracy or with some redundancy. Data collection can also be based on the type of event or traffic generated by the environment. The energy consumed by sensor node components for sensing, processing, and transmission is significant. WSNs for EMAs have gained popularity in recent years as demand for automation has increased. This growing popularity is because WSNs enable real-time communication, are self-sufficient, and provide intelligent and accurate information. The WSN architecture for EMAs is intended to facilitate the collection, processing, transfer, storage, retrieval, and, in some cases, data management. They provide real-time access to monitoring data, long-term monitoring, and scalability [13]. The type of application that requires WSN affects sensor networks' architecture, scope, and complexity. WSNs used in EMAs are primarily dynamic sensor deployment systems that rely on multi-hop techniques to function correctly. When an environmental application necessitates the deployment of static sensors, point-to-point or single-hop infrastructure is suitable [14].

Additionally, WSNs for EMAs have data collection procedures and energy consumption characteristics. Because data in WSNs is generated from multiple sources, it may be collected accurately or with a certain degree of redundancy. Collecting real-time sensor data enables the accurate representation of current environmental conditions and forecasting of future environmental conditions and threats. Precision agriculture, for example, allows farmers to alter their farming strategies at any time by utilizing real-time data from field-installed sensors. Precision agriculture data will enable farmers to strategize and adjust land management activities accordingly, rather than relying on hypothetical average farmland conditions that may not exist anywhere in real time. In EMAs, data collection depends on either traffic generation or event detection, likely affecting the amount of energy consumed by each sensor node. For example, sensor nodes near a sink rapidly deplete their energy compared to other sensor nodes. Energy is consumed by sensing, processing, and data transmission in WSNs.

When WSN architectures are adopted for deployment in EMAs, they present new opportunities and challenges. For example, introducing machine learning and Internet of Things techniques in WSN for EMAs has associated design challenges requiring new dimensions into algorithm design that impact the network protocol stack. Hence, the researchers must be interested in the sensor node and network architectures, algorithms, and protocol design that support WSNs for EMAs. It is imperative to reconsider the underlying architectures influencing how nodes may be deployed (placement, coverage, and connectivity). Finding novel approaches to maximize the network throughput and lifetime are essential in WSNs for EMAs. It is, therefore, worth considering the various WSN architectures and the environmental characteristics of EMAs in the different application areas.

Given the above, it is essential to specify the architectural requirements for WSNs for EMAs to achieve the design goals and enable continuous environmental monitoring. Hence, this paper presents the state-of-art on wireless sensor networks for environmental monitoring applications. Starting with a description of EMAs, we provide an overview of WSN designs, including hardware and software architectures for EMAs. We

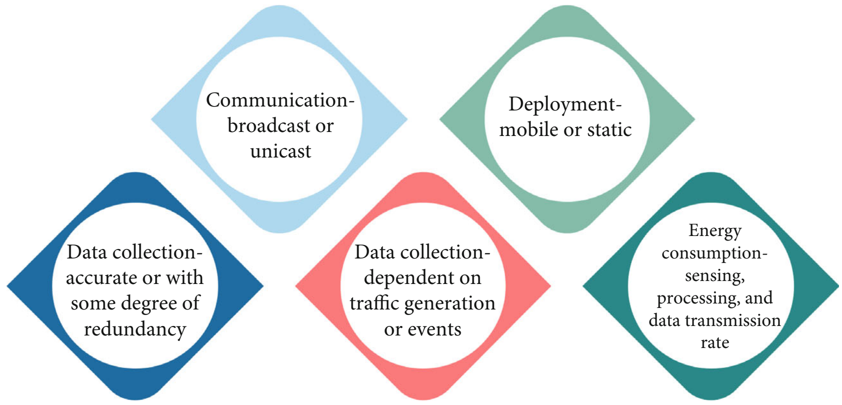

Figure 2: Properties of environmental monitoring applications.

then describe the sensor node architecture and present the maximum coverage and connectivity characteristics suitable for the different WSN application environment. In addition, we discuss critical aspects of WSNs for EMAs, including sensor type, sensor node placement, sensor node power consumption, node communication, and remote sensor node control. Finally, the paper discusses current advancements that benefit EMAs, such as machine learning (ML) and the Internet of Things (IoT) and the associated challenges. We present novel approaches for dealing with WSNs for EMAs when monitoring various environmental parameters, considering the different application characteristics. Our work differs from previous review attempts presented in the literature in that it focuses on specific application domains and their underlying algorithms [15–18].

The rest of the paper is organized as follows: Section 2 discusses related works to EMAs. Section 3 presents the wireless sensor node architecture, emphasizing layered and clustered architectures. We describe the suitability of these architectures in EMAs. Section 5 examines sensor node deployment approaches that guarantee EMAs' maximum area coverage and connectivity. Section 5 introduces WSN Applications, concentrating on environmental characteristics and data gathering strategies used in diverse environments. Section 6 discusses current advances in WSNs concerning machine learning and the Internet of Things, relevant simulators, and the underlying operating systems that enable EMA (environmental monitoring applications) architectures. Section 7 concludes the paper by suggesting future research directions.

2. Related Works

EMAs provide a continuous real-time approach to monitoring environmental phenomena using WSNs and IoT (Internet of Things). Traditionally, monitoring the environment involves testing equipment that needs to be checked regularly and reported to a receiving station. However, the monitoring mode is not very efficient due to rapid changes in the weather and other environmental changes that cannot be entirely predicted.

In [10], the authors reviewed the latest works on some implementations of IoT in monitoring water quality parameters efficiently and cost-effectively. In their work, an IoT system was developed to test water quality parameters such as pH, conductivity, turbidity, and temperature. The sensor nodes were placed in water, and the ADC and core controller monitored data values read from the cloud. Similar works were done by [19] to measure the pH, conductivity, turbidity, oxidation-reduction, oxygen, and temperature of a moving river in the Greater Accra region of Ghana. The setup included the sensor probes dipped in water connected to a base station placed at a safe place above the water. The base station is connected via a GSM module to cloud storage, from where a web portal visualizes the stream of data produced. In [11], they surveyed current state-of-the-art IoT-enabled WSNs to monitor the water quality parameters for domestic use as safe drinking water. In their paper, they included recommendations for the design of efficient IoT water quality monitoring systems (IoT-WQMS) and a review of contemporary IoT-WQMS.

The authors review current IoT-based water management systems [20]. Their study examined measurement parameters such as pH, turbidity, salinity, and water levels. An architectural design of IoT-based intelligent water management systems with machine learning was proposed but not implemented. Machine learning (ML) tools such as decision trees and support vector machines were implemented as classification algorithms on real data sets obtained from a Tunisian water treatment station [21]. The performance evaluation performed by the authors suggested linear SVM to better classify and detect anomalies in the water distribution network in Tunisia. Other ML classification tools used in water quality applications include the K-nearest neighbor (KNN), single layer, and deep neural networks. Software architectures that combine event processing with remote sensing applications for air quality monitoring using satellite sensors were proposed by [22].

The architecture of the smart water management system considers the controllers and some sensors, and an application is proposed by [20]. Some radios suggested as best for water management systems include LoRa, NB-IoT, Zigbee, and 6lowpan. Hardware and software platforms supporting IoT for EMAs include Arduino, ESP8266, Raspberry Pi, Beagle Bone, Bluetooth, Wi-Fi, RFID, and microcontrollers [9]. Large-scale applications such as unmanned aerial vehicles

(UAVs) and crowdsensing monitoring technologies also use radio and WSN protocols to achieve comprehensive area monitoring [2].

Smart cities have peculiar environmental monitoring concerns such as authentication, data security, device vulnerability, and sustainability. The architecture of smart cities that may support their purposes was considered in these four layers: sensing, transmission, data management, and application [23]. This is similar to our work which considers the WSN architecture of Smart Cities. However, our paper emphasizes the layered and clustered layers in different applications, including smart cities, while [23] view the attributes and possible functions of the layers as mentioned earlier. The layered and clustered architectures highlighted in our paper point to possible EMAs that could be developed under each layer. The work also highlights the general protocols and energy consumption factors these layers and EMAs face. Finally, we discuss the different types of machine learning tools and protocols that can be supported and used in EMAs. To reduce energy consumption in EMAs, our research focuses on potential machine learning tools used in IoTs and the factors influencing their implementation.

3. Wireless Sensor Network Architectures (WSNA)

WSNs enable continuous monitoring of environmental conditions. Sensor nodes comprise WSNs. The sensor node detects and processes the parameters locally or across the network or transfers them to a base station (sink) for processing. For EMAs, the scalability of WSNs is critical. SNA (sensor network architecture) enables the provision of environmental monitoring services. Architecture abstracts physical devices and services from physical manifestations [15]. EMA architectures must be hardware and software agnostic and based on diverse architectures. An animal tracking system may require hardware and software architectures that differ from earthquake monitoring. As a result, the architectures of wireless sensor networks (WSNs) are application-specific (that is, it considers the requirements for the various application domains). When sensor nodes on animals come into contact, pairwise connections allow them to communicate. Static sensor nodes can be installed indoors or outdoors to monitor air quality. The sensor, node, and sensor network architectures are described here. Additionally, the section will discuss OSI-based architectures that are traditional/layered, clustered, and hybrid. Each case is discussed in detail in terms of its EMA suitability.

3.1. Sensor Node Architecture. A wireless sensor network comprises sensor nodes that work together to complete a particular task. Sensor nodes are equipped with components that detect parameters of interest in their immediate environment. Sensing data from a single node can be analyzed and transmitted to another sensor node in the sensor network or a sink. As a result, the sensor node oversees data collection, aggregation, and fusion in a WSN. A wireless sensor node comprises several components: a sensor unit, interface circuitry, a processor, a transceiver system, and a power supply unit, as depicted in Figure 3. The sensing unit is directly responsible for data collection and environmental interaction, and the computing unit handles data computation, processing, analysis, and storage. The communication unit is in charge of communication between connected sensor nodes and data transmission from sensor nodes to a base station.

The node can communicate with neighboring domains via communication interfaces and wireless links. Additionally, the sensor node's location and positioning information may be provided by a global positioning system (GPS). While it is frequently assumed that all sensor nodes have similar functionality, sensor functionality can be heterogeneous in some cases. The sensor unit is the sensor node architecture component responsible for capturing physical events in the real world. A computing unit handles data processing and aggregation. It comprises an analog to digital converter (which converts analog data to digital), a central processing unit (or microprocessor), memory, protocols, and storage memory.

Additionally, a communication unit comprises a transceiver for data transmission and reception. The transceiver handles the transmission and reception of signals. Finally, a power unit provides power to every component of the sensor node.

3.2. Sensor Network Architecture (SNA). Sensor network architecture (SNA) is used in WSNs. Temperature, humidity, pressure, location, vibration, and sound are all monitored by the wireless SNA nodes. These nodes can perform intelligent detection, neighbor node detection, data processing and storage, data collection, target tracking, monitoring and control, synchronization, node localization, and efficient routing between the base station and nodes in various real-time applications [24]. SNA is developed using the open system interconnection (OSI) model and consists of five layers (physical, data link, network, transport, and application layers). Numerous protocols are being developed to operate at each layer of the SNA. For example, protocols control the transceiver's operation at the physical layer of SNA, and medium access control (MAC) protocols manage channel sharing, timing, and locality at the data link layer. The routing protocols manage networking tasks such as topological and adaptive topology management at the network layer. Transport layer protocols facilitate data dissemination and caching [25]. The sections that follow provide an overview of the layered and clustered architectures. When designing WSNs for EMAs, several design issues must be considered when using the SNA (sensor network architecture). Several of these issues include but are not limited to energy consumption, quality of service (QoS), security, processing, localization, and network design cost. Consumption of energy is critical, as the sensor nodes are battery-powered. Additionally, it is challenging to replace batteries in EMAs.

As a result, the sensor node's sensing, transmission, and computation components must be managed, while the node is operational. Protocols designed efficiently at multiple layers (physical, data link, network, and transport) can significantly reduce the energy consumed by sensor nodes.

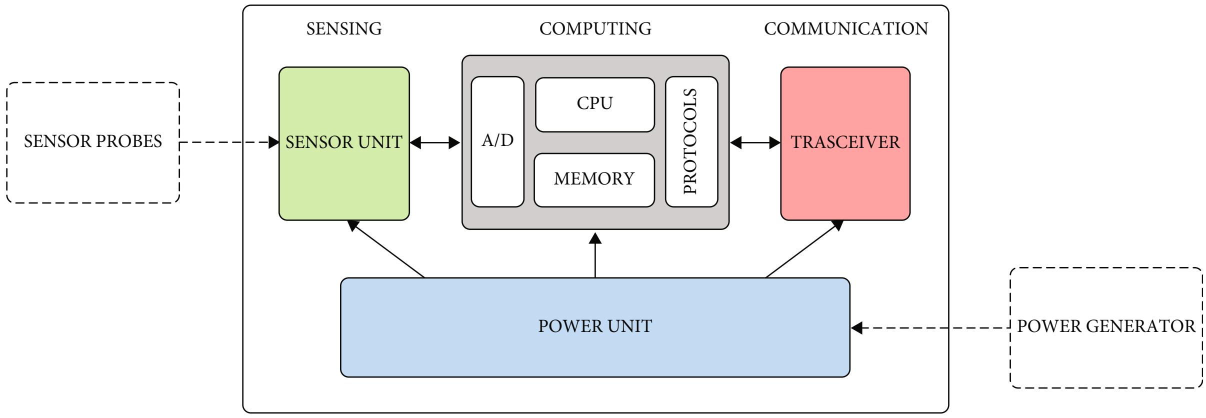

Figure 3: Wireless sensor node architecture.

With the quality of service, data is expected to be distributed in real time to enable stakeholders to use it. To effectively detect and report environmental phenomena in EMAs, the nodes should be placed so that they cover a large area within the deployed environment, as illustrated in Figure 4. Sensor nodes in WSNs have a sensing range within which they can detect an event. The sensor node cannot detect events outside of its sensing range. The random placement of nodes may affect coverage and limit sensing of the targeted area. The coverage problem is solved in full sensing coverage because the sensor nodes cover the entire deployable area. This deployment's sensor nodes cover the whole region of interest (see Figure 4(a)). Figure 4(b) shows a similar number of nodes deployed with a sensing limited sensing range that cannot cover most of the deployment area due to the sensor node's shorter sensing range.

Algorithms for coverage have been developed to provide efficient solutions for coverage in WSNs. Three procedures can be modified in SNA to process data sensed by nodes. In-node processing, in-network processing, and data processing at the sink are the data processing techniques. Energy may be consumed in each case. As a result, efficient computational or data processing approaches are required for effective resource utilization. In WSNs, the position of each node is unknown to the others, posing the problem of localization. In most cases, nodes equipped with GPS capabilities can resolve this issue, but the primary challenge associated with GPS implementation is the sensor node's limited energy supply.

3.3. Layered Architectures. As illustrated in Figure 5, the layered architecture consists of five layers with three cross layers. The LSNA include physical, data link, network, transport, application, power management, mobility, and task management. In a deployable environment, sensor nodes connected to this type of architecture may number in the hundreds [26]. The sensor nodes are connected to a base station, from which the collected data can be sent to the cloud or a central server via a communication architecture. Each sensor node transmits data to neighboring nodes within its sensing range in the layered architecture. As a result, nodes typically consume little power during packet transmission. Table 1 summarizes a detailed description of the layers and cross-plane layers.

3.4. Clustered Architectures. Thousands of sensor nodes are organized into clusters in a clustered architecture. Each group is assigned a cluster head, which automatically creates clusters and schedules communication according to a predefined schedule, as illustrated in Figure 6. The cluster architecture is based on low energy adaptive clustering hierarchy (LEACH) technique. The clustered architecture is designed so that each node in the cluster can communicate with other nodes via the cluster head. Due to energy consumption constraints, the cluster head may sometimes be rotated. Cluster heads transmit data to the base station or sink node after receiving it from all sensor nodes within their cluster. Clustered architectures are well suited for EMA data fusion in WNS. Self-organizing groups are capable of rotating cluster heads and ensuring network availability.

3.5. Wireless Sensor Network Architectures (WSNA) Challenges. In this section, we present different challenges that affect the smooth operation of WSNAs (wireless sensor network architectures) for EMAs. These challenges include energy consumption, quality of service (QoS), security, processing and computation, localization, and network design cost. The challenges enumerated in this section indicate significant constraints that must be addressed and resolved before WSN can be used as a supporting technology for EMAs. In what follows, we discuss these challenges about WSNA for EMAs.

3.5.1. Energy Consumption. Environmental monitoring applications require low-power sensor nodes capable of long-term operation, autonomy, and real-time functionality in a deployable environment (W. [27]). WSN sensor nodes must be energy-efficient for WSNs to perform optimally in their environment and give reliable data. Without energy optimization, the sensor node's battery will only last a few days, negating the long-term design needs of WSNs for EMAs. Alternative ways to extend the battery life of sensor nodes include energy harvesting from various energy sources, particularly solar power, using large capacity batteries, load balancing, and energy neutral operation (ENO) [28]. In some applications, minimizing energy use through energy-efficient protocols has been used to prolong the sensor node and network lifetime [29]. Minimizing energy

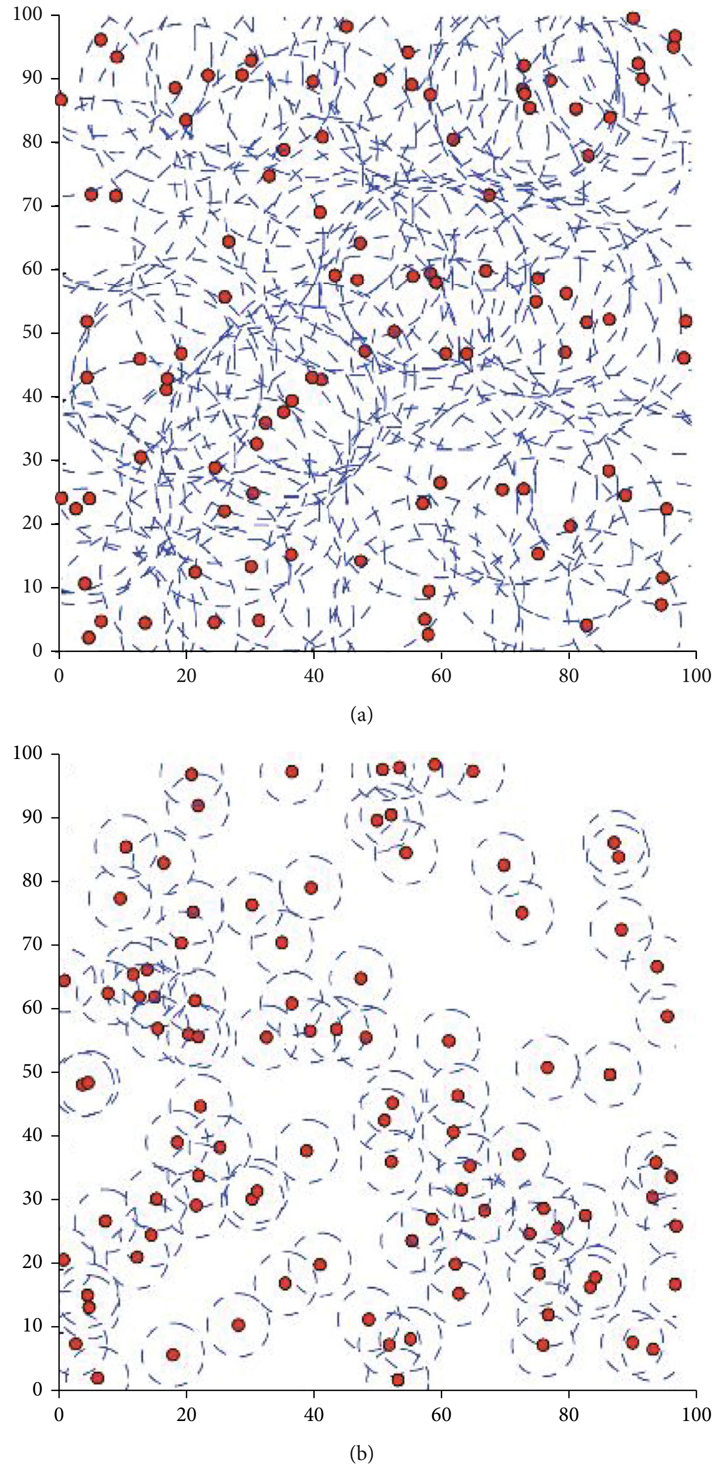

Figure 4: Node sensing range providing (a) full coverage and (b) partial coverage in a deployed environment.

consumption is ideal for the long-term operation of the sensor nodes in challenging application environments such as forests with dense vegetation, oceanography, and animal surveillance.

3.5.2. Quality of Service. Quality of service (QoS), essential in WSNs, has recently received much attention. Achieving a specific performance by measuring various environmental characteristics is necessary for designing, developing, and deploying sensor nodes in WSN for EMAs [30]. It is challenging to improve all QoS parameters at once in WSNs. For instance, reducing latency might result in more energy used by the sensor network. Throughput, packet delivery ratio, end-to-end delay, jitter, and dependability are key performance indicators that may be used in environmental monitoring applications [31]. As a result, maintaining

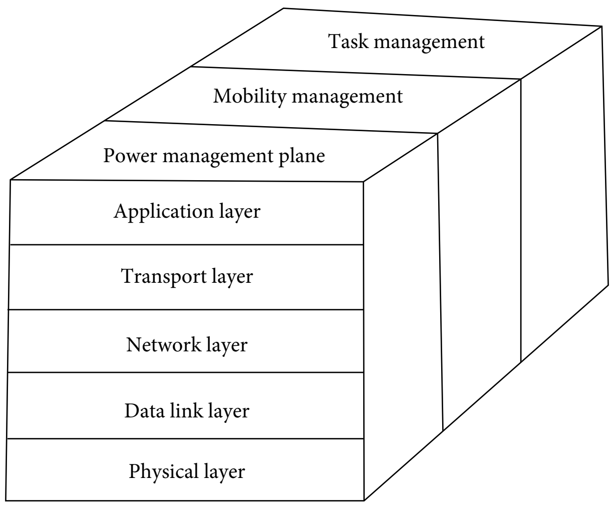

Figure 5: Layered sensor network architecture (LSNA).

trade-offs between the performance criteria chosen during the design phases of the specific application domain is necessary. Recently, strategies have been used to enhance service quality while considering the dynamic network and the crucial parameter needed in the application environment to achieve the desired QoS.

3.5.3. Security. WSN advancements enable data collection from various areas of the environment. The data sensed and collected by sensor nodes necessitates extreme care in terms of security. Wireless sensor network security issues are evident in hardware, infrastructure, and software. Identifying all security issues and challenges associated with WSNs and implementing appropriate mitigation measures is critical [32]. Some threats are node replication, selective forwarding, eavesdropping, Sybil, wormhole, signal or radio jamming, and sinkhole [18]. Data integrity and safety, as well as confidentiality and privacy, must be maintained during data transmission. The sensor node should also be safeguarded against theft and vandalism [33]. Physical security measures should be provided when sensor nodes are installed in the field. Other techniques, such as data encryption, should be incorporated in WSNs aimed at EMAs before the sensor nodes are deployed in the environment to improve node efficiency.

3.5.4. Localization. Node localization is critical in WSNs, mainly when WSNs are used in EMAs. Determining the position or location of nodes in WSNs is crucial because it influences the accuracy of the information acquired by sensor nodes [34]. Nonetheless, in WSN for EMAs, it is difficult for nodes to know about other nodes in the deployable environment, making localization an arduous task [35]. Localization presents several challenges, including energy consumption, node dimensionality, node mobility, sensor node security, and global positioning system (GPS) access. Researchers have proposed new methodologies and algorithms to address the inaccuracy in distance and position estimations of unknown sensor node locations. Other approaches are designed to solve the localization problem by optimizing the selection of reference nodes.

3.5.5. Processing and Computation. WSNs for EMAs are designed to measure various environmental factors to improve our living standards in our immediate surroundings. Several architectures manage data processing and computing when the sensor nodes initiate a sensing operation. In some protocols or architectures, the sensor nodes process and compute data locally or across the network after sensing phenomena before sending the data to a central repository for analysis [31]. In other architectures, the node transmits it to a base station after sensing data, which requires a lot of energy for processing and computation. It then forwards it to a central repository for analysis. Cloud-based architectures have recently been used to analyze and compute data collected from the environment. These cloud-based architectures may visualize processed data through web portals, allowing users to access processed data through their smartphones.

3.5.6. Cost of Network Design. WSNs for EMAs are designed to be alive to meet the application requirements. Some environmental monitoring applications require specialized network design. Animal tracking applications, for example, must be operational at all times to allow users to track the animals' location at any given time. As a result, the type of network architecture improves coverage, connection, robustness, and network lifetime. To meet the goals while staying within budget, sensor network design must be meticulous. Because of the dynamic nature of EMAs, a sensor node deployment plan capable of enhancing coverage and preserving connectivity, while staying under budget is highly recommended for WSNs for EMAs.

4. Sensor Node Deployment Strategies

To ensure maximum area coverage and connectivity, the deployment type must be considered to avoid nodes rapidly depleting their energies in WSNs. The sensor node architecture should be such that nodes within the monitoring area are protected by at least one neighboring node. The coverage of sensor nodes affects how remote network monitoring is administered and the network's lifetime [36]. Nodes may be placed to cover the monitored zone entirely or partially, considering the wireless sensor node's sensing range. Nodes are manually deployed in human-accessible locations where their placement is dangerous.

On the other hand, random deployments occur in hazardous and inaccessible domains that require complete coverage. For instance, battlefield surveillance and open zones for natural life are examples. The primary objectives of researchers studying deployment strategies are to find ways to improve connectivity, maximize coverage, maximize energy efficiency, and maximize network lifetime. Figure 7 illustrates the distinct types of sensor node deployments suitable for EMAs. Details of each deployment strategy are described in the following sections.

Table 1: Description of layered sensor network architecture.

Layer/data type	Functions	Related challenges	Recent protocols
Layers of the SNA			
Physical bits	The physical layer is responsible for transmitting bitstreams, frequency selection, carrier frequency generation, modulation, data encryption, and signal detection. The physical layer includes the specification of the transmission medium and the topology of the network (performs encoding and decoding of signals)	Channel-related concerns, radio frequency bands, bandwidth, propagation mode effects, power efficiency, and channel impairments	PL-SKG (physical layer secure key generation) (physical layer secure key generation) IEEE 802.15.4 EAP (energy-aware routing protocol) AKA (authentication and key agreement) (authentication and key agreement) Decode-and-forward protocol
Data link frames	The data link layer is responsible for multiplexing data streams, frame detection, medium access control (MAC), and error control. It is also responsible for ensuring the reliability of point-to-point or multi-point channel access policies, scheduling, and buffer management	Co-channel interference at the MAC layer, multipath fading, and shadowing at the physical layer	MACAW (multiple access with collision avoidance for wireless) (multiple access with collision avoidance for wireless) IEEE 802.11 PAMAS (power-aware multiaccess with signalling) S-MAC (sensor medium access control) (sensor medium access control) T-MAC (timeout MAC) TRAMA (traffic adaptive medium access protocol) DMAC (dynamic *MAC*) IEEE 802.15.4 IEEE 802.15.4e CSMA/CA (carrier-sense multiple access with collision avoidance) CDMA (code division multiple access) ALOHA (ALOHA system) OFDMA (orthogonal frequency-division multiple access)
Network datagrams/ packets	The network layer provides the functionality required to support network configuration, device discovery, security, and topology management. It is also responsible for routing. Routing is responsible for power conservation, buffering, and the ability to be self-organized. The performance of routing protocols depends on the application domain	Limited memory and buffers, power saving, no global ID, and limited communication range	DEEC (distributed energy-efficient clustering) DDEEC (developed distributed energy-efficient clustering) EDEEC (enhanced distributed energy efficient clustering) EDDEEC (enhanced developed distributed energy efficient clustering) BEENISH (balanced energy efficient network integrated super heterogeneous) protocol DSR (dynamic source routing) Open shortest path first Intermediate system to intermediate system protocol AODV (ad hoc on-demand distance vector) RPL (routing protocol for low) (routing protocol for low power and loss network) IP (internet protocol) ICMP (internet control message protocol)

Table 1: Continued.

Layer/data type	Functions	Related challenges	Recent protocols
Transport datagrams/segments	The transport layer is responsible for providing reliability and congestion control or avoidance. Transport layer protocols designed to provide these functionalities use upstream or downstream techniques. Transport layer protocols are grouped into packet-driven and event-driven. The layers rely on the collaborative capabilities of sensor nodes	Limited memory, overhead in avoiding congestion, power constraints, and high traffic events	Sensor transmission control protocol (STCP) Price-oriented reliable transport protocol (PORT) Pump slow fetch quick (PSFQ) OpenFlow Transmission control protocol (TCP) Stream control transmission protocol (SCTP) User datagram protocol (UDP) Cyclic UDP (CUDP) Reliable UDP (RUDP) AppleTalk transaction protocol (ATP) Multipath TCP (MTCP) Transaction control protocol (TCP) Sequenced packet exchange (SPX)
Application user data	The application layer performs management functionalities, including network management, query processing, communication, time synchronization, and localization. The application layer also manages traffic and provides software for various apps that transform data into intelligible formats or send queries to seek specific information	The application-specific nature of EMAs creates many challenges	SMP (simple management protocol) Constrained application protocol HTTP (hypertext transfer protocol) SMTP (simple mail transfer protocol) FTP (file transfer protocol)
Cross layers			
Power management	The power management plane controls the network and ensures the sensor nodes' functionality. The goal is to improve network efficiency. The power plane is responsible for monitoring the power among the sensor node during sensing, data computation, transmission, and reception of data	Network and MAC layer challenges	Energy-efficient distributed schedule-based (EEDS) Fuzzy and ant colony optimization (ACO) based MAC/routing cross-layer protocol (FAMACRO)
Mobility management	The mobility plane monitors the movement among sensor nodes to improve network efficiency	Quality of services-related challenges, performance metric issues, MAC layer issues, and reliability issues	Distributed energy efficient hierarchical clustering Energy efficient unequal clustering Cross-layer adaptive routing (CLAR) protocol
Task management	The task plane monitors the task distribution among sensor nodes to improve the network performance. The task plane coordinates with the mobility and power plane to regulate and lower the energy consumption of sensor nodes to prolong the network lifetime	Link quality issues	Improved fuzzy unequal clustering protocol Cross-layer energy-efficient protocol (CLEEP) Fuzzy-cross-LEACH protocols

4.1. Square and Random Deployments. For instance, nodes in the deployment area may be arranged in a square pattern to detect events within that region. Due to the environment in which pollution spreads over time, a square deployment model may not be appropriate for river network monitoring. Another method for sensor node deployment is through randomization. It could be uniform or dispersed. Square and random deployments are suitable for stationary freshwater sources with little movement, such as lakes [37]. EMA requires an optimal sensor node deployment strategy that ensures complete coverage of the region of interest within the sensing range to detect events occurring anywhere within the area of interest. Full coverage provides network connectivity, ensuring that sensed data is transmitted to other network nodes and the sink node.

4.2. Grid Deployment. Grid-based deployments are typically used in static, deterministic applications where the sensor nodes' positions are fixed following a regular grid pattern. Triangular, square, or hexagonal patterns may be used, with

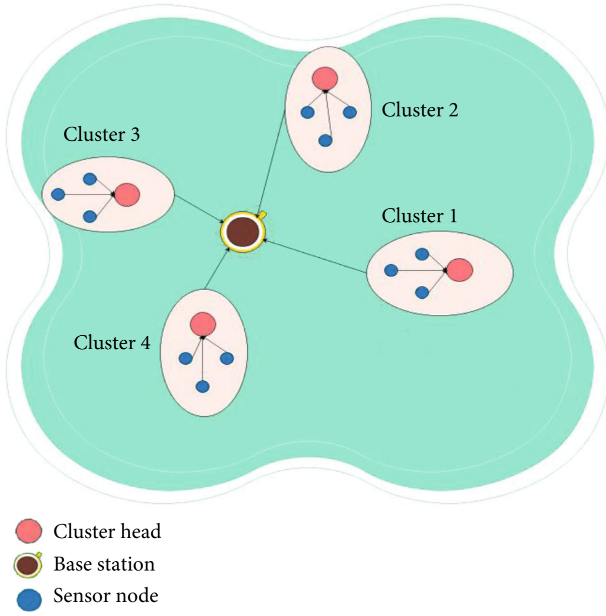

Figure 6: WSN for EMAs—clustered architecture.

the monitoring area divided into smaller grids. As a result, sensor nodes are placed in the grid's center or vertices to maximize connectivity with a small number of nodes. Grid configurations can be triangular, hexagonal, square, or random. Grid deployments are typically two-dimensional or three-dimensional, with some applications in monitoring air pollution [38] and target detection and tracking [39]. According to these deployment applications, the grid is most advantageous for deployments with a limited number of available nodes.

4.3. Mesh Deployment. Nodes are placed in a mesh deployment so that each node serves as a relay to other nodes. In the event of a failure, mesh nodes are fault-tolerant. Recent mesh deployments have rendered the earlier mesh network hubs' single half-duplex radio obsolete. These advancements pave the way for deploying a switched mesh network [40]. Interoperability, energy efficiency, scalability, mobility, and robustness are critical requirements for applications that use mesh in WSNs. Environmental monitoring, home construction, industrial automation and control, and precision agriculture benefit from mesh applications [41]. Earlier mesh topologies such as Zigbee (IEEE.15.4), IEEE 802.15.4e, and Wireless Hart were possible. Newer platforms, such as IEEE 802.15.15, are gradually introduced and integrated into WSN.

4.4. Distributed Deployment. Distributed deployments are critical for establishing an optimal coverage area for WSN systems. In distributed systems, deployment schemes are determined by the sensor node's coordinate information and name (A. [42]). Typically, nodes are homogeneous in terms of their roles and algorithm implementation. Algorithms are based on the base station to allow scattered nodes to be positioned optimally for coverage. Examples of these implementations can be found in the deployment of mobile sensors [43].

4.5. Centralized Deployment. Centralized deployments are used in mobile sensor nodes to improve barrier coverage. Most barrier enhancement strategies involve relocating the sensor nodes. However, their primary challenge is optimizing relocating these sensor nodes' communication and moving costs. Due to the deployment of these centralized nodes, their primary disadvantages are the massive message overheads associated with relocations and their inability to scale. Several examples of centralized implementations are presented in [33, 44].

4.6. Sparse and Dense Deployment. This deployment classification is typically determined by the number of sensor nodes used. While dense deployments involve the placement of many sensor nodes in each area, sparse deployments involve a small number of nodes. When the cost of deploying a substantial number many nodes is prohibitively high, sparse implementations are considered. As a result, sensor nodes are assumed to be static during deployment but reposition themselves to maintain connectivity and coverage. Nodes must remain within their neighbors' communication radius to achieve optimal coverage. Dense deployments are required for applications that require detection of every event, and multiple sensors may act as redundant nodes within a given area [45]. Environmental monitoring applications enable sparse sensor networks across large areas, and robot-based data scavengers collect data from sparse sensor fields.

4.7. Dynamic Deployment. Dynamic deployment entails randomly deploying mobile sensor nodes, moving to optimal locations for coverage and connectivity. The virtual force, force-oriented particles, simulated annealing, and particle swarm optimization algorithms are suitable for such deployments. The critical challenges associated with dynamic deployment are energy efficiency, load balancing, increased throughput, data reliability, and cost reduction. Because the position of the sensor node is unknown in advance, dynamic deployment is applicable in situations where sensor node placement is impractical. Applications such as disaster and battlefield monitoring are examples.

5. WSN Applications

Sensor nodes and base station nodes are used in WSN applications for EMAs. The sensor nodes monitor the parameters (as described in the following sections, depending on the application environment). The parameters sensed or obtained from the environment through a communication infrastructure are transferred from the base station to the central repository, typically a local server or the cloud (GSM, ZigBee, GPRS, Ethernet, RF, and WIFI). When data is stored on a server or in the cloud, it is organized, processed, analyzed, and reported to stakeholders via web portals, SMS gateways, and mobile applications.

The data is presented to stakeholders using data visualization techniques. EMA architectures should be cost-effective, lightweight, reliable, scalable, and self-organizing [46]. There is a guarantee of the environment in WSN applications, which may be static or dynamic/mobile, affecting the

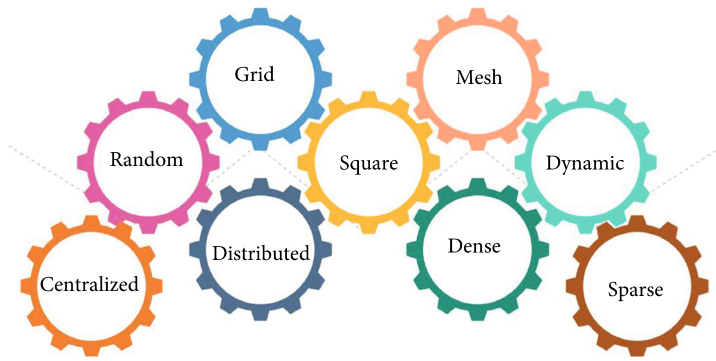

Figure 7: Sensor node deployment strategies in environmental monitoring applications.

Table 2: Characteristics of WSN applications.

Application	Type of environment	Data gathering approaches
Water monitoring (freshwater/ocean)	Dynamic	Event tasks/periodic
Animal tracking	Dynamic	Tracking event messages
Agriculture	Static	Periodic tasks
Oceanography	Dynamic	Tracking
Earthquake/landslide monitoring	Static	Approximation based
Air quality	Dynamic/static	Event-based/periodic
Forest fire	Static	Event

stability of connections between communicating devices (nodes, sinks, or base stations). Table 2 summarizes the types of applications, the appropriate environment, and the data collection methods.

5.1. Agriculture. Wireless sensor networks can significantly improve a variety of agricultural activities. In agriculture, sensor networks can optimize resource utilization while also increasing the quality and productivity of agricultural products [47]. WSNs enable efficient data collection, transmission, and processing from sensors deployed underground and aboveground in agriculture [48]. WSN has many advantages for farming and agricultural environments. These advantages include monitoring various elements such as microclimates and Phytophthora. This fungal disease spreads rapidly among plants, which is why monitoring water levels and scheduling irrigation based on the temperature of the plant's canopy is critical [49]. WSNs can also be used to monitor and detect microorganisms, antibodies, and other substances in the field, such as soil moisture, temperature, and humidity [50]. Finally, sensor networks can be used for intelligent irrigation, fertilization, pest control, and disease detection in their initial stages [51].

5.2. Animal Tracking. Tracking wild and endangered animals is critical for monitoring them in their natural habitats. There are two ways to track animals with wireless sensor nodes: (1) by attaching devices to the animals or (2) using unmanned aerial vehicles (UAVs) without device attachments. GPS devices may be attached to the animals to ascertain their precise location and movement patterns. Animal health can also be tracked using sensor nodes and sensor network architectures. WSN application design for animal tracking aims to create architectures that effectively monitor animals in their ecosystem without disturbing or negatively affecting their habitat. Additionally, WSNs will assist rangers in conserving animal sanctuaries and natural areas by recording various sites, rare and protected species migrations, and trend monitoring to ensure that the reserves are well-managed. Collars are worn around animals' necks to collect and transmit location data to sink nodes. Sensor networks have been developed to track zebras (ZebraNet), turtles (TurtleNet), elephants (JumboNet), and red deer (Cervus elaphus) [28]. Using WSNs to track these and other wild animals lays the groundwork for researchers to develop models for adequate wildlife resource protection, sustainable use, and scientific management. imote2, infrared motion detectors, Panasonic AMN41121 sensor, RFID tags, RFID readers, radio signal detectors, actuators, and mobile robots are the hardware architectures used for animal tracking applications. Additionally, animal tracking applications may use communication technologies such as 802.15.4 (ZigBee), GSM, GPS, and clustering architectures.

5.3. Water Monitoring. Water monitoring considers freshwater sources (water quality monitoring) and ocean environment monitoring. The critical difference is that water quality monitoring ensures safe and clean water among freshwater sources. In contrast, marine/ocean monitoring focuses on detecting climate changes or pollution of the marine environment, which affects human and animal habitats. WSNs have proven to be the best alternative to traditional methods when adapted for monitoring freshwater bodies and marine environments. Research in water environment monitoring classifies the monitoring process into water quality monitoring and ocean/marine environment monitoring [8]. Sensor nodes collect parameters such as water temperature, pH, dissolved oxygen, and others in freshwater sources and measure parameters such as the sea level and marine environment pollution. Sensors may detect climatic changes in the marine environment [19]. The data is transmitted to a base station through a communication architecture. The hardware architectures for water quality monitoring applications are pH, turbidity, temperature, and ammonia concentration.

The marine environment is monitored for different conditions, and uncontrollable human activities affect the health of living organisms. Traditional monitoring approaches are expensive and time-consuming. Hence, the activities require extensive and robust monitoring approaches such as wireless sensor networks to measure the following parameters: pressure, wind direction, water temperature, chlorophyll, wind speed, salinity levels, turbidity, and oxygen density. The data obtained from oceanography or marine monitoring applications are sent from the sensor nodes to base stations using wireless communication infrastructure. An efficient application may be built by employing the following hardware: sensors to measure physical parameters, sink nodes, mobile robots, buoy devices, robot-based sensors, seismic sensors, underwater sensors and transducers, autonomous underwater vehicles, and floating buoys. Some of the communication architectures include ZigBee, WIFI, and WiMAX.

5.4. Air Quality. Air quality monitoring is critical for human health. Industrialization, urban development, fertilizers, and pesticides are human activities that pollute the atmosphere. Furthermore, the increased use of vehicles has exacerbated air pollution in recent years. Monitoring air pollution is necessary to provide data to authorities to improve livelihood. Traditional methods of collecting data on air pollution are expensive, complex, and time-consuming, necessitating WSNs [52]. Air pollution is monitored using wireless sensor nodes. Carbon monoxide (CO), carbon dioxide (CO2), and total volatile organic compounds (TVOC) concentrations, as well as ambient temperature, relative humidity, air pressure, moisture content, and luminosity, are all measured [53]. Air quality measurements are reported in real time via a web server that can be accessed via the internet. CCS811 Sensor, MQ Sensor, BME280 Sensor, humidity, temperature, pressure sensors, MQ series sensors, CO Sensor, MQ7 Sensor, MQ135 Sensor, MQ136 Sensor, SO2 Sensor, and NH3 Sensors are among the sensor devices used to measure air pollution levels. These applications ensure that air quality parameters are monitored effectively and efficiently. They created a practical, low-cost air quality monitoring system using sensor nodes and robust communication infrastructure.

5.5. Earthquake and Landslide Monitoring. Earthquakes are a hazardous type of natural disaster. Earthquakes are the most violent natural disturbances in the earth's crust, significantly affecting the surrounding environment. Earthquakes occur when plate movements exert pressure on the rocks, which causes them to fracture and shift. The sensing element for earthquake detection is a wireless acceleration sensor device [54]. Dissemination of information about the likelihood of an earthquake must occur at the appropriate time [55]. A large mass of rock, rubble, or earth slides down a slope, which is referred to as a landslide. Although gravity is the primary cause of a landslide, numerous other natural (weak materials, weathering, river erosion, rapid snowmelt, and heavy rain) and human-caused factors can affect slope stability (excavations, deforestation, mining, and artificial vibration). Sensors are deployed to monitor various parameters, and an early warning system can be built based on the measured values to minimize losses. Sliding is responsible for the movement of the earth's crust, which can occur anywhere globally. Each incident spreads several kilometers across the continent in a matter of minutes, wreaking havoc on vulnerable structures, dams, and bridges and occasionally resulting in death. Wireless sensor networks are the most efficient method of sensing and detecting the earth's crustal movement.

Additionally, they have been demonstrated to increase earthquake and landslide detection [56]. The deployment of various wireless sensor nodes in the earth's crust enables the detection of earth crust movement more quickly, which can then be transmitted immediately to sinks for preemptive action via communication architectures. WSNs have the potential to significantly enhance the accuracy and efficiency of earthquake and landslide detection [56]. WSNs can collect data from multiple sensors and transmit it to a web server via a GSM cellular network or other communication architecture [57]. In earthquake and landslide monitoring applications, hardware devices such as displacement, angle, and rainfall sensors, geophysical sensors, pore pressure transducers, FBG sensors, microsensors, geophones, soil moisture sensors, strain gauges, optical fiber sensors, temperature, humidity, land movement sensors, slope sensors, tiltmeters, raindrop sensors, microwave radar sensor for motion detection, extender, and rainfall gauges are primarily used. Software applications such as three-dimensional WebGIS, WiSuN, Raman optical time-domain reflectometry, and SLOPEIW are available to operate earthquake and landslide applications. ZigBee protocol, GSM communication between 900 MHz and 1800 MHz, WIFI and satellite terminals, optical remote sensing, RFID technology, LoRa technology, and Bluetooth technology are all examples of communication architectures that support earthquake and landslide applications [54, 56, 58].

5.6. Forest Fire. Forest fires have become more prevalent in recent years, wreaking havoc on the environment, natural resources, and lives of humans and animals alike. Climate change in most of the world's landmasses may result in forest fires. In countries with scorching and dry weather, fires may rise. Forest fires wreak havoc on the habitats of wild animals and have a detrimental effect on agricultural yields. As a result, it is necessary to develop systems that provide authorities with timely and high-quality information to combat forest fires in the shortest possible time [59]. WSNs can bring a meaningful change in the fight against forest fires. WSNs can detect forest fires and transmit data to a remote-control center via a communication architecture.

Parameters such as temperature, smoke, oxygen levels, and humidity can be collected to help mitigate forest fires. WSNs are advantageous for the early detection of fires through sensor nodes. WSN architectures are designed to detect forest fires faster than traditional methods and forecast the direction of the fire's flow [60].

Sensor nodes can be used to determine the exact location of the fire and its path of spread. By utilizing WSNs, forest guards can intervene more quickly and ensure that the identification and location of an incident are communicated to relevant stakeholders for immediate action. In detecting forest fires, fire, smoke, and temperature sensors may be distributed randomly throughout the forest or used to regulate a forest region prone to fire [61]. Typically, sensors are configured so that when temperature values exceed a predefined threshold, the nodes activate their radios for data transmission. The sensor nodes continuously monitor the forest environment to ensure temperatures remain within specified ranges [59]. In these application domains, collected data is processed centrally and distributed to appropriate stakeholders via alerts or notifications via a communication architecture. Sensor nodes deployed for forest fire detection made efficient energy use, extending the sensor nodes' lifetime. The power can be distributed evenly among the nodes, and in some areas, energy can be harvested to extend the life of the nodes. Forecasting the direction and speed of forest fire spread is critical for firefighting (Y. H. [62]).

Forest fire detection systems employ a variety of hardware architectures, including temperature sensors, humidity sensors, gas sensors, infrared sensors, pressure sensors, solar radiation sensors, and smoke recognition sensors. Other researchers have detected forest fires using unmanned aerial vehicles, carbon dioxide sensors, GPS devices, and raspberry pi sink nodes. TinyOS, routing (flooding routing, AODV), time synchronization protocols, MAC layer (IEEE 802.15.4, LEACH) protocols, and ad hoc clustering techniques or architectures have all been adopted. To address the application requirements for forest fire detection, clustered hierarchical network architectures and intra- or intercluster architectures may be used.

6. Advances in WSNs

This section presents the advances in WSN architectures with the introduction of machine learning and the Internet of Things.

6.1. WSNs and Machine Learning Architectures. The primary goal of WSN deployments is energy conservation, which results in a more extended network lifetime. Machine learning is used to significantly reduce data communications in typical WSN deployments' distributive environments. Recent research has explored machine learning techniques (supervised, unsupervised, and reinforcement learning) in all layers of the communication stack. Most approaches occur at the routing and medium access layers. These protocols' purpose is to provide current information about the reliability of connections to neighboring nodes. Its properties for reliable networks include its ability to adapt rapidly to changes, energy efficiency, and resistance to short-term aberrations [63].

Q-learning, a reinforcement learning technique, has been applied to WSNs to optimize routing performance and extend network lifetime [64]. Decision trees employ learning trees to forecast output labels based on repeating data. Decision trees have been used in wireless sensor networks to identify link reliability characteristics such as loss rate, restore time, and failure time. Support vector machines (SVM), neural networks, and Bayesian networks are used in environmental monitoring [65]. Additionally, machine learning has been used to design MAC protocols that aid WSNs in adapting to changing environmental monitoring conditions. Q-learning and reinforcement learning techniques have optimized MAC protocols, including Q-learning in Slotted Aloha and RL-MAC.

Smart environmental monitoring applications have benefited from artificial intelligence (AI) and machine learning (ML) by providing precise and optimum control of undesirable effects on the environment. Classifications, clustering, and anomaly detections are some of the many uses of AI and ML in smart monitoring. However, concerns are raised in their implementations due to the pervasion of applications in agriculture, transport, buildings, air quality, water quality, and human and animal tracking and monitoring. Interoperability of the sensors, data structures, standards, and protocols in implementing and controlling smart environmental systems is a significant concern.

Classification and anomaly detection are some tools deployed to mitigate the cost of energy consumption and data deduplication on systems [66, 67]. For a brief survey on anomaly detection systems, the reader may refer to the work by [67]. The authors discuss advances and implementations of ML and AI in smart buildings with strategies in smart vision, architectural design and visualization, progress monitoring and safety, and data storage [66]. ML tools used and implemented in these applications include, but are not limited to, support vector machines (SVM), neural networks (NNs), regression models, deep convolutional neural networks (Deep CNN), Markov chains, and particle swarm optimization (PSO) [66].

Using AI and ML brings innovations in personalized designs, enhances communications and control, and reduces human factor failures.

6.2. WSNs and IoT Architectures. The Internet of Things (IoT) is the network of everyday physical objects embedded with tiny sensors and connected through software and other enabling technologies. IoT networks collect environmental data and transmit it to other connected devices and systems via the internet. By 2025, researchers estimate that there will be over 25 billion connected devices worldwide. Through various standard protocols, domains, and applications, the IoTs connect machines in ways that go beyond machine-to-machine (M2M) communications. Microcontrollers, for example, are frequently used in sensor nodes due to their low cost, ease of connection to other devices, programming ease, and energy efficiency. The Raspberry Pi, Arduino boards, the Giant board, the XBee module, and the ATMEGA32 series are all examples. In IoTs, communication standards such as Bluetooth, Zigbee, Wi-Fi, and RFIDs are used to implement short-range communication networks that enable IoTs. Radio frequency (RF), optical communication (laser), and infrared are all possible wireless transmission media. The most pertinent mode of communication is radio frequency-based, as it applies to most WSN applications. WSNs communicate at the following license-free frequencies: 173, 433, 868, 915 MHz, and 2.4 GHz.

6.3. Simulators. Most WSN applications are implemented using simulations to evaluate new applications at a lower cost. Simulations enable researchers to experiment with and isolate different network factors by easily tweaking and tuning parameters without regard for cost. As a result, the development of WSN simulators is expanding rapidly. However, simulations are not trivial to implement. Several factors affect the simulation results, including the simulator's suitability and the tools' suitability for implementing the simulation solutions. Network Simulator 2 (NS2), Network Simulator 3 (NS3), TOSSIM (TinyOS Simulator), Castalia OMNeT++, J-SIM, OPNET, and Avrora are all examples of simulators.

NS2 is an IEEE 802.11, IEEE 802.16, and IEEE 802.15.4 discrete event simulator. It is written in two major programming languages, that is, C++ and object-oriented yool command (OTcL), and supports network routing and MAC protocols but only a limited set of energy modelling algorithms. It does not support modelling for nodes greater than 100, which complicates scalability in NS2. Network Simulator 3 was created to address these issues. It is not a replacement for NS2 but an entirely new simulator written in C++ with optional Python bindings, and NS3 provides enhanced energy devices and source support. NS3 has a more advanced WIFI Radio implementation, comparable to IEEE 802.11, the primary networking channel in most WSNs. Castalia is an open-source simulator written in the OMNeT++ programming language. The simulator validates distributed algorithms and protocols by simulating radio models and wireless channels in the real world. It uses real-world node characteristics to simulate the radio's behavior. It includes parameters for sensor bias, clock drift, node energy consumption, memory consumption, CPU energy consumption, CPU time, and the implementation of the MAC and routing protocols.

TOSSIM is not a simulator but a TinyOS emulator. It is a Python-based bit-level discrete event emulator. TOSSIM can be run on Linux or Windows via Cygwin. It can be used to simulate network and radio models and code executions. Power TOSSIM is another TinyOS variant of TOSSIM that simulates each node's energy consumption. TOSSIM-enabled nodes run NesC on TinyOS. TOSSIM's design is limited to the emulation of mote-like nodes. OMNeT++ is also a C++-based discrete event simulator. It provides programmers with a graphical user interface and a framework for sensor node mobility. OMNeT++ includes channel controls, MAC addresses, and a limited number of routing protocols. It only supports a limited amount of information about the energy consumption of individual sensor nodes [28].

6.4. Operating Systems. In WSNs, operating systems must support fundamental power management, portability, scheduling, simulation support, and execution models. Operating systems manage the sensor devices' limited resources and function differently depending on their application domains. Operating systems, on the other hand, are highly communicative. As a result, energy is the primary resource it cannot obtain. Some OS used include TinyOS and Contiki, Mantis [68], Pixie [69], SOS [70], and LiteOS [71]. Contiki and Pixie use a software approach to track the power state in all the system components.

TinyOS is an event-driven, open-source operating system for wireless sensor nodes. It is not an operating system per se but a framework for developing embedded systems tightly coupled with the network embedded system C programming language (NesC). A typical WSN application is approximately 15 kilobytes, with about 400bytes representing the application and approximately 64 kilobytes illustrating the database query system (for example, PostgreSQL). TinyOS primarily comprises a TinyOS simulator (TOSSIM) and a visualiser (the TinyViz).

Pixie is a data-intensive platform for programming sensor networks. It is used in high-data-flow applications requiring extensive in-network processing, such as acoustic and seismic monitoring, acceleration, and water quality monitoring. Pixie's implementation in NesC is backwards compatible with TinyOS. In Pixie, the user must forecast the application's energy requirements and delegate resource management to the operating system. The operating system is aware of and manages the system's resource constraints, which include energy, storage, and bandwidth. It is divided into three primary components: a dataflow programming model, resource tickets, and resource brokers. The data flow model enables the operating system to exert visible control over the application's limited resources. The resource tickets are the abstractions used to manage and discretely allocate available resources. Finally, it includes resource brokers, which implement code modules that have Pixie resource management policies.

The multimodal system for networks of in situ wireless sensors (Mantis) is a multimodal embedded system operating system. Its primary goal is to provide an easy-to-use system that addresses the resource-constrained challenges of developing sensor network applications. Multithreading, time slicing, and pre-emptive scheduling are all features of the Mantis OS architecture, and its core is written in standard C. It includes an implementation of the RC5 security algorithm. Mantis's development enables it to cross-platform and multimodal prototyping of environmental monitoring applications.

7. Future Research Directions and Conclusions

In this section, we present novel research directions from WSNs for EMAs that will require further investigation and provide a conclusion to the paper.

7.1. Future Research Directions

7.1.1. Cloud Computing in WSN for EMAs. The use of cloud computing in WSN for EMAs aims to improve sensor networks' energy efficiency, processing capability, and node communication. Integration of cloud computing with WSNs for EMAs may be investigated further to leverage the advantages of cloud computing to meet complex application needs and novel architectures for EMAs. In developing virtual sensors in EMAs, using sensor-based cloud computing functions applying virtualization on cloud computing platforms should be investigated. More research on reconfigurable physical, network and MAC layers in the protocol stack should be conducted to improve the protocol design for WSNs for EMAs. Researchers should thoroughly investigate novel ways to employ virtualization in EMAs to satisfy the data gathering approaches (event-based, periodic, and approximation-based) while considering peculiarities of the various application environments (dynamic or static) to meet the needed service requirements.

7.1.2. Integration of Artificial Intelligence and Data Fusion. In recent years, AI has advanced rapidly in wireless networks. AI-based technologies (e.g., machine learning, reinforcement learning, and deep learning) have been used in wireless sensor networks for EMAs. When powerful computational capabilities are introduced for use in WSNs for EMAs, sensor nodes produce more accurate data for use by stakeholders in effective decision-making. As a result, it is time to apply AI-based technologies to EMAs, which opens up new avenues for researchers to obtain more intelligent approaches to enhance data computation going into the future. WSN for EMAs is targeted for the generation of huge tons of data. Exploiting lightweight data fusion approaches to correlate the data gathered from sensor nodes in EMAs is worth researching.

7.1.3. Dynamic Network-Wide Protocol Design. In WSNs for EMAs, it is essential to use the right deployment strategy to optimize the energy utilized in the overall network. By exploiting advanced networking protocols, the sensor nodes will form the required communication paths and establish connectivity for nodes to observe their environment and transmit the phenomena to the base station. Robust network-wide protocols that support dynamic network topology for applications such as animal tracking, freshwater monitoring, oceanography, and air quality monitoring present new challenges to the WSN for the EMAs research community. Considerations for network-wide protocol design for WSNs for EMAs should center on energy-and data-based due to the architectures used in these environments.

7.1.4. Advanced Data Visualization Technologies. One of the essential considerations for EMAs is the measurement, collection, and transmission of enormous amounts of data from nodes to a central repository for processing, analysis, and reporting. Online IoT visualization tools like ThingsBoard have recently been developed to provide real-time data visualization in WSNs to monitor environmental conditions [72]. These technologies could be enhanced further to perform an intelligent assessment of various environmental characteristics obtained from the sensor network. Intelligent monitoring software for EMAs can be designed with a range of real-time visualization techniques to meet the specific requirements of the numerous domains in EMAs.

7.1.5. Novel Approaches for Access Control and Authentication. WSNs for EMAs are susceptible to hacking attacks, particularly with the rise of the Internet of Things technologies used to monitor various environmental conditions. Despite recent research focusing on the Internet of Things security, there are still security problems with IoT implementation in EMAs. As a result, efficient and secure mutual authentication procedures that consider the specific environmental characteristics of EMAs and the architecture developed for use would improve dynamic resource management and performance for modern WSNs for EMAs.

7.2. Conclusions. The sensor network architecture suitable for environmental monitoring applications has been discussed in this paper. The sensor node architecture can be used for a variety of applications. The various components of the sensor node all contribute to the amount of energy expended during the node's operation in each environment. The different strategies presented in this paper must be carefully implemented to coordinate the sensing, data communication, and computation components that consume most of the sensor nodes' energy to implement WSNs for EMAs efficiently. As a result, when designing WSNs for EMAs, the number of sensors, the type of parameters, and the sensor network architecture should all be considered to maintain the wireless sensor network's quality of service and lifetime. Due to the hardware design, addressable communication between sensor nodes in EMAs may be possible. Data collected from sensor nodes deployed in WSNs for EMAs can be transferred to a web server or the cloud and displayed on a web portal for real-time monitoring by stakeholders. The web portal typically includes a dashboard for displaying sensor readings derived from parameters. EMAs benefit from wireless sensor node architectures in energy conservation, hardware reuse, resource management, and real-time performance. This paper also discussed advances in WSNs made possible by machine learning and the Internet of Things (IoT).

Data Availability

There is no data available.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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