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Smart Sensor Technologies and Communication Interfaces for Environmental Monitoring at Schools

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Abstract: Indoor environmental quality in educational institutions has a significant impact on students' health, cognitive performance, and overall well-being. Smart sensor technologies offer an effective solution for real-time, automated monitoring of critical environmental parameters such as temperature, humidity, carbon dioxide (CO_2), particulate matter (PM), light intensity, and noise levels. This paper presents an overview of smart sensor systems and their communication interfaces, focusing on their application in school environments. Smart sensors integrate sensing units with onboard signal processing and communication capabilities, enabling autonomous data acquisition, pre-processing, and transmission to centralized or cloud-based platforms. The study explores both wired and wireless communication protocols, comparing them based on power consumption, data rate, coverage, and suitability for deployment in school infrastructures. Additionally, the integration of Internet of Things (IoT) frameworks facilitates scalable and remote monitoring, supporting data-driven decision-making for improving classroom conditions. This work highlights the potential of smart environmental monitoring to enhance learning environments, reduce health risks, and support energy-efficient school building management through reliable and continuous sensing systems.

Keywords: smart sensors; environmental monitoring; school; IoT; communication protocols

1. INTRODUCTION

Environmental degradation, driven by rapid urbanization, industrial expansion, and climate change, poses significant threats to ecosystems, public health, and global sustainability. Effective environmental monitoring at school is essential to protect the student's health. Traditional monitoring methods, based on manual sampling and laboratory analysis or isolated sensing units are often labor-intensive, geographically limited, and incapable of providing real-time data. In this context, the emergence of smart sensor technology marks a paradigm shift in the way environmental data is collected, transmitted, and analyzed.

Smart sensors [1-5] are advanced devices that integrate three core functionalities: sensing of physical, chemical, or biological parameters, embedded processing for data filtering, calibration, and compression, and communication capabilities for data exchange with external systems or networks. These intelligent nodes can be configured to autonomously detect environmental changes and transmit actionable information to centralized platforms or edge computing devices. Compared to traditional sensors, smart sensors offer increased efficiency, reduced maintenance, and adaptability for deployment in remote, distributed, or dynamic environments.

In recent years, smart sensor systems have become central to Internet of Things (IoT)-based environmental monitoring networks [6-9], in which a large number of interconnected sensor nodes generate continuous streams of data. These systems are further enhanced by wireless communication protocols (e.g., ZigBee, LoRaWAN, NB-IoT), low-power microcontrollers, cloud computing, and machine learning algorithms for anomaly detection, pattern recognition, and forecasting. Such advancements enable high-resolution spatiotemporal monitoring of critical environmental variables, including air quality (e.g., PM2.5, CO_2, NO_x), water quality (e.g., pH, turbidity, dissolved oxygen), soil conditions (e.g., moisture, nutrients), radiation levels, noise pollution, and meteorological parameters.

The interdisciplinary nature of smart environmental sensing—encompassing sensor engineering, wireless communications, data science, and environmental science has led to the rapid development of versatile monitoring platforms [10-12]. For example, wireless sensor networks (WSNs) can be deployed in urban air quality grids, precision agriculture fields, or coastal zones for flood early-warning systems. Similarly, mobile and wearable environmental sensors enable personal exposure tracking in smart health and occupational safety applications.

Despite the growing deployment of smart environmental sensors, several challenges remain. These include sensor calibration and drift in harsh environments, energy efficiency and power management for long-term operation, data reliability and fusion from heterogeneous sources, and cybersecurity in IoT networks. Addressing these issues is crucial for developing scalable, robust, and trustworthy environmental monitoring infrastructures.

This paper provides a comprehensive overview of smart sensor technology for environmental monitoring, with a focus on sensor types, data transmission techniques, and application domains. We review state-of-the-art research and industrial solutions, examine current technological limitations, and outline future directions for integrating smart sensing into sustainable environmental management strategies.

2. SMART SENSORS IN SCHOOL ENVIRONMENTAL MONITORING

Smart sensors represent a transformative advancement in measurement technologies, offering significant improvements in the collection, processing, and communication of environmental data. Unlike traditional sensors, which are limited to raw signal generation, smart sensors incorporate sensing elements alongside embedded microprocessors, digital communication modules, and often power management systems [13-19]. This integration enables them not only to measure physical or chemical quantities but also to process the data locally, detect faults, perform self-calibration, and communicate with external systems autonomously.

The core architecture of a smart sensor typically includes a transducer that responds to a specific environmental stimulus, such as temperature, humidity, gas concentration, or particulate matter, and converts it into an electrical signal. This signal is then conditioned through amplification and filtering circuits and digitized using an analog-to-digital converter. Embedded microcontrollers or digital signal processors carry out local computations, which may involve filtering, statistical analysis, compensation for temperature or drift effects, and, increasingly, decision-making processes based on embedded algorithms or lightweight machine learning models.

Monitoring indoor environmental quality (IEQ) in schools requires the measurement of several key parameters. Smart sensors are capable of tracking temperature, humidity, and carbon dioxide (CO_2) concentrations to assess thermal comfort and ventilation effectiveness. Additionally, particulate matter (PM2.5 and PM10) and volatile organic compounds (VOCs) are measured to evaluate air pollution levels originating from traffic, cleaning products, or building materials.

Noise levels are another critical factor, especially in classrooms where excessive background sound can impair speech intelligibility and student concentration. Light intensity monitoring also contributes to comfort and energy efficiency, allowing dynamic control of artificial lighting based on daylight availability. Some smart systems also include motion or occupancy sensors to optimize resource use and HVAC control [20].

The implementation of smart sensors in school environments provides multiple benefits. From a health and safety perspective, they ensure that students and staff are exposed to air quality that meets regulatory and health standards. By tracking parameters like CO_2 and PM in real time, school administrators can identify when classrooms require increased ventilation or air purification. From a pedagogical standpoint, the indoor environment significantly affects student focus, cognitive function, and academic performance. Several studies have demonstrated correlations between high CO_2 levels and reduced test scores or attentiveness. Smart sensor systems, by maintaining optimal conditions, support better learning outcomes. Operational efficiency is another significant advantage. Smart sensors can interface with building automation systems to enable data-driven control of heating, ventilation, lighting, and air conditioning. This results in reduced energy consumption and lower operational costs. Furthermore, by collecting and analyzing environmental data over time, facility managers can implement predictive maintenance and long-term planning strategies with high-advanced technologies [21-25].

Smart sensor networks also offer educational value. Data collected from real classroom environments can be used in science and technology lessons, giving students hands-on experience with data interpretation, sustainability topics, and sensor technologies.

3. COMMUNICATION INTERFACE IN SMART SENSORS

The communication interface is a critical component of smart sensors, enabling seamless data exchange between the sensor node and external systems such as edge devices, gateways, or cloud platforms. In contrast to conventional sensors that typically rely on analog signal output or basic wired connectivity, smart sensors are equipped with digital communication protocols that support both wired and wireless transmission of data. This functionality allows for real-time monitoring, remote configuration, and system scalability, all of which are essential in distributed environmental monitoring applications. Smart sensors typically employ one or more of the following communication protocols depending on application requirements, energy constraints, and deployment conditions:

One of the core strengths of smart sensors is their compatibility with modern communication protocols, both wired and wireless. Their scalability allows for gradual deployment across classrooms, laboratories, and common areas. Cloud-based data storage and IoT dashboards enable centralized monitoring, while mobile applications allow teachers and administrators to receive alerts and insights in real time. Scalability also supports future integration with AI-based control systems, where environmental data can be used not only for monitoring but also for predictive analytics and automated responses tailored to the needs of each classroom.

In addition to measuring air quality and comfort parameters, smart environmental monitoring systems can benefit from inertial measurement units (IMUs) [26] that include magnetometers. A magnetometer measures the strength and direction of the ambient magnetic field, and when combined with accelerometer and gyroscope data, it enables accurate orientation tracking of sensor nodes. This is particularly useful for mobile or repositionable sensors in classrooms, where consistent spatial context enhances data reliability. Furthermore, magnetometers can detect electromagnetic interference (EMI) from nearby electronic equipment or infrastructure, offering insight into potential disturbances in the learning environment. In fixed installations, changes in magnetic field readings can also indicate sensor displacement or tampering, supporting system security and maintenance. Thus, the integration of magnetometers extends the capabilities of smart sensor networks by providing spatial awareness, EMI detection, and contextual integrity for improved environmental monitoring in educational settings.

3.1 Wired Communication Protocols

Wired communication [27, 28] remains a reliable and widely used method for interfacing smart sensors with data acquisition systems, particularly in applications that demand high data integrity, low latency, and electromagnetic interference (EMI) resistance. In environmental monitoring systems, wired communication is especially advantageous in fixed infrastructure setups—such as laboratory environments, industrial facilities, and indoor environmental stations—where power is readily available and sensor nodes are located within a manageable distance from the host system.

The most implemented wired protocols in smart sensors include Inter-Integrated Circuit (I^2C), Serial Peripheral Interface (SPI), and Universal Asynchronous Receiver-Transmitter (UART). Each protocol provides specific advantages based on bus complexity, data speed, distance, and power consumption.

I^2C is a synchronous, multi-master, multi-slave serial communication protocol developed by Philips (now NXP). It requires only two lines, SDA (data) and SCL (clock) to transfer data between components. Its simplicity and minimal wiring make it well-suited for applications where multiple low-speed sensors are connected to a single microcontroller. In environmental monitoring systems, I^2C is frequently used to interface temperature, humidity, gas, and pressure sensors with microcontrollers or data loggers. However, I^2C is limited in terms of speed (typically up to 400 kbps for standard mode, and up to 3.4 Mbps for high-speed mode) and cable length (generally under 1 meter), which constrains its use in large or remote installations.

SPI is a high-speed, full-duplex synchronous communication protocol ideal for applications requiring fast and continuous data exchange. It uses four lines: MISO (Master In Slave Out), MOSI (Master Out Slave In), SCLK (Serial Clock), and SS/CS (Slave Select or Chip Select). Unlike I^2C, SPI supports higher data rates (up to tens of Mbps), making it preferable for interfacing high-speed analog-to-digital converters, digital signal processors, and memory devices. In environmental monitoring, SPI is often used in sensor nodes that demand real-time acquisition of large datasets, such as multi-channel gas sensors or high-resolution optical particulate sensors. However, its lack of standardization for multi-slave communication and higher pin count can complicate wiring in dense systems.

UART is an asynchronous serial communication protocol commonly used for long-distance wired data transmission between two devices. It transmits data as a series of bits framed by start and stop bits, eliminating the need for a clock signal. UART is widely employed in environmental monitoring systems for interfacing sensors with microcontrollers, GPS modules, or serial data loggers. It supports moderate data rates (commonly up to 1 Mbps) and allows for more flexible cabling over longer distances compared to I^2C or SPI. UART's simplicity and robustness make it a common choice in industrial environmental sensors with Recommended Standard (RS-232 or RS-485) transceivers, especially when combined with differential signaling to suppress EMI in harsh environments.

Beyond these primary protocols, certain applications may require robust industrial communication standards such as CAN (Controller Area Network) and Modbus, particularly in large-scale, multi-device environmental monitoring systems within factories, power plants, or water treatment facilities. CAN is designed for real-time, fault-tolerant communication, while Modbus (typically over RS-485) is valued for its simplicity and interoperability with supervisory control and data acquisition (SCADA) systems.

3.2 Wireless Communication Protocols

Wireless interfaces [29, 30] are indispensable in modern environmental monitoring systems, where sensors are often deployed over wide geographic areas. Common wireless protocols include:

- Wi-Fi provides high data throughput and internet connectivity but is power-intensive, making it suitable primarily for fixed, powered installations.
- Bluetooth Low Energy (BLE) offers low power consumption and short-range communication, suitable for wearable environmental sensors and indoor air quality monitors.
- ZigBee and Thread are mesh networking protocols designed for low-power, low-data-rate applications, enabling reliable communication across sensor networks with redundancy and self-healing capabilities.
- LoRa and LoRaWAN have Long-range, low-power protocols that support kilometer-scale communication distances with low energy consumption. LoRa-based smart sensors are increasingly adopted for outdoor environmental monitoring such as air and water quality, flood detection, and forest fire risk assessment.
- NB-IoT (Narrowband Internet of Things) is a cellular-based LPWAN technology designed for deep coverage and low power usage. It supports massive deployments of smart sensors in remote or urban settings without the need for localized infrastructure.
- 5G emerges as a viable option for high-speed, low-latency applications involving smart sensor networks, particularly in smart city and autonomous environmental systems.

The choice of communication interface is governed by trade-offs among data rate, power consumption, latency, transmission range, and network topology. In many cases, environmental monitoring systems employ hybrid architectures where smart sensors use low-power protocols for

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local communication and edge gateways relay aggregated data to cloud servers via cellular or broadband links.

Moreover, modern smart sensors often integrate support for Internet of Things (IoT) protocols such as MQTT (Message Queuing Telemetry Transport) and CoAP (Constrained Application Protocol), which are optimized for low-bandwidth and resource-constrained environments. These protocols facilitate scalable, secure, and lightweight data transmission, enabling efficient remote monitoring and control.

Generally, the communication interface of smart sensors is fundamental to their role in distributed environmental systems. It determines the feasibility of real-time data acquisition, influences system energy efficiency, and enables interoperability within heterogeneous sensor networks. The continued evolution of wireless technologies, especially LPWAN and IoT protocols, is expected to further enhance the capabilities of smart sensor systems in environmental applications.

Table 1 summarizes the pros and cons of the wired and wireless communication protocols for sensors.

Table 1. Comparison of Wired and Wireless Communication Protocols for Sensors

Communication Type	**Pros**	**Cons**	**Common Protocols**
Wired Communication	Reliable and stable data transfer High data rates Low latency Less susceptible to interference No need for batteries in sensors	Limited mobility and flexibility Complex wiring and installation Potential higher maintenance costs Not scalable for large or distributed networks	I^2C, SPI, UART, RS-485
Wireless Communication	Flexible sensor placement and mobility Easier installation with no cables Scalable for large deployments Supports remote and distributed monitoring	Potential interference and signal loss Limited bandwidth compared to wired Requires battery power and energy management Possible security vulnerabilities	BLE, ZigBee, Wi-Fi, LoRa, NB-IoT

4. CONCLUSION

Smart sensor technologies are playing an increasingly critical role in transforming how environmental conditions are monitored and managed in school settings. By integrating sensing, processing, and communication capabilities within a single device, smart sensors enable continuous, autonomous, and high-resolution monitoring of key parameters such as temperature, humidity, air quality, noise levels, and light intensity. These data are essential for maintaining healthy, safe, and energy-efficient learning environments.

The effectiveness of smart sensor systems largely depends on the choice of communication interface. Wired protocols such as I^2C, SPI, and UART offer simplicity and reliability in fixed installations, while wireless technologies such as BLE, ZigBee, Wi-Fi, LoRa, and NB-IoT enable scalable deployment across classrooms and campuses. Each protocol presents trade-offs in terms of data rate, power consumption, range, and infrastructure requirements, making the selection highly application dependent.

In the schools, the deployment of smart environmental monitoring systems offers several benefits, including improved indoor air quality, reduced health risks for students and staff, and support for data-driven building management. Moreover, integration with IoT platforms allows for real-time data visualization, remote access, and long-term trend analysis, enabling proactive responses to environmental issues. As schools increasingly adopt digital infrastructure and prioritize student well-being, smart sensor networks will be essential tools for supporting safe, productive, and sustainable learning environments. Future work should focus on system integration, user-friendly data platforms, and the development of adaptive control strategies based on sensor feedback.

5. REFERENCES

[1] Jiang Y, Yin S, Dong J, Kaynak O. A Review on Soft Sensors for Monitoring, Control, and Optimization of Industrial Processes. IEEE Sensors Journal 2021;21:12868–81. https://doi.org/10.1109/jsen.2020.3033153

[2] Ziegler S, Woodward RC, Iu HH-C, Borle LJ. Current Sensing Techniques: A Review. IEEE Sensors Journal 2009;9:354–76. https://doi.org/10.1109/jsen.2009.2013914.

[3] Luo RC, Yih C-C, Su KL. Multisensor fusion and integration: approaches, applications, and future research directions. IEEE Sensors Journal 2002;2:107–19. https://doi.org/10.1109/jsen.2002.1000251.

[4] Hoang ML. Artificial Intelligence Development in Sensors and Computer Vision for Health Care and Automation Application. Bentham Books; 2024. https://doi.org/10.2174/97898153130551240101

[5] Hoang ML, Pietrosanto A. New Artificial Intelligence Approach to Inclination Measurement based on MEMS Accelerometer. IEEE Transactions on Artificial Intelligence 2021:1–1. https://doi.org/10.1109/tai.2021.3105494

[6] Hoang ML, Nkembi AA, Pham PL. Real-Time Risk Assessment Detection for Weak People by Parallel Training Logical Execution of a Supervised Learning System Based on an IoT Wearable MEMS Accelerometer. Sensors 2023;23:1516. https://doi.org/10.3390/s23031516

[7] Tran-Dang H, Krommenacker N, Charpentier P, Kim D-S. Towards the Internet of Things for Physical Internet: Perspectives and Challenges. IEEE Internet of Things Journal 2020;7:1–1. https://doi.org/10.1109/jiot.2020.2971736.

[8] Hoang ML. Smart Drone Surveillance System Based on AI and on IoT Communication in Case of Intrusion and Fire Accident. Drones 2023;7:694–4. https://doi.org/10.3390/drones7120694

[9] da Silva TB, Chaib RS, S. AC, Righi R da R, Alberti AM. Towards Future Internet of Things Experimentation and Evaluation. IEEE Internet of Things Journal 2021:1–1. https://doi.org/10.1109/jiot.2021.3114540.

[10] Hoang ML. Photovoltaic system optimization by new maximum power point tracking (MPPT) models based on analog components under harsh condition. Energy Harvesting and Systems 2019;6:57–67. https://doi.org/10.1515/ehs-2020-0001

[11] Hoang ML, Delmonte N. Digital Twin-Based Real-Time Monitoring System for Safety of Multiple Laptops in Working Environment. IEEE Open Journal of Instrumentation and Measurement 2024;3:1–9. https://doi.org/10.1109/ojim.2024.3502879

[12] Lyu B, Yang Z, Gui G, Feng Y. Wireless Powered Communication Networks Assisted by Backscatter Communication. IEEE Access 2017;5:7254–62. https://doi.org/10.1109/access.2017.2677521.

[13] Hoang ML, Matrella G, Ciampolini P. Artificial Intelligence Implementation in Internet of Things Embedded System for Real-Time Person Presence in Bed Detection and Sleep Behaviour Monitor. Electronics 2024;13:2210–0. https://doi.org/10.3390/electronics13112210

[14] Hoang ML. Unlocking robotic perception: comparison of deep learning methods for simultaneous localization and mapping and visual simultaneous localization and mapping in robot. International Journal of Intelligent Robotics and Applications 2025. https://doi.org/10.1007/s41315-025-00419-5

[15] Hoang ML. A Comprehensive Review of Machine Learning, and Deep Learning in Wearable IoT Devices. IEEE Access 2025:1–1. https://doi.org/10.1109/access.2025.3573937

[16] Hoang ML, Pietrosanto A. An Effective Method on Vibration Immunity for Inclinometer based on MEMS Accelerometer. 2020 International Semiconductor Conference (CAS) 2020. https://doi.org/10.1109/cas50358.2020.9267997

[17] Hoang ML, Pietrosanto A. A New Technique on Vibration Optimization of Industrial Inclinometer for MEMS Accelerometer Without Sensor Fusion. IEEE Access 2021;9:20295–304. https://doi.org/10.1109/access.2021.3054825

[18] Hoang ML, Pietrosanto A. Yaw/Heading optimization by drift elimination on MEMS gyroscope. Sensors and Actuators A: Physical 2021;325:112691. https://doi.org/10.1016/j.sna.2021.112691

[19] Hoang ML, Pietrosanto A. Yaw/Heading optimization by Machine learning model based on MEMS magnetometer under harsh conditions. Measurement 2022;193:111013. https://doi.org/10.1016/j.measurement.2022.111013

[20] Belic F, Hocenski Z, Sliskovic D. HVAC control methods - a review. 2015 19th International Conference on System Theory, Control and Computing (ICSTCC) 2015. https://doi.org/10.1109/icstcc.2015.7321372.

[21] Nkembi AA, Delmonte N, Cova P, Hoang ML. The Design and Dynamic Control of a Unified Power Flow Controller with a Novel Algorithm for Obtaining the Least Harmonic Distortion. Electronics 2024;13:877–7. https://doi.org/10.3390/electronics13050877

[22] Hoang ML, Delmonte N. K-centroid convergence clustering identification in one-label per type for disease prediction. IAES International Journal of Artificial Intelligence 2024;13:1149–9. https://doi.org/10.11591/ijai.v13.i1.pp1149-1159

[23] Hoang ML, Matrella G, Ciampolini P. Comparison of Machine Learning Algorithms for Heartbeat Detection Based on Accelerometric Signals Produced by a Smart Bed. Sensors 2024;24:1900–0. https://doi.org/10.3390/s24061900

[24] Hoang ML, Delmonte N, Bonalumi F, Hu M, Miragoli M, Depoorter P, et al. Image Processing System Based on Mesh Technology for Cell Kinematic Measurement. IEEE International Instrumentation and Measurement Technology Conference (I2MTC) 2024:1–6. https://doi.org/10.1109/i2mtc60896.2024.10561037

[25] Hoang ML. Object size measurement and camera distance evaluation for electronic components using Fixed-Position camera. Computer Vision Studies 2023. https://doi.org/10.58396/cvs020101

[26] Hoang, M.L.; Matrella, G.; Giannetto, D.; Craparo, P.; Ciampolini, P. Benchmarking Accelerometer and CNN-

Based Vision Systems for Sleep Posture Classification in Healthcare Applications. Sensors **2025**, 25, 3816. https://doi.org/10.3390/s25123816

[27] Wan S, Tang L, Shen X. The Core Chip Design of Inter-Integrated Circuit in 40nm CMOS. 2022 7th International Conference on Integrated Circuits and Microsystems (ICICM) 2021:124–7. https://doi.org/10.1109/icicm54364.2021.9660335

[28] Oudjida AK, Berrandjia ML, Tiar R, Liacha A, Tahraoui K. FPGA implementation of I2C & SPI protocols: A comparative study. 2009 16th IEEE International Conference on Electronics, Circuits and Systems - (ICECS 2009) 2009. https://doi.org/10.1109/icecs.2009.5410881

[29] Dong Y, Arslan T, Yang Y. Real-time NLOS/LOS Identification for Smartphone-based Indoor Positioning Systems using WiFi RTT and RSS. IEEE Sensors Journal 2021:1–1. https://doi.org/10.1109/jsen.2021.3119234

[30] Lin B, Su H. Experimental Evaluation and Performance Improvement of Bluetooth Mesh Network With Broadcast Storm. IEEE Access 2023;11:137810–20. https://doi.org/10.1109/access.2023.3339795