Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 04, April-2025

A Review on Wireless Sensor Networks

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***Abstract*— This is a highly efficient wireless network that operates without the need for infrastructure where A vast network of wireless sensors is deployed in an ad-hoc manner to monitor system performance, physical parameters, or environmental conditions. Sensor nodes play a major role in WSN having the onboard processor to manage and monitor the environment. A Wireless Sensor Network (WSN) consists of three layers: the Physical Layer, the Data Link Layer, and the Application Layer. These layers are used for data work flow, Monitoring and data collection. This paper concentrating on reviewing the research works on WSN by focussing its structure of WSN, Characteristics, working and challenges of WSN.**

***Index Terms*—WSN- Wireless Sensor Networks, security, key Distribution, Authentication.**

I. INTRODUCTION

The idea of Wireless Sensor Networks (WSNs) emerged in the late 20th century, initially driven by military applications, particularly for surveillance. Over the years, the evolution of WSN technology has seen tremendous advancements, transitioning from simple monitoring systems to complex networks capable of intelligent decision-making. Early Wireless Sensor Networks in homes were like basic smoke alarms functioned by emitting a beep only when smoke was detected [1]. Now, WSNs in smart homes can detect smoke or fire and pinpoint its exact location, send instantly alerts to your phone and automatically notify emergency services.

Sensors are the elements that are accountable for gathering data, as they collect environmental data (variables) and transform it into electrical signals through a mechanism called transduction. Simply put, sensors are small electric noses, ears, and fingers that 'sense' the environment and inform a computer what it 'detects' in a language it comprehends. Radio Nodes come with a microcontroller for processing data, a transceiver for wireless communication, external memory for storing data, and a power source to keep functioning. They capture the electric signals from the sensors and transmit this information to the WLAN access point. WLAN Access Points wirelessly collect data from radio nodes, often via the Internet, and then transmit it to evaluation software for processing. Evaluation Software evaluates the information received from the WLAN Access Point and converts raw data into useful insights for the user.

Non-Deterministic Deployment in Wireless Sensor Networks entails the distribution of sensors in hard-to-reach or difficult terrains where specific placement cannot be achieved. This technique is distinguished by the haphazard dispersion of sensors without following a certain pattern throughout a predetermined area, usually launched from an aircraft or other means. It predominantly works well in situations when manual placement is impractical because of hard terrain or sheer size. In wireless sensor networks, deterministic deployment refers to the clear and planned positioning of sensors in the regulated environments.

This method is applied in settings that allow for proper careful planning and implementation of sensor placement, such as indoor, outdoor, and industrial settings. Every sensor must be arranged precisely to meet the application's unique data collection requirements.[2] The structure of WSN architecture is clearly divided into discrete layers to improve the efficiency and scalability. By supporting a wide range of applications, this unique multi-layer architecture ensures that wireless sensor networks are highly robust and adaptable. Sensor nodes that pick up physical circumstances and translate them into electrical signals make up the sensing layer. In WSNs, this layer serves as the important basis for data collection and includes components like temperature, motion, and pressure sensors.

In the approach of processing layer, nodes do preliminary data processing to remove redundancies and filter out noise. This stage lowers the volume of data sent, protecting bandwidth and lowering energy usage. Techniques like data compression and filtering are used to increase the model's efficiency. Data transport between gateways and nodes is handled by the communication layer. It incorporates protocols for wireless communication and uses efficient routing strategies to ensure true data delivery while monitoring network structure and node connectivity.

Through sophisticated visualization systems and user-friendly dashboards, the application layer acts as the interpretative

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 04, April-2025

interface, turning pre-processed data into actionable intelligence. This layer serves as the contact point where the technical infrastructure of Wireless Sensor Networks (WSNs) converges and their end-user functionalities, enabling diverse implementations such as environmental surveillance, industrial process automation, and smart city integrations. The hierarchical WSN architecture increases the operational effectiveness and overall efficacy of WSNs by promoting modular scalability, simplified diagnostic processes, and autonomous component optimization.

II. WSNS OPERATION

With a structured framework that converts raw data into important useful intelligence, Wireless Sensor Networks (WSNs) are essential for continuous monitoring and controlling a huge variety of situations. To measure variables like temperature, humidity, and vibration, sensor nodes are positioned strategically throughout a predetermined area. These sensors, for instance, continuously measure soil moisture levels in most precision agriculture to maximize irrigation techniques. [1], [2] To guarantee correctness, consistency, and smooth network integration, the collected data is digitalized in real time at the source.

To improve data quality, each sensor node performs preliminary processing after data capture. By removing redundancies and filtering out noise, this effectively lowers the amount of data that is sent. WSNs maximize bandwidth utilization and conserve energy by using data compression techniques at this point, which are crucial for increasing network lifespan. Following refinement, the data is conveyed via multi-hop communication, which involves the progressive propagation of information among interconnected nodes until it reaches a base station or gateway for additional integration and analysis. This methodology ensures effective data transfer from distant nodes while preserving strong network coverage and connectivity.

The combined data undergoes the advanced analysis using advanced analytics techniques after arriving at a central server or cloud platform. This stage enables users to spot trends and irregularities, which is most essential for quickly coming to well-informed conclusions. For instance, in industrial settings, this analysis might reveal patterns in the operation of machinery that point to the necessity of maintenance. In the end, users are empowered to take well-informed actions by the analytical insights obtained from data processing. WSNs provide predictive decision-making in a variety of fields, whether it is by dynamically modifying environmental controls in response to real-time variations or warning staff of new abnormalities. — from healthcare infrastructures that continuously monitor patient vitals to sophisticated transportation systems that optimize urban traffic flow. WSNs are advanced frameworks for real-time surveillance, optimization, and autonomous management across a variety of operational landscapes by seamlessly combining sensing, data processing, transmission, analytical evaluation, and responsive action.

III. TYPES OF WSNs

Networks of Ground Deployed: Fixed nodes placed on land for tasks like environmental monitoring and structure health assessment are known as ground-deployed WSNs.

Networks of Grosvenor WSNs: Sensors positioned beneath the surface of the earth to monitor subterranean facilities, seismic activity, or soil conditions.

Networks of Marine Sensor: Nodes designed to withstand water currents and pressure; frequently used for oil pipeline monitoring or marine biodiversity..

WSNs of Mobility-Enabled : Nodes that can function on their own or with the help of outside forces, making them appropriate for wildlife monitoring or search and rescue missions.

WSNs of Multimedia-enabled: Equipped with cameras or microphones, these networks collect and transmit audio-visual data for emergency response or surveillance.

IV. CHARACTERISTICS OF WSNs

Conventional wireless networks include Bluetooth-based networks, wireless personal area networks (WPANs), wireless local area networks (WLANs), and mobile communication systems, among others. Their architecture is mainly designed to support several human-centric needs at once, such as picture transmission, video streaming, voice communication, and more.In contrast, wireless sensor networks (WSNs) are purpose-driven, designed for specialized applications [3]. As previously discussed, WSNs represent a distinct subset of Ad Hoc networks. Consequently, beyond inheriting fundamental Ad Hoc network attributes—such as dynamic topology, decentralized self-organization, multi-hop routing, and constraints on energy and bandwidth—WSNs exhibit unique characteristics that differentiate them from conventional Ad Hoc networks:

(1) Resources are significantly more limited. Due to cost considerations and hardware dimensions, the signal processing and computing capabilities of wireless sensor network nodes are lower, and their storage capacities are diminished.

(2) The network operates on a significantly larger scale, covering an extensive geographical area. Wireless sensor networks typically consist of hundreds or thousands of nodes, with some deployments even reaching tens of thousands. To ensure comprehensive coverage, a high density of nodes is distributed across the region, leading to a densely populated network architecture.

(3) Sensor network nodes lack global identifiers, such as IP addresses. Instead, each node maintains only localized awareness, storing the identities and locations of its immediate neighbors. Signal processing and data communication are achieved through distributed collaboration among adjacent nodes, highlighting the network's robust cooperative capabilities. [3]

(4) The network exhibits notable topological stability. Unlike mobile ad hoc networks where topology changes stem predominantly from node mobility, wireless sensor networks experience topological shifts chiefly due to energy depletion in nodes. This occurs while maintaining largely static physical node configurations, resulting in fundamentally different network dynamics.

V. APPLICATIONS OF WSNs

A. Smart Home/ Smart Office

Smart homes and offices can deliver personalized services tailored to individual users. Significant research has been devoted to this field [4], and smart home technologies are gradually entering the mainstream market. Establishing a smart home requires substantial effort and careful planning. Currently, numerous commercial products are available that perform specialized functions characteristic of smart environments. As highlighted by Hussain et al. (2009), wireless sensor networks (WSNs) enable various beneficial applications by utilizing collected data.

B. Military

Cutting-edge technologies, particularly advanced networking systems, enhance military operations by ensuring the rapid and precise delivery of critical intelligence to the appropriate personnel or units when needed. This capability significantly boosts mission effectiveness. To address contemporary challenges, these emerging technologies must be seamlessly integrated into a comprehensive operational framework. Enhanced situational awareness (Chien-Chung Shen, 2001) remains a fundamental requirement. As identified by Doumit and Agrawal (2002), key applications include tracking enemy movements across land and sea, securing military installations against intrusions, assessing chemical and biological threats, and supporting urban combat logistics. Akyildiz (2002) further elaborates on integrated systems for command, control, communications, computing, intelligence, surveillance, reconnaissance, and targeting (C4ISRT).

C. Industrial and Commercial

Wireless data transmission has been prevalent in industrial environments for an extended period, but its importance has surged recently. The proven effectiveness of wireless sensor networks in supervisory control and data acquisition (SCADA) systems demonstrates their capability to meet industrial application requirements. These networks play vital roles in monitoring critical process parameters including temperature, flow rate, and pressure. As wireless technology advances and becomes more cost-effective, industrial adoption continues to expand. In manufacturing environments, WSNs contribute significantly to enhanced quality control through continuous monitoring capabilities.

D. Traffic Management and Monitoring

Traffic congestion has become a universal challenge for major cities globally. Authorities are actively implementing solutions to address these transportation issues. Strategic traffic planning and regulation can significantly reduce congestion [5]. Effective peak-hour traffic management requires real-time automated data collection systems. These solutions fall within the research domain of Intelligent Transport Systems (ITS), which Chinrungrueng (2006) defines as the application of computer, communication, and sensor technologies to surface transportation. A key ITS application involves vehicle tracking systems that locate and monitor moving objects. This study specifically examines wireless sensor network (WSN) implementation for vehicle monitoring, emphasizing the critical need for energy-efficient sensor node design due to limited battery capacity.

E. Structural Healthcare

Current maintenance practices often rely on scheduled inspections and time-based replacement rather than assessing actual structural conditions. As Tiwari et al. (2004) demonstrated, embedded sensors enable condition-based monitoring of critical infrastructure. When sensors identify possible problems, wireless sensing technology enables real-time structural examination, drastically lowering maintenance costs and averting catastrophic failures. Sensor networks installed on bridges (Arms et al., 2001), in concrete and composite materials, and inside huge structures are examples of practical usage.

F.Agriculture

VI. CHALLENGES OF WSNs

According to Wang and Wang (2006), wireless sensor networks (WSNs) have a lot of promise for use in agriculture, especially when it comes to monitoring important variables like water scarcity and soil degradation. By facilitating accurate monitoring and effective irrigation water resource management, these technologies promote more environmentally friendly farming methods.

A.Topology and Coverage Control

A crucial issue in wireless sensor networks (WSNs) is topology control, which is essential for increasing network lifetime, reducing radio interference, and enhancing the functionality of routing and media access control protocols..

Furthermore, it maintains reliable connectivity and coverage while enhancing overall network service quality. While substantial progress has been made in WSN topology control research [1], persistent challenges remain, including the absence of a universally optimal algorithm, inadequate assessment of network performance metrics, and the over-idealization of mathematical models. As highlighted by Jardosh and Ranjan (2008), current research focuses on graph-theoretical modeling approaches, emerging trends, and future directions in this field.

B.Mobility management

"Mobility represents a critical component in next-generation network architectures. As wireless sensor networks (WSNs) increasingly integrate with the future Internet, developing robust mobility support models becomes essential. The diverse deployment scenarios for WSNs complicate the establishment of standardized mobility frameworks. Camilo (2008) identifies several key mobility paradigms such as Intra-WSN mobility, the most prevalent scenario, where individual sensor nodes relocate locally while maintaining continuous connectivity with their sensor router (SR), Inter-WSN mobility, involving node migration between distinct sensor networks, each managed by its respective SR, Whole-network mobility, exemplified by the IETF NEMO working group's study (Devarapalli, 2005, RFC3963), where an entire WSN relocates, as demonstrated by bus-mounted sensor networks,A fourth emerging paradigm involves interdependent WSNs, where one network leverages another to sustain Internet connectivity. Another example is the MANEMO project (Wakikawa et al. , 2007).

C.Security

Privacy protection in wireless sensor networks (WSNs) remains a critically understudied aspect of network security. This encompasses sensitive payload data collected by sensors and transmitted to centralized servers, as well as contextual metadata such as the originating sensor's location. In operational WSN deployments, safeguarding both data content and transmission context constitutes a fundamental security requirement. As Li and Das (2009) demonstrate through their comprehensive analysis, effective privacy preservation in WSNs requires interdisciplinary approaches drawing from wireless networking, database security, and data mining. Developing robust privacy-enhancing techniques tailored to WSNs' unique constraints represents an urgent research priority.

D.Biomedical/Medical

Wireless sensor networks (WSNs) are gaining increasing adoption in biomedical and healthcare applications. Biomedical wireless sensor networks (BWSNs) demonstrate significant potential for enabling mobile monitoring of vital physiological functions across both clinical and home environments. However, BWSN development must address critical challenges including security vulnerabilities, enhanced signal processing, and advanced data visualization capabilities. These systems promise to expand patient mobility beyond traditional clinical settings, enable concurrent monitoring of multiple patients, and better adapt to clinicians' evolving information needs. The growing ubiquity of internet connectivity has further stimulated substantial research and commercial interest in eHealth services, positioning BWSNs as a key enabling technology for next-generation healthcare solutions.

VII. CONCLUSION

This research paper focuses on review of Wireless Sensor Networks in terms of its structure, characteristics, types of networks, operations, applications and challenges. Current research on WSNs meet the required modifications in the scenario of WSNs.

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