IoT

MDPI

Review

Review of IoT Systems for Air Quality Measurements Based on LTE/4G and LoRa Communications

Mpho Gift Doctor Gololo [1,2,*,†], **Clinton Wenfrey Nyathi** [1,†], **Lennox Boateng** [1,†], **Edward Khomotso Nkadimeng** [3,*,†], **Ryan Peter Mckenzie** [1,3,†], **Iqra Atif** [1,†], **Jude Kong** [4,5,6,†], **Muhammad Ahsan Mahboob** [1,†], **Ling Cheng** [1,†] and **Bruce Mellado** [1,3,†]

[1] Institute of Collider and Particle Physics, University of the Witwatersrand, 1 Jan Smuts Avenue, Braamfontein, Johannesburg 2000, South Africa; 2172631@students.wits.ac.za (C.W.N.); 1833993@students.wits.ac.za (L.B.); ryan.peter.mckenzie@cern.ch (R.P.M.); iqra.atif@wits.ac.za (I.A.); mahsan.mahboob@wits.ac.za (M.A.M.); ling.cheng@wits.ac.za (L.C.); bruce.mellado@wits.ac.za (B.M.)
[2] Department of Electrical Engineering, Engineering and the Built Environment, University of Johannesburg, Auckland Park Kingsway Campus, P.O. Box 524, Johannesburg 2006, South Africa; mphog@uj.ac.za
[3] National Research Foundation iThemba Laboratory for Accelerator Based Sciences, Cape Town 7100, South Africa
[4] Dalla Lana School of Public Health, University of Toronto, 27 King's College Circle, Toronto, ON M5S 1A1, Canada; jude.kong@utoronto.ca
[5] Africa-Canada Artificial Intelligence and Data Innovation Consortium (ACADIC), York University, Toronto, ON M3J 1P3, Canada
[6] Global South Artificial Intelligence for Pandemic and Epidemic Preparedness and Response Network (AI4PEP), York University, Toronto, ON M3J 1P3, Canada
* Correspondence: mpho.gift.doctor.gololo@cern.ch (M.G.D.G.); edward.khomotso.nkadimeng@cern.ch (E.K.N.)
† These authors contributed equally to this work.

Abstract: The issue of air pollution has recently come to light due to rapid urbanization and population growth globally. Due to its impact on human health, such as causing lung and heart diseases, air quality monitoring is one of the main concerns. Improved air pollution forecasting techniques and systems are needed to minimize the human health impact. Systems that fall under the Internet of Things (IoT) topology have been developed to assess and track numerous air quality metrics. This paper presents a review of IoT systems for air quality measurements, where the emphasis is placed on systems with LTE/4G and LoRa communication capabilities. Firstly, an overview of the IoT monitoring system is provided with recent technologies in the market. A critical review is provided of IoT systems regarding air quality using LTE/4G and LoRa communications systems. Lastly, this paper presents a market analysis of commercial IoT devices in terms of the costs, availability of the device, particulate matter each device can measure, etc. A comparative study of these devices is also presented on LTE/4G and possibly LoRa communications systems.

Keywords: IoT; LTE/4G; LoRa

Citation: Gololo, M.G.D.; Nyathi, C.W.; Boateng, L.; Nkadimeng, E.K.; Mckenzie, R.P.; Atif, I.; Kong, J.; Mahboob, M.A.; Cheng, L.; Mellado, B. Review of IoT Systems for Air Quality Measurements Based on LTE/4G and LoRa Communications. *IoT* **2024**, *5*, 711–729. https://doi.org/10.3390/iot5040032

Academic Editor: Amiya Nayak

Received: 12 July 2024
Revised: 16 October 2024
Accepted: 23 October 2024
Published: 31 October 2024

1. Introduction

According to the World Health Organization (WHO), ambient air pollution refers to the presence of air pollutants originating from various sources, such as residential buildings, commercial establishments, and vehicular emissions. The aforementioned air pollutants include both gaseous air pollutants and particulate matter (PM) [1]. The emission of fine PM resulting from the combustion of fossil fuels in residential, commercial, industrial, and transportation sectors has been found to have adverse effects on human health [2], especially in low- and middle-income countries [3]. People's physical health and mental well-being are dramatically impacted by air pollution, and prolonged exposure raises the risk of cardiovascular and respiratory conditions [4]. Furthermore, based on projections provided by the WHO, it is estimated that approximately 4.2 million individuals are expected to die annually due to the adverse effects of air pollution [1].

In addition to having detrimental impacts on human health, by declining air quality, and increasing airborne PM, air pollution can also produce major environmental issues, including reduced visibility, disrupted and irregular rainfall patterns, acid rain, global warming, and other phenomena related to climate change.

Therefore, air pollution and its consequences are of particular concern in urban areas characterized by high population densities. Airborne particles can be categorized into three distinct groups: The first category consists of particles that are inhalable, with a size of 100 mm or smaller. These particles have the potential to enter the respiratory system by inhalation through either the oral or nasal cavity during regular breathing. The second type consists of particles measuring 10 mm or less. Regular inhalation might result in their entry into the respiratory system [5]. Lastly, the third PM category includes the smallest inhalable ones, sized 2.5 microns or less. During the process of normal respiration, gaseous substances have the ability to reach the pulmonary system and, subsequently, the bloodstream through diverse mechanisms of gas exchange.

Since people are more likely to be exposed to air pollution during increased traffic, it is important to understand human behavior [6]. Governments can thus obtain pertinent information to suggest new transportation regulations or alternatives that are tailored to the unique features of each community.

The Internet of Things (IoT) has the potential to replace the large government-managed infrastructure, consisting of stationary and expensive monitoring stations, with affordable, portable monitoring equipment, changing the way air pollution is monitored [7]. The development of low-cost air pollution sensing technology has sparked the interest of numerous researchers, who are now working on air monitoring system research based on the IoT. The IoT [8] refers to a network of physical devices, vehicles, appliances, and other objects embedded with sensors, software, and network connectivity that allows them to collect and share data. The realization of real-time management, tracking services, information exchange, and item identification is the last step. With minimum assistance from humans, these IoT-enabled physical devices may collaborate and interact, offering customers services that are insightful, comprehensive, and quick to respond [9].

Figure 1 shows the IoT architecture divided into three layers: perception, network, and application layers. The primary purpose of the sensors, read/write devices, cameras, GPS, and other sensor nodes and gateways that make up the perception layer is to recognize, gather, and communicate information. The network layer includes a range of technologies and systems, such as the Internet, wireless communication networks, mobile air networks (3G/4G/5G), private networks, network management systems, and cloud computing platforms. The key objective of this layer is to effectively communicate a wide range of data and information that has been gathered by the perception layer in real time [10]. Different network layer protocols in relation to air quality measurements in the IoT are presented in the next sections. In accordance with users' actual needs, the application layer offers an efficient information interaction system for the IoT and users [11].

Figure 2 shows a framework for the Construction site PM Monitoring System (CPMS) development [12]. A portable, compact particulate matter (PM) monitoring device designed for use on building sites was created as a result of the study. Together with temperature, humidity, and CO_2 sensors, a cheap PM sensor helped to minimize the device's weight and size. It was intended to be installed using a cradle on walls or floors or put on typical site posts. The power system's USB connector, which could run on batteries or be plugged in, provided versatility. The study assessed the IoT network's communication strategies at building sites. Although the range of WiFi and Zigbee was sufficient, obstructions from site structures and equipment caused problems for them. WiFi was chosen for short-distance communication, especially in interior environments, and RS485 was chosen for long-distance communication because of its dependability in overcoming hurdles. This combination made sure that data were transmitted across the site efficiently. With field workers exposed to PMs and in charge of site emissions management, the study created a web-based PM monitoring program for construction sites. All sensor sites may be monitored in real time thanks to the software, which also offers data plots, exports and saves data, and sends SMS notifications for high-concentration occurrences. Users of the system can also monitor trends in environmental data and promptly address certain problems. In the future, the software can be upgraded to incorporate an index-based method for intuitive health risk evaluations, but for now, it uses the concentration display method for quantitative PM management.

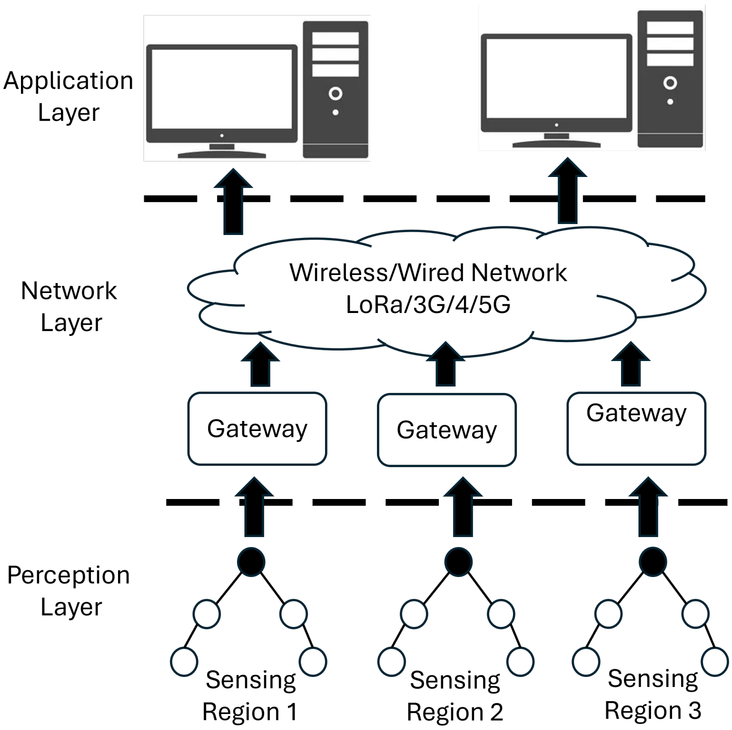

Figure 1. Architecture of IoT with three layers (adapted from [10,11]).

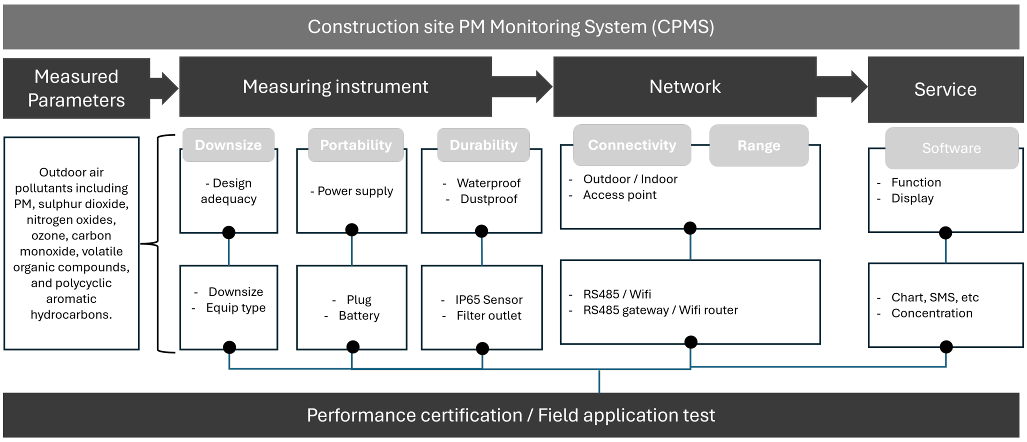

Figure 2. Framework for the Construction site PM Monitoring System (CPMS) development (adapted from [12]).

In relation to the IoT architecture, this paper presents a comprehensive narrative overview of the IoT systems for air quality measurements. A review of the perception layer and the sensor nodes for various IoT systems is presented, followed by the study of the network layers: 4G/LTE and long-range (LoRa) communication systems. Lastly, a market analysis based on the application layer and different IoT devices is provided.

2. IoT Systems Based on LTE/4G for Air Quality Measurements

Figure 3 shows real-time, large-scale air quality monitoring for metropolitan areas, integrating thousands or millions of sensors. This approach combines devices with varying precision, from expensive reference stations to low-cost sensors in vehicles or carried by pedestrians, to ensure dense coverage. Accurate and reliable data are essential, especially in high-population areas, where pollution impacts health the most. To maintain data quality, periodic re-calibration of sensors is required. Given the scale, manual calibration is impractical, so we propose opportunistic calibration, using mobile sensors (e.g., in taxis) that pass by reference stations to update nearby sensors.

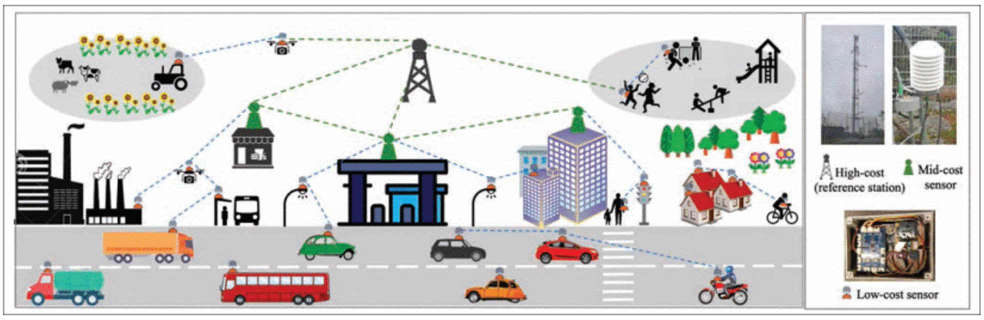

Figure 3. Massive-scale air quality monitoring system with opportunistic sensor calibration. Green lines represent calibration links between reference and mid-cost sensors, while blue lines indicate calibration links between low-cost sensors [13].

IoT systems based on LTE/4G for air quality measurements leverage the capabilities of LTE/4G communication technology to collect and transmit air quality data in real time. These systems typically consist of various components, including air quality sensors, LTE/4G-enabled IoT devices, communication networks, cloud platforms, and data analytics tools. Below is an overview of the key components and functionalities of IoT systems based on LTE/4G for air quality measurements.

2.1. Overview of LTE/4G Communication for Air Quality Monitoring

IoT systems based on LTE/4G technology for the purpose of air quality measurements provide a robust and flexible solution for the continuous monitoring of air quality in real time. These systems are of utmost importance in the field of environmental management as they facilitate evidence-based decision-making and the adoption of efficient measures to enhance air quality and encourage sustainable practices.

High-quality air quality sensors are deployed to measure various pollutants, such as PM, nitrogen dioxide (NO_2), ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2), and volatile organic compounds (VOCs) [14]. These sensors may be integrated into standalone devices or integrated into existing infrastructure, such as lamp posts or buildings, to create a sensor network. IoT devices equipped with LTE/4G communication modules are responsible for collecting data and transmitting it to the central monitoring platform [15].

These devices may also incorporate microcontrollers for data processing and handling communication protocols. LTE/4G cellular networks act as the communication backbone for transmitting air quality data from IoT devices to the cloud platform [16]. The wide coverage and high data throughput of LTE/4G networks ensure seamless data transmission even over large geographical areas.

IoT devices with LTE/4G connectivity enable real-time data transmission, allowing for air quality measurements to be continuously sent to the cloud [16]. Real-time data are crucial for a timely response to pollution events and for providing up-to-date information to relevant stakeholders. A cloud-based central monitoring platform receives and processes the data transmitted by the IoT devices. This platform typically includes a database for storing the collected data and various analytics tools for data processing and visualization [17,18].

The central monitoring platform employs data analytics techniques to process and analyze the air quality data collected from multiple sensors. Visualization tools are used to present the data in a user-friendly format, such as interactive maps or graphs, to aid in data interpretation and decision-making [19,20]. Mobile applications [17,18] or web-based dashboards may be provided to users, enabling them to access real-time air quality information and receive alerts or notifications based on predefined thresholds. To ensure the security and privacy of sensitive air quality data, encryption and authentication mechanisms are implemented for data transmission and storage. Elliptic Curve Cryptography (ECC) and the Advanced Encryption Standard (AES) are two popular security techniques used in Internet of Things (IoT) systems that strike a compromise between security and resource limitations in IoT devices [21,22]. In addition, bidirectional authentication techniques are used in gas sensor networks (MDPI) to stop data breaches and unwanted access, such as sensor-based Physical Unclonable Functions (PUFs) [23,24].

2.2. Case Studies of IoT Deployments Using LTE/4G in Urban Environments

Figure 4 presents an overview of cloud variants and their reach/scale, with a scenario for e-health applications overlaid on the fog IoT architecture. Unlike typical cloud-based IoT systems, which are service-centric, the fog IoT architecture is user-centric. In this system, users control the granularity of services and data access, along with the monetary and energy costs. While this approach increases processing and power at the edge, it offers advantages in privacy, mobility control, and elastic offloading, allowing users to manage data access effectively. A Real Ad hoc Multi-hop Peer-to-Peer Wireless IoT Application (RAMP-WIA) presents a novel solution that facilitates the development, deployment, and management of applications in sparse smart city environments, characterized by users willing to collaborate by allowing for new applications to be deployed on their smartphones to remotely monitor and control fixed/mobile devices [25]. An extensive LTE measurement campaign in Dublin, Ireland, used a custom performance measurement tool to derive a model of the characteristics of link layer RTT and bandwidth versus a link signal strength [26].

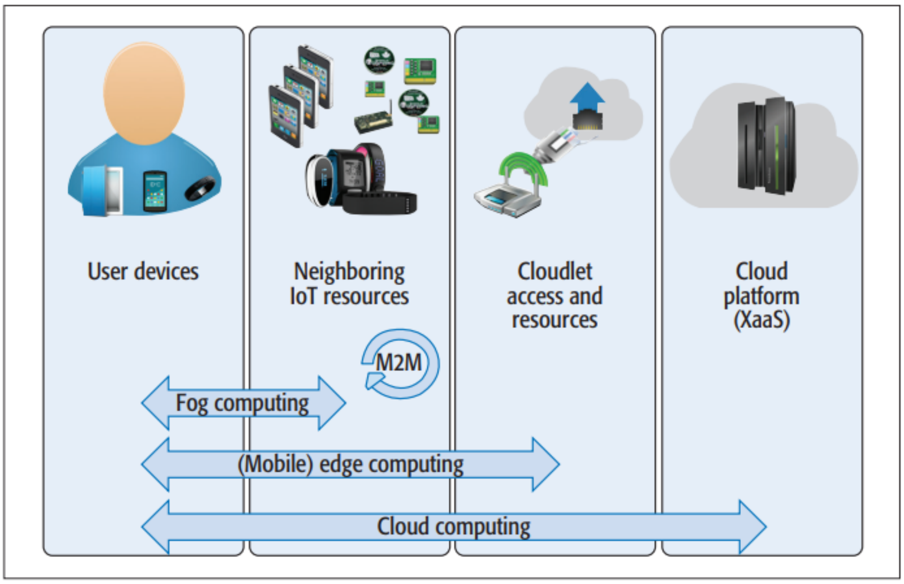

Figure 4. The relationships between cloud variations and a user-centric fog Internet of Things architecture [27].

The work proposed in [28] aimed to correlate and expand the standard IoT systems from personal to wide areas, thus improving performance in terms of providing fast data processing and distant connectivity for IoT data access and showing the relatively close performance of 5G IoT and LTE IoT systems. A novel architecture of a smart city that incorporates IoT, AI, and distributed cloud computing technologies has been described in the literature, with the smart city having its own independent self-management system for managing almost everything related to the needs of the inhabitants' daily life [29].

MARGOT is a platform for distributed edge computing, implemented to enable the secure and domain-specific exploration of Internet of Things (IoT) resources in smart cities. It supports domain-aware and secure discovery of IoT resources and can effectively reduce discovery latency and bandwidth consumption under the considered use cases and network conditions [30].

2.3. Advantages of LTE/4G in Real-Time Data Transmission and High Data Throughput

LTE/4G communication technology offers several significant advantages in real-time data transmission and high data throughput, making it well suited for applications that require timely and continuous data updates.

There is, indeed, a need for a communication protocol that provides lower latency and enhanced flexibility for the remote management of nodes in order to enhance the modularity of the nodes. The MQTT protocol has been empirically shown to exhibit a latency reduction of 90 times compared to other protocols, including the HTTP protocol, in the context of experimental evaluations conducted on 3G networks [31]. LTE has inherent advantages in vehicle-to-infrastructure (V2I) communications due to its high data rate, high penetration rate, extensive QoS support, and wide coverage [32]. Air quality monitoring systems generate substantial amounts of data, especially when multiple sensors are deployed across different locations. The high data throughput of LTE/4G ensures that these data can be transmitted efficiently without significant delays.

Using an onboard WiFi network connected to numerous 3G and 4G networks placed outside on the devices and aggregating their cumulative capacity at the IP protocol level is one way to solve the continuous activity problem [33]. IoT devices equipped with LTE/4G modules can maintain a persistent connection to the network, ensuring uninterrupted data transmission. This continuous connectivity is crucial for applications that require constant monitoring and real-time data updates. With real-time data transmission capabilities, air quality measurements are available in real time or with minimal delay. This enables stakeholders, such as environmental agencies, policymakers, and the general public, to make informed decisions promptly. For instance, in case of sudden pollution spikes or hazardous conditions, immediate actions can be taken to mitigate the impact [34].

LTE/4G networks are designed to be highly reliable, reducing the likelihood of data transmission failures or disruptions. This reliability is essential for critical applications like air quality monitoring, where the accuracy and availability of data are paramount [34]. LTE/4G networks are well suited for mobile applications. IoT devices equipped with LTE/4G connectivity can move freely within the network coverage area while maintaining data connectivity. This mobility support is valuable for monitoring air quality in moving vehicles [32], drones, or other mobile platforms.

LTE/4G networks are designed to handle a large number of connected devices simultaneously. As the number of air quality sensors and monitoring devices increases, LTE/4G networks can easily scale to accommodate the growing data traffic without compromising performance [35,36]. LTE/4G is a well established and widely adopted communication technology. It is expected to remain relevant and supported for the foreseeable future, making it a reliable choice for long-term IoT deployments in air quality monitoring [36]. LTE/4G networks are already well established in many regions, and the infrastructure is readily available. This makes it easier and more cost-effective to integrate LTE/4G-based IoT devices into existing communication networks for air quality monitoring [35,36].

Overall, the advantages of LTE/4G in real-time data transmission and high data throughput make it a compelling choice for IoT-based air quality monitoring systems. Its ability to deliver data quickly and reliably facilitates more effective environmental management and a timely response to air pollution events, contributing to improved air quality and public health.

2.4. Challenges Related to Power Consumption and Cost Considerations

IoT-based LTE/4G technology for the purpose of air quality monitoring can provide a multitude of benefits. However, these systems also encounter distinct challenges pertaining to power consumption and cost considerations. These problems have the potential to significantly affect the practicality and adaptability of these systems.

Continuous connectivity and data transmission frequency are two crucial factors that significantly impact the power consumption of LTE/4G-enabled IoT devices. In order to maintain real-time data transmission, LTE/4G-enabled IoT devices necessitate a constant connection to the cellular network, hence ensuring continuous connectivity. Maintaining uninterrupted connectivity might result in increased power usage, hence depleting the device's battery at an accelerated rate. The power consumption is increased when there is a higher frequency of data transfer to the central monitoring platform [32,33]. For applications that demand real-time monitoring and frequent data updates, the power usage of IoT devices can be challenging to address in battery-powered designs.

The limited battery life of IoT devices poses a challenge for long-term deployments in remote or inaccessible areas. Frequent battery replacements can be costly and logistically challenging, especially in large-scale sensor networks [37]. LTE/4G communication relies on cellular data plans, and the costs associated with data usage can become a significant factor, especially in large-scale IoT deployments. For extensive sensor networks, the cumulative data usage expenses may be substantial [38].

Implementing LTE/4G-based IoT systems requires an initial investment in cellular network infrastructure. This includes setting up base stations and ensuring sufficient network coverage across the desired deployment area, which can be costly [38]. IoT devices with LTE/4G connectivity typically come with higher costs compared to devices using other communication technologies, like LoRa or Narrowband IoT (NB-IoT). These higher hardware costs can impact the overall budget of the air quality monitoring project [38].

3. IoT Systems Based on LoRa for Air Quality Measurements

IoT systems based on LoRa for air quality measurements leverage the capabilities of this low-power, wide-area networking (LPWAN) technology to enable long-range communication and low energy consumption. These systems are well suited for applications where extensive coverage, extended battery life, and cost-effectiveness are crucial.

3.1. Overview of LoRa Communication Technology for Air Quality Monitoring

LoRa technology provides long-range communication, enabling air quality data to be transmitted over several kilometers in urban, suburban, or rural environments without the need for additional infrastructure. This long-range capability is beneficial for air quality monitoring systems deployed over large geographic areas, such as smart cities or industrial zones [39,40]. One of the key advantages of LoRa is its low-power operation, which allows for air quality sensors and IoT devices to operate on battery power for extended periods. The low energy consumption of LoRa devices significantly extends the battery life of the sensors, often lasting for several years before requiring battery replacements [41].

LoRa operates at low data rates ranging from 0.3 kbit/s to 5.5 kbit/s, which is suitable for applications that require periodic transmission of small amounts of data, such as air quality sensor readings [42]. Air quality data are typically collected at regular intervals, and the low data rates of LoRa are sufficient for transmitting essential data points [43]. LoRa networks can support a large number of devices, making it a scalable solution for extensive air quality monitoring networks. The reduced infrastructure requirements and lower data transmission costs contribute to the cost-effectiveness of LoRa-based IoT systems [44,45].

Setting up a LoRa-based network is relatively straightforward, requiring minimal infrastructure and a few gateways to cover vast areas. LoRa's simplicity in network setup facilitates quicker deployment and reduces overall project costs [46]. LoRa-based IoT systems often employ data aggregation techniques to optimize energy consumption and reduce data transmission. Sensor data from multiple nodes can be aggregated before transmission, reducing the number of data packets sent over the network [43].

This capability is particularly valuable for air quality monitoring in hard-to-reach or remote locations. LoRa technology easily integrates with other components of the IoT ecosystem, including cloud platforms, data analytics tools, and mobile applications [47], allowing for seamless data processing, analysis, and presentation of air quality data [48].

Overall, LoRa communication technology offers an efficient and cost-effective solution for air quality monitoring applications. LoRa uses license-free sub-Gigahertz radio frequency bands, like 169 MHz, 433 MHz, 868 MHz (Europe), and 915 MHz [49]. Its long-range communication, low-power operation, and simple network setup make it an attractive choice for various air quality monitoring projects, contributing to more sustainable environmental practices and improved public health.

3.2. Case Studies of Successful LoRa-Based IoT Deployments in Remote and Wide-Area Applications

A LoRa-based Smart Home (SH) system has been described for remote monitoring and maintenance of IoT sensors and devices using the artificial intelligence (AI) concept with an AI-based data flow system for an IoT server and cloud [50]. The i-car system consists of a remote diagnostic system, a LoRa gateway, and a cloud platform that can actively give necessary assistance to vehicle maintenance plants for needing vehicles to achieve driving safety [51].

A system architecture with integrated AI that combines edge and fog computing, LPWAN technology, IoT, and deep learning algorithms to perform health monitoring tasks has also been described, demonstrating the feasibility and effectiveness via a use case of fall detection using recurrent neural networks [52]. A wearable LoRa-based system for remote safety monitoring of people performing activities in remote areas with no network coverage and that is supposed to detect possible heart problems and/or a "man-down" situation is another possible application [53].

The suggested modular constructed smart system utilized considerably less electricity while providing excellent remote monitoring and management of home appliances, and an appropriate parameter setting is required to cover vast urban areas while keeping the airtime low enough to keep packet losses at acceptable levels [54]. The key outcome of these investigations is the cost trade-off analysis between battery replacement and damage penalty along different sensing intervals, which demonstrates a linear increase in the aggregate cost up to GBP1500 in the case of a 5 min sensing interval in the plain (nonenergy-harvesting) industrial environment, while it tends to decrease after a certain interval up to five times lower in EH scenarios [55].

3.3. Advantages of LoRa in Long-Range Communication and Low Power Consumption

LoRa communication technology offers distinct advantages in long-range communication and low power consumption, making it a preferred choice for IoT applications, including air quality monitoring.

LoRa provides exceptional long-range communication capabilities, allowing for data transmission over several kilometers in non-line-of-sight (NLoS) environments. This extended communication range is ideal for air quality monitoring systems that require coverage over large geographic areas, such as smart cities, rural regions, or industrial complexes [39,40]. LoRa signals can penetrate buildings and obstacles effectively, ensuring data transmission in challenging urban environments or dense industrial settings. The ability to provide wide coverage even in harsh environments makes LoRa suitable for air quality monitoring in various applications and locations [39,40].

A standout advantage of LoRa is its ultra-low power consumption of 20 mW. LoRa-enabled sensors and IoT devices can operate on battery power for extended periods, often lasting several years. The low power requirements minimize the need for frequent battery replacements, reducing maintenance costs and ensuring uninterrupted data collection in remote or difficult-to-access areas [41]. LoRa employs energy-efficient modulation techniques, such as the Chirp Spread Spectrum (CSS), which enable long-range communication with minimal power consumption. The low duty cycles and adaptive data rate capabilities of LoRa ensure that devices transmit data only when necessary, conserving energy and prolonging battery life [41].

LoRa's long-range communication eliminates the need for extensive infrastructure and gateways, resulting in lower deployment and operational costs, especially in remote areas. Reduced infrastructure requirements and extended battery life contribute to overall cost savings in LoRa-based air quality monitoring systems [45]. LoRa networks can accommodate a large number of devices, making them highly scalable for extensive air quality monitoring deployments. The ability to handle numerous sensors and devices efficiently supports the growth and expansion of air quality monitoring networks as needed [44].

Minimal infrastructure and few gateways are required to cover vast areas, simplifying deployment logistics [44]. LoRa has gained widespread adoption, leading to the development of a robust ecosystem with a variety of LoRa-enabled devices, sensors, and gateways available from multiple vendors. This ecosystem support ensures interoperability and a diverse range of options for air quality monitoring solutions [44].

The combination of long-range communication and low power consumption makes LoRa an excellent choice for air quality monitoring systems, especially in scenarios where extensive coverage, low maintenance, and cost-effectiveness are critical considerations. These advantages enable the efficient collection and transmission of air quality data, contributing to improved environmental management and sustainable practices.

3.4. Limitations Concerning Data Rate and Latency for Real-Time Applications

While IoT systems for air quality based on LoRa offer several advantages, they do have limitations concerning the data rate and latency, particularly for real-time applications. As shown in Table 1, the comparison between LTE/4G and LoRaWAN highlights critical trade-offs in data rate and latency, which impact real-time air quality monitoring. These limitations arise due to the trade-offs made to achieve low-power, long-range communication. The following paragraphs present key limitations of LoRa communication.

LoRa operates at low data rates [43] to achieve its long-range communication capabilities and low power consumption. This limitation means that the amount of data that can be transmitted in a given time is relatively small compared to high-speed communication technologies, like LTE/4G. For real-time applications that require frequent and large data updates, the low data rates of LoRa may not be sufficient to deliver data in real-time or with low latency. LoRa's low data rates also influence the frequency at which data can be transmitted.

LoRa networks inherently introduce latency due to the low data rates and the use of spread spectrum modulation techniques. Latency refers to the delay between the time data are sent by the sensor and the time they are received and processed at the central monitoring platform. The latency in LoRa-based systems can be noticeable and may not meet the stringent real-time requirements of certain air quality monitoring applications.

For certain air quality monitoring applications, real-time [32] data are critical for timely decision-making and immediate responses to pollution events. LoRa's inherent limitations in data rate and latency may hinder the ability to provide up-to-the-minute information for time-sensitive actions. In burst traffic scenarios [48] where multiple sensors simultaneously send data to the central monitoring platform, LoRa networks might face congestion, leading to increased latency and reduced data throughput.

To optimize battery life and reduce data transmission [43], LoRa-based systems may employ data aggregation techniques. Aggregating data over time intervals can lead to data being sent in batches rather than continuously, affecting real-time data availability. As the number of LoRa devices in a network [46] increases, the available bandwidth must be shared among more devices, potentially impacting the overall data rate and increasing latency in congested areas.

Table 1. Comparison between LTE and Lora systems.

Feature	LTE/4G	LoRaWAN
Technology type	Cellular	Low-power area network (LPWAN)
Throughput	High (up to 100 Mbps)	Low (0.3 kbps to 50 kbps)
Bandwidth	Urban: up to 30 km Rural: up to 100 km	Urban: 2–5 km Rural: 15 km or more
Frequency spectrum	Licensed (700 MHz to 2.6 GHz)	Unlicensed (e.g., 868 MHz in EU, 915,868 MHz in US)
Power consumption	Moderate to high	Low
Latency	Low (30–100 ms)	High (1–10 s)
Connection density	High (thousands of devices per km^2)	Moderate to High (thousands to millions per km^2)
Cost	Moderate to high (subscription based)	Low (subscription based)
Security	Strong (encryption, authentification)	Strong (end-to-end encryption)
Applications	Mobile internet, video streaming, voice calls, etc.	IoT devices, smart agriculture, asset tracking, etc.
Deployment	Extensive global infrastructure	Can be privately deployed
Quality of service (QoS)	High (guaranteed through SLAs)	Variable (depends on network congestion)
Scalability	Highly scalable	Scalable but may require careful planning
Interference resistance	Managed through licensed spectrum between cells	Susceptible to interference in unlicensed bands
Mobility support	Low to moderate	Low to moderate

Mitigating these limitations involves careful consideration of the specific requirements of the air quality monitoring application. For applications that demand real-time data updates, LoRa may be better suited for less critical data transmission or where data frequency can be optimized based on the environmental context. In scenarios where low power consumption and wide coverage are prioritized over real-time requirements, LoRa remains a strong candidate for effective air quality monitoring solutions. Additionally, a hybrid approach that combines LoRa with other communication technologies, like LTE/4G, may be employed to achieve a balance between long-range coverage and real-time data updates when both aspects are essential.

4. Comparative Analysis

4.1. Evaluation of Performance Metrics Between LTE/4G and LoRaWAN

Comparing IoT communication technologies such as LTE/4G and LoRaWAN in terms of evaluation of performance metrics offers insights into their distinct advantages and disadvantages for various IoT applications, including air quality monitoring. Table 1 presents a comparison of these communication technologies for IoT systems based on air quality monitoring applications.

4.2. Comparison of IoT Commercial Devices and Monitoring Systems

The functionality, costs, and market availability of the IoT for air quality systems offered on the market must be examined, given the expansion of the Internet of Things (IoT) sector [56]. Table 2 provides an overview of measurement capabilities, communication options, and power sources for various sensors used in commercial air quality monitoring systems. The following section reviews various sensors, focusing on functionality, communication options, and costs. Table 3 outlines the pricing and data plan costs associated with these sensors, illustrating significant cost variations that affect accessibility for large-scale deployments.

Table 2. Comparison of different sensors in terms of air quality measurements, communication options, and power input options.

Name of Sensor	Air Quality Measurements	Communication Options	Power Input Option
SACAQM AI_r sensor node	PM1.0, PM2.5, PM10, temperature, geolocation, relative humidity	4G	Power bank
AirBeam3	PM1, PM2.5, PM10, temperature, relative humidity	BLE, WiFi, cellular 4G	3350 mAh 3.7 V rechargeable lithium battery
AQMesh monitoring system	PM1, PM2.5, PM10, TPC, TSP (up to 30 microns), NO, NO_2, O_3, CO, SO_2, H_2S, TVOC, CO_2, relative humidity, pod temperature, atmospheric pressure, wind speed, direction	Cellular 3G/4G, NB-IoT	Solar/battery (variable)
PM Monitor—iMonPM	TSP, PM1.0, PM2.5, PM10, temperature, relative humidity	WiFi, cellular 3G/4G, LoRa, Zigbee, LTE-M	IP67 power supply (5VDC and 12VDC) 2 A max
Ecomesure—Ecomsmart	PM1, PM2.5, PM4, PM10, TSP, O_3, NO, NO_2, SO_2, H_2S, NH_3, HCl, Cl_2, CH_2O, air temperature, air pressure, relative humidity	WiFi, cellular 3G/4G, LoRa, Zigbee, LTE-M	100–260 VAC (standard), 12 VDC regulated
Aeroqual Dust Sentry pro	PM1.0, PM2.5, PM10, TSP	WiFi, Ethernet (LAN), optional cellular IP 3G HSPA/4G LTE modem	100–260 VAC (standard), 12 VDC regulated
Oizom Dustroid Monitor	PM1, PM2.5, PM10, PM100, temperature, humidity	LTE 3G/4G, GSM, GPRS, WiFi, LoRa, NBIoT, Ethernet, Modbus	External 110–230 V AC 50–60 Hz, 40 Watt monocrystal solar panel

Table 3. Comparison of different sensors in terms of prices in USD.

Name of Sensor	Price per Unit (USD)	SIM Card Cost	Data Plan (MB)
SACAQM AI_r sensor node	100	Local SIM required from manufacturing location	0.61
AirBeam3	249	25	25
Ecomesure—Ecomsmart	7800	SIM cost not specified	Data cost not specified
AQMesh monitoring system	6579.53	SIM card + 3G data plan	256.3
PM Monitor—iMonPM	1995	Local SIM required from manufacturing location	Data cost not specified
Aeroqual Dust Sentry pro	4543.87	Local SIM required from manufacturing location	Data cost not specified
Oizom Dustroid Monitor	17,509.12	35.00	281.91

4.2.1. AirBeam3

This air monitoring device, called AirBeam3, was developed by HabitatMap, a company in the United States, and it includes an optical sensor (Plantower PMS7003). AirBeam3 is low-cost (USD249) and measures the temperature, relative humidity (RH), and PM concentrations (PM1, PM2.5, and PM10) [57]. The collected data are transmitted over Bluetooth, WiFi, and cellular 4G, among other data transmission methods. By using the AirCasting app and web platform or serial data logging using a USB-C connector, the data are logged and retrieved.

They frequently need to be combined with additional parts, such as GPS modules or microcontrollers, and an Internet of Things (IoT) platform needs to be set up for data visualization [57]. A monitoring station's design, component assembly, and tool development are three separate phases that can take some time. An online platform [58] is already available through HabitatMap for viewing and downloading AirBeam3 data.

4.2.2. Aeroqual Dust Sentry Pro

Aeroqual Dust Sentry pro has the ability to measure a variety of parameters, such as particulate matter, gaseous contaminants, and environmental variables [59]. This system can simultaneously measure PM1, PM2.5, and PM10 along with particle counts and filter sampling and a temperature range that allows for below-freezing operation (−10 to 50 °C); the Aeroqual Dust Sentry pro is viewed as the greatest instrumentation option available for the cost due to its ability [59]. Aeroqual Dust Sentry pro comes at a relatively high price making it quite expensive for most of the lower- (or unemployed) and mid-class working populous to acquire. This is also a disadvantage to an extent because most of the regions with people who require more information on the air quality are usually in the lower- to mid-earning work. We present a more affordable option of air quality monitoring that is about 194 times lower than the price of the Aeroqual Dust Sentry proair quality system. This means it would also be easier for deployment in certain low-income regions.

4.2.3. AQMesh Air Quality Monitoring System

The AQMesh AQM is a multi-sensor system for air quality that can measure a variety of gases using electrochemical (EC) gas sensors, varying size fractions of particles with an optical particle counter, temperature, and humidity [60]. A typical small sensor air quality monitoring system called AQMesh keeps track of up to six different gases, such as noise levels, wind speed and direction, and particulate matter ((PM with diameter 1 m), PM2.5, and PM10 size) [61]. Though AQMesh also offers cloud-based data representations of air quality characteristics, it falls short of the product we propose since AQMesh does not offer an AI-based modeling system that produces statistically accurate forecasts and predictions. The integration of AI (PM2.5 GNN) for modeling air quality characteristics in our product allows for the reading and viewing of a diverse range of information other than just presenting readings alone. The AI GNN modeling aspect of our product allows for including predictions and projections of the air quality readings, which is something AQMesh does not currently offer.

One of its limiting features is that it requires its electrochemical sensors to be replaced every two years. This can actually be an inconvenience due to the cost of getting replacements as well as the need for technical assistance to complete the process. SACAQM, on the other hand, does not require this kind of maintenance, which will spare a consumer the inconvenience and costs of recurring replacements or maintenance.

4.2.4. Ecomesure—Ecomsmart

Ecomsmart—It is a device that can measure a wide range of parameters, including meteorological variables, air temperature, air pressure, and relative humidity, as well as concentrations of air pollutants, including PM1, PM2.5, PM4, PM10, TSP, O_3, NO, NO_2, SO_2, H_2S, NH_3, HCl, Cl_2, and CH_2O. Ecomsmart can gather real-time data, wirelessly transmit it to a sophisticated dedicated web platform, manage it, study it, upload it to smart platforms, and import it into the software. Ecomsmart is able to provide comprehensive data or information about air quality in the form of warning alerts for high pollutant detections; however, it does not incorporate AI to forecast or predict air quality. Ecomsmart would only give a user access to present-moment air quality information as opposed to forecasting long-term air quality characteristics.

4.2.5. PM Monitor—iMonPM

The iMonPM sensor is an air quality monitoring device made by PM Monitor, a division of GRIMM Aerosol Canada [62]. It provides real-time measurements of mass concentrations of PM1.0, PM2.5, and PM10, along with environmental variables like temperature and relative humidity, as well as internal temperature and relative humidity measurements [62]. The PM Monitor dashboard allows you access to and the visualization of data. Data logging and retrieval: WiFi or cellular (cellular was utilized for the evaluation). The data are uploaded to the cloud and accessed using the dashboard of PM Monitor [63].

4.2.6. Oizom Dustroid Smart Air Particulate Monitor—Dustroid®

The Oizom Dustroid Smart Air Particulate Monitor, also known as the Dustroid®, is a continuous air quality monitoring device [64]. It provides precise measurements that may be used for a variety of tasks, including streamlining the pollution process and spotting false alarms [65]. The most important ambient air quality metrics, including PM1, PM2.5, PM10, PM100, carbon monoxide, carbon dioxide, sulfur dioxide, nitrogen dioxide, ozone, hydrogen sulfide, noise, light, UV, temperature, and humidity, may all be measured by the Dustroid® [66]. Numerous networking methods, including GSM, GPRS (cellular 3G), WiFi, LoRa, NBIoT, Ethernet, and Modbus, are supported by the Dustroid® [66].

As mentioned, the Dustroid® offers different sensors designed to monitor specific types of gases. Each of these sensors detects specific gases, meaning that a consumer or customer would need to be very selective or specific when it comes to the device they would like. This also implies that a customer would need to spend more in order to acquire air quality information since they would have to actually buy more than one device. Our low-cost IoT sensor suite, on the other hand, is a device that would give a user access to data about all the mentioned gases and air quality characteristics. This one device is all you require for a target place of application.

Although Oizom offers several quality AQ services, it is relatively high priced for the average person or buyer. Oizom charges 4799.17 USD per devicem making it at least 48 times the cost of our low-cost IoT sensor system. We offer a more cost-effective device that performs the full function of an air quality sensor system (and more through our integration of advanced AI for predictions and projections) at a low cost of under ZAR1781.51 (100 USD).

4.2.7. AIRQO Air Quality Monitoring System

The AirQo monitor is a specially made air quality monitoring system made to adapt to design space needs: Air quality sensing that is low-cost and high-resolution; portability and flexible deployment options; flexible power and communication options; and resilience to regional environmental conditions are the four main design requirements [67]. With an effective range of 0–500 g/m^3, AirQo instruments monitor particulate matter PM2.5 and PM10 in the air. Along with longitude, latitude, interior and external air temperatures, relative humidity, and atmospheric pressure, the monitoring system also measures other parameters required for modeling and analysis. The AirQo device is made to accommodate a variety of power sources, including motorbike alternators, solar energy, mains electricity, and has the ability to switch between them. The AirQo monitoring system sensors assess PM2.5 and PM10 particle size and concentration in g/m^3 using a laser scattering technology [67].

5. Comparison of Low-Cost IoT-Based Air Quality Monitoring Systems

The development of inexpensive air quality monitoring systems has accelerated because of these devices' accessibility, affordability, and potential for broad application in a variety of settings. These Internet of Things (IoT)-based devices allow for real-time data analysis, monitoring, and decision-making to improve air quality, especially in locations with limited resources or high risk. This section contrasts two different uses for inexpensive Internet of Things air quality monitoring systems: one was created for monitoring indoor air quality in buildings housing pigs, while the other was created for a cloud-based platform that made use of inexpensive sensors.

5.1. Development and Validation of Low-Cost Indoor Air Quality Monitoring System for Swine Buildings

Since they house a lot of livestock, swine buildings pose a serious threat to interior air quality because of the buildup of gases, including ammonia (NH_3) and carbon dioxide (CO_2), and dust particles. It is essential to maintain air quality to protect worker health and animal welfare. To solve these problems, a low-cost interior air quality monitoring system was created especially for swine buildings.

Important metrics including NH_3, CO_2, temperature, and humidity are intended to be measured by this device. The system was tested for accuracy and dependability using inexpensive sensors in agricultural settings, where animal movement, manure management, and ventilation systems can cause abrupt changes in air quality. Farm operators can monitor air quality and promptly alter ventilation or other environmental controls thanks to the system's continuous data collection and transmission to a local control panel or mobile device.

This system's affordability is one of its key benefits; conventional air quality monitoring systems for these kinds of establishments are costly and need specific equipment. This method lowers installation and maintenance costs dramatically by utilizing inexpensive sensors and Internet of Things technologies. However, the accuracy of inexpensive sensors may differ from that of more expensive options, necessitating annual calibration to guarantee long-term dependability.

In terms of development, the system consists of a data collection unit that transmits the obtained data to a local or cloud-based storage system via wireless communication technologies (e.g., WiFi, Zigbee, or LoRa). This enables farmers to keep an eye on data in real time, set up alarms for gas concentrations that could be unsafe, and take preventative action to lower emissions by modifying operations or improving ventilation. Validation attempts demonstrated that the inexpensive system outperformed more costly reference devices, indicating that it is a workable alternative for continuous indoor air quality monitoring in swine barns.

5.2. Developing a Cloud-Based Air Quality Monitoring Platform Using Low-Cost Sensors

Systems for monitoring air quality that are cloud-based provide a scalable way to collect, store, and evaluate data from several sources at once. This strategy is especially helpful in metropolitan settings, where it is important to monitor air quality at a network of places in order to evaluate pollution patterns and public health hazards and make data-driven decisions.

In this instance, low-cost sensors were used to assess the temperature, humidity, CO_2 levels, and particulate matter (PM2.5 and PM10) as part of the development of a cloud-based air quality monitoring platform. The system combines Internet of Things (IoT) with sensor integration to provide real-time data to a cloud server for processing and visualization on a user-accessible web dashboard. Users can browse historical data and real-time air quality indicators and receive notifications when air pollution levels surpass predefined criteria thanks to the data's continual updating.

Scalability is one of this platform's main advantages; it can be set up in multiple locations to build an extensive network for monitoring air quality. Governments, nonprofits, and companies looking to offer an affordable yet reliable option for extensive environmental monitoring will find it suitable. The cloud platform also makes it possible to integrate machine learning algorithms, perform advanced analytics, and access data remotely in order to forecast pollution patterns and pinpoint probable causes of deteriorating air quality.

Like the swine construction system, sensor precision is still a challenge despite its advantages. To guarantee consistent operation, low-cost sensors—especially those for particulate matter—may need to be calibrated and maintained on a regular basis. It is also necessary to take into consideration how environmental elements like temperature and humidity affect sensor data. The cloud-based system can handle this by updating often and using error-correcting algorithms.

Additional benefits of using cloud computing include improved data storage, processing capability, and real-time data sharing with many stakeholders, such as the general public, urban planners, and environmental organizations. This increases the system's flexibility and adaptability to a wider range of air quality monitoring requirements, such as tracking urban pollution and evaluating the indoor air quality of public spaces, like workplaces.

5.3. Comparison of Indoor Monitoring and Cloud-Based Monitoring Platform Systems

While they serve different contexts and purposes, both low-cost IoT-based air quality monitoring systems seek to provide affordable, real-time data on air quality. The cloud-based platform is intended for more extensive environmental monitoring across numerous locations, while the system for swine barns concentrates on monitoring indoor air quality to guarantee the health of animals and workers. Table 4 presents a comparison of the features of these two monitoring systems.

Table 4. Comparison of indoor monitoring and cloud-based monitoring platform systems.

Feature	Indoor Monitoring (Swine Buildings)	Cloud-Based Monitoring Platform
Main Purpose	Ensure air quality in livestock facilities	Monitor urban and environmental air quality
Key Sensors	NH_3, CO_2, temperature, humidity	PM2.5, PM10, CO_2, temperature, humidity
Communication Method	WiFi, RS485, Zigbee	WiFi, LoRa, cellular, Cloud Integration
Data Storage	Local storage or cloud	Cloud-based data storage and analytics
Scalability	Limited to one facility or location	Scalable across multiple locations
Accuracy and Maintenance	Periodic calibration required for long-term use	Regular calibration and error-correcting algorithms
Cost	Low-cost sensors, affordable installation and maintenance	Low-cost sensors but requires investment in cloud services
Alerts and Notifications	Local real-time monitoring and alerts	Cloud-based notifications via SMS, email, or dashboards
User Interface	Local displays, mobile devices	Web-based dashboard, remote access

6. Conclusions and Future Directions

The respiratory and cardiovascular health of individuals and their overall well-being can be significantly impacted by many outdoor air pollutants, including PM, sulfur dioxide, nitrogen oxides, ozone, carbon monoxide, volatile organic compounds, and poly-cyclic aromatic hydrocarbons. These contaminants have a significant role in the development and severity of several disorders. A substantial amount of scholarly research suggests a clear and direct correlation between some air pollutants and both acute communicable diseases (including viral infections) and chronic non-communicable disorders in humans, resulting in detrimental effects on the respiratory system. This paper provides a comprehensive assessment on the integration of LTE/4G technology with LoRaWAN in the context of the IoT. The main factors of comparison in this evaluation are the specifications pertaining to power consumption, data transfer, and coverage.

In summary, LTE/4G is advantageous when real-time data transmission, high data throughput, and seamless connectivity are critical. It is well suited for applications involving mobile IoT devices, rapid data updates, and data-intensive tasks. LoRaWAN is more suitable when long-range communication, extended battery life, and cost-effective deployment are essential. It excels in applications where data transmission can occur at lower frequencies and where devices need to operate on battery power for long periods.

For air quality monitoring, where low-power, wide-area coverage, and long-term deployment are often prioritized, LoRaWAN is a compelling choice. However, a hybrid approach, combining the strengths of both technologies, can also be employed to create a more versatile and efficient IoT solution based on the specific requirements of the monitoring project.

The integration of machine learning into the modeling process enables artificial intelligence (AI) to effectively extract information from extensive and complex datasets. The effectiveness of prediction capabilities is essential in the development of early detection systems. To predict the occurrence of catastrophes or outbreaks, anomalies are identified within integrated datasets. Limited research has been conducted on the integration of artificial intelligence (AI) into the Internet of Things (IoT) using LTE/4G and LoraWan technologies.

The focus of future research will be directed toward the development of cost-effective sensors for IoT devices, as well as the integration of AI technologies. Reliable predictive models for geo-spatial pollution dispersion can be developed by the utilization of AI techniques, using extensive datasets obtained from cost-effective sensors. The implementation of evidence-based policies is vital to mitigate the adverse impacts of pollution on populations at risk.

Author Contributions: All authors contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by Canada's International Development Research Centre (IDRC) (Grant No. 109981-001). JDK acknowledges support from the NSERC Discovery Grant (Grant No. RGPIN-2022-04559), NSERC Discovery Launch Supplement (Grant No: DGECR-2022-00454), and New Frontier in Research Fund-Exploratory (Grant No. NFRFE-2021-00879). We would like to also express our gratitude to Sibanye-Stillwater for their generous funding support provided through DigiMine towards this research.

Acknowledgments: We would like to extend our gratitude to University of the Witwatersrand, National Research Foundation, iThemba LABS, University of Toronto, University of Johannesburg, and all affiliated schools for their support and collaboration throughout this research.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. World Health Organization. Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease. 2016. Available online: https://apps.who.int/iris/bitstream/handle/10665/250141/?sequence=1 (accessed on 28 October 2024).
2. Dominski, F.H.; Branco, J.H.L.; Buonanno, G.; Stabile, L.; da Silva, M.G.; Andrade, A. Effects of air pollution on health: A mapping review of systematic reviews and meta-analyses. *Environ. Res.* **2021**, *2021*, 111487. [CrossRef] [PubMed]
3. Pavanaditya, B.; Arun, K.; Jayapriya, J. Meta analysis of health effects of ambient air pollution exposure in low-and middle-income countries. *Environ. Res.* **2023**, *216*, 114604.
4. Hernandez, W.; Mendez, A.; González-Posadas, V.; Jiménez-Martín, J.L.; Camejo, I.M. Robust Inferential Techniques Applied to the Analysis of the Tropospheric Ozone Concentration in an Urban Area. *Sensors* **2021**, *21*, 277. [CrossRef] [PubMed]
5. Xing, Y.-F.; Xu, Y.-H.; Shi, M.-H.; Lian, Y.-X. The impact of PM2.5 on the human respiratory system. *J. Thorac. Dis.* **2016**, *8*, E69. Available online: https://jtd.amegroups.org/article/view/6353/6196 (accessed on 28 October 2024). [PubMed]
6. Francesco, C.; Mineraud, J.; Lagerspetz, E.; Varjonen, S.; Liu, X.; Puolamäki, K.; Nurmi, P.; Tarkoma, S. Low-Cost Outdoor Air Quality Monitoring and Sensor Calibration: A Survey and Critical Analysis. *arXiv* **2021**. [CrossRef]
7. Malleswari, S.M.S.D.; Mohana, T.K. Air pollution monitoring system using IoT devices. *Mater. Today Proc.* **2022**, *51*, 1147–1150. [CrossRef]
8. The International Business Machines Corporation (IBM). What Is the Internet of Things? Available online: https://www.ibm.com/topics/internet-of-things (accessed on 22 August 2023).

9. Virendra, B.; Viral, K. Air Quality Monitoring Systems using IoT: A Review. In Proceedings of the 2020 International Conference on Computational Performance Evaluation (ComPE), Shillong, Meghalaya, India, 2–4 July 2020; North-Eastern Hill University: Shillong, Meghalaya, India, 2020. [CrossRef]
10. Mahmoud, P.; Christopher, S.; Thomas, K. A Novel Three-Layer IoT Architecture for Shared, Private, Scalable, and Real-time Machine Learning from Ubiquitous Cyber-Physical Systems. *Procedia Manuf.* **2020**, *48*, 959–967. [CrossRef]
11. Mohammed, R.A.; Djamel, T.; Imed, R. Architecting the Internet of Things: State of the Art. In *Robots and Sensor Clouds, Special Edition in the "Studies in Systems, Decision and Control"*; Springer International Publishing: Berlin/Heidelberg, Germany, 2015; pp. 55–75. [CrossRef]
12. Kim, H.; Tae, S.; Zheng, P.; Kang, G.; Lee, H. Development of IoT-Based Particulate Matter Monitoring System for Construction Sites. *Int. J. Environ. Res. Public Health* **2021**, *18*, 11510. [CrossRef]
13. Motlagh, N.H.; Lagerspetz, E.; Nurmi, P.; Li, X.; Varjonen, S.; Mineraud, J.; Siekkinen, M.; Rebeiro-Hargrave, A.; Hussein, T.; Petaja, T.; et al. Toward Massive Scale Air Quality Monitoring. *IEEE Commun. Mag.* **2020**, *58*, 54–59. [CrossRef]
14. Kennedy, O.; Etinosa Noma-Osaghae, O.M.; Samuel, J.; Oluga, O. A Smart Air Pollution Monitoring System. *Int. J. Civ. Eng. Technol.* **2018**, *9*, 799–809. Available online: http://www.iaeme.com/IJCIET/index.asp (accessed on 28 October 2024).
15. Mohsen, A. The impact of 5G on the evolution of intelligent automation and industry digitization. *J. Ambient Intell. Humaniz. Comput.* **2021**, *14*, 5977–5993. [CrossRef]
16. Karina, G.; Leonardo, G.; Tinku, R.; Laurent, R. Enabling disaster-resilient 4G mobile communication networks. *IEEE Commun. Mag.* **2014**, *52*, 12. [CrossRef]
17. Wan, J.; Al-awlaqi, M.A.A.H.; Li, M.; O'Grady, M.; Gu, X.; Wang, J.; Cao, N. Wearable IoT enabled real-time health monitoring system. *EURASIP J. Wirel. Commun. Netw.* **2018**, *2018*, 298. [CrossRef]
18. Han, Q.; Nesi, P.; Pantaleo, G.; Paoli, I. Smart City Dashboards: Design, Development, and Evaluation. In Proceedings of the 2020 IEEE International Conference on Human-Machine Systems (ICHMS), Rome, Italy, 7–9 September 2020; p. 20007451. [CrossRef]
19. Marjani, M.; Nasaruddin, F.; Gani, A.; Karim, A.; Hashem, I.A.T.; Siddiqa, A.;Yaqoob, I. Big IoT Data Analytics: Architecture, Opportunities, and Open Research Challenges. *IEEE Access* **2017**, *5*, 2169–3536. [CrossRef]
20. Shao, C.; Yang, Y.; Juneja, S.; Seetharam, T.G. IoT data visualization for business intelligence in corporate finance. *Inf. Process. Manag.* **2022**, *59*, 102736. [CrossRef]
21. Hu, S.; Wang, P.; He, H.; Zhang, Y.; Li, X. Gas Sensor Physically Unclonable Function-Based Lightweight Bidirectional Authentication Protocol for Gas Sensor Networks. *Electronics* **2024**, *13*, 3385. [CrossRef]
22. Silva, C.; Cunha, V.A.; Barraca, J.P.; Aguiar, R.L. Analysis of the Cryptographic Algorithms in IoT Communications. *Inf. Syst. Front.* **2023**, *26*, 1243–1260. [CrossRef]
23. Device Authority Company. Understanding IoT Security Challenges. 2023. Available online: https://deviceauthority.com/security-issues-of-iot-securing-your-iot-device-in-2023/ (accessed on 26 September 2023).
24. Sharma, V.P.; Dugyala, R.; Padmavathi, V.; Gurram, V.R. Gas leakage detection system using iot and cloud technology: A review. *EDP Sci.* **2023**, *391*, 01063. [CrossRef]
25. Bellavista, P.; Giannelli, C.; Lanzone, S.; Riberto, G.; Stefanelli, C.; Tortonesi, M. A Middleware Solution for Wireless IoT Applications in Sparse Smart Cities. *Sensors* **2017**, *17*, 2525. [CrossRef]
26. Albaladejo, M.B.; Leith, D.J.; Manzoni, P. Measurement-based modelling of LTE performance in Dublin city. In Proceedings of the 2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), Valencia, Spain, 4–8 September 2016; pp. 1–6. [CrossRef]
27. Oteafy, S.M.A.; Hassanein, H.S. IoT in the Fog: A Roadmap for Data-Centric IoT Development. *IEEE Commun. Mag.* **2018**, *56*, 157–163. [CrossRef]
28. Malekzadeh, M. Enabling efficient and reliable IoT deployment in 5G and LTE cellular areas for optimized service provisioning. *J. Supercomput.* **2023**, *79*, 1926–1955. Available online: https://link.springer.com/article/10.1007/s11227-022-04722-x#citeas (accessed on 19 August 2024). [CrossRef]
29. Mishra, K.N.; Chakraborty, C. A Novel Approach Toward Enhancing the Quality of Life in Smart Cities Using Clouds and IoT-Based Technologies. *Internet Things* **2019**, *5863*, 19–35. Available online: https://link.springer.com/chapter/10.1007/978-3-030-18732-3_2 (accessed on 28 October 2024).
30. Campioni, L.; Fontana, N.; Morelli, A.; Suri, N.; Tortonesi, M. A Federated Platform to Support IoT Discovery in Smart Cities and HADR Scenarios. In Proceedings of the 2020 15th Conference on Computer Science and Information Systems (FedCSIS), Sofia, Bulgaria, 6–9 September 2020; pp. 511–519. [CrossRef]
31. Cheimaras, V.; Trigkas, A.; Papageorgas, P.; Piromalis, D.; Sofianopoulos, E. A Low-Cost Open-Source Architecture for a Digital Signage Emergency Evacuation System for Cruise Ships, Based on IoT and LTE/4G Technologies. *Future Internet* **2022**, *14*, 366. [CrossRef]
32. Chen, S.; Hu, J.; Shi, Y.; Zhao, L. LTE-V: A TD-LTE-based V2X solution for future vehicular network. *IEEE Internet Things J.* **2016**, *3*, 997–1005. [CrossRef]
33. Alasali, M.; Beckman, C.; Karlsson, M. Providing internet to trains using MIMO in LTE networks. In Proceedings of the 2014 International Conference on Connected Vehicles and Expo (ICCVE), Vienna, Austria, 3–7 November 2014; pp. 810–814. [CrossRef]

34. Mohbey, K.K. An efficient framework for smart city using big data technologies and internet of things. In *Progress in Advanced Computing and Intelligent Engineering: Proceedings of ICACIE 2017*; Springer: Singapore, 2019; Volume 2, pp. 319–328. Available online: https://link.springer.com/chapter/10.1007/978-981-13-0224-4_29 (accessed on 1 July 2023).
35. Ekelund, B. The technical challenges of the future generations of telecommunication technologies (LTE/4G). In Proceedings of the 2010 International Symposium on VLSI Technology, System and Application, Hsinchu, Taiwan, 26–28 April 2010; pp. 6–8. [CrossRef]
36. Chettri, L.; Bera, R. A comprehensive survey on Internet of Things (IoT) toward 5G wireless systems. *IEEE Internet Things J.* **2019**, *7*, 16–32. [CrossRef]
37. Callebaut, G.; Leenders, G.; Van Mulders, J.; Ottoy, G.; De Strycker, L.; Van der Perre, L. The art of designing remote iot devices—technologies and strategies for a long battery life. *Sensors* **2021**, *21*, 913. [CrossRef]
38. Wahyudin, A.; Amalia, N.; Lindra, I. Cost benefit analysis of MVNO business models for LTE 4G services in Bandung city. In Proceedings of the 2017 4th International Conference on New Media Studies (CONMEDIA), Yogyakarta, Indonesia, 8–10 November 2017; pp. 102–107. [CrossRef]
39. Lavric, A.; Popa, V. A LoRaWAN: Long range wide area networks study. In Proceedings of the 2017 International Conference on Electromechanical and Power Systems (SIELMEN), Iasi, Romania, 11–13 October 2017; pp. 417–420. [CrossRef]
40. Jabbar, W.A. Subramaniam, T.; Ong, A.E.; Shu'Ib, M.I.; Wu, W.; de Oliveira, M.A. LoRaWAN-based IoT system implementation for long-range outdoor air quality monitoring. *Internet Things* **2022**, *19*, 100540. [CrossRef]
41. San Cheong, P.; Bergs, J.; Hawinkel, C.; Famaey, J. Comparison of LoRaWAN classes and their power consumption. In Proceedings of the 2017 IEEE Symposium on Communications and Vehicular Technology (SCVT), Leuven, Belgium, 14 November 2017; pp. 1–6. [CrossRef]
42. Adelantado, F.; Vilajosana, X.; Tuset-Peiro, P.; Martinez, B.; Melia-Segui, J.; Watteyne, T. Understanding the limits of LoRaWAN. *Netw. Internet Archit.* **2017**, *55*, 34–40. [CrossRef]
43. Kufakunesu, R.; Hancke, G.P.; Abu-Mahfouz, A.M. A survey on adaptive data rate optimization in lorawan: Recent solutions and major challenges. *Sensors* **2020**, *20*, 5044. [CrossRef]
44. Jouhari, M.; Saeed, N.; Alouini, M.S.; Amhoud, E.M. A survey on scalable LoRaWAN for massive IoT: Recent advances, potentials, and challenges. *IEEE Commun. Surv. Tutor.* **2023**, *25*, 1841–1876. [CrossRef]
45. Mekki, K.; Bajic, E.; Chaxel, F.; Meyer, F. Overview of cellular LPWAN technologies for IoT deployment: Sigfox, LoRaWAN, and NB-IoT. In Proceedings of the 2018 IEEE International Conference on Pervasive Computing and Communications Workshops (Percom Workshops), Athens, Greece, 19–23 March 2018; pp. 197–202. [CrossRef]
46. Parri, L.; Parrino, S.; Peruzzi, G.; Pozzebon, A. A LoRaWAN network infrastructure for the remote monitoring of offshore sea farms. In Proceedings of the 2020 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Dubrovnik, Croatia, 25–28 May 2020; pp. 1–6. https://dl.acm.org/doi/abs/10.1109/I2MTC43012.2020.9128370
47. Bhavatharangini, S.; Ramakrishnan, S. Reducing the internet traffic in IoT-based monitoring and control system through a combination of WSN and LoRaWAN networks. *Int. J. Ad Hoc Ubiquitous Comput.* **2022**, *39*, 211–222. [CrossRef]
48. Dumitru, M.C.; Pietraru, R.N.; Moisescu, M.A. LoRaWAN as Open Scalable IoT Ecosystem. In Proceedings of the 2023 13th International Symposium on Advanced Topics in Electrical Engineering (ATEE), Bucharest, Romania, 23–25 March 2023; pp. 1–6. [CrossRef]
49. Tzortzakis, K.; Papafotis, K.; Sotiriadis, P.P. Wireless self powered environmental monitoring system for smart cities based on LoRa. In Proceedings of the 2017 Panhellenic Conference on Electronics and Telecommunications (PACET), Xanthi, Greece, 17–18 November 2017; pp. 1–4. [CrossRef]
50. Shahjalal, M.; Hasan, M.K.; Islam, M.M.; Alam, M.M.; Ahmed, M.F.; Jang, Y.M. An overview of AI-enabled remote smart-home monitoring system using LoRa. In Proceedings of the 2020 International Conference on Artificial Intelligence in Information and Communication (ICAIIC), Fukuoka, Japan, 19–21 February 2020; pp. 510–513. [CrossRef]
51. Chou, Y.S.; Mo, Y.C.; Su, J.P.; Chang, W.J.; Chen, L.B.; Tang, J.J.; Yu, C.T. i-Car system: A LoRa-based low power wide area networks vehicle diagnostic system for driving safety. In Proceedings of the 2017 International Conference on Applied System Innovation (ICASI), Sapporo, Japan, 13–17 May 2017; pp. 789–791. [CrossRef]
52. Queralta, J.P.; Gia, T.N.; Tenhunen, H.; Westerlund, T. Edge-AI in LoRa-based health monitoring: Fall detection system with fog computing and LSTM recurrent neural networks. In Proceedings of the 2019 42nd International Conference on Telecommunications and Signal Processing (TSP), Budapest, Hungary, 1–3 July 2019; pp. 601–604. [CrossRef]
53. Tayeh, G.B.; Azar, J.; Makhoul, A.; Guyeux, C.; Demerjian, J. A wearable lora-based emergency system for remote safety monitoring. In Proceedings of the 2020 International Wireless Communications and Mobile Computing (IWCMC), Limassol, Cyprus, 15–19 June 2020; pp. 120–125. [CrossRef]
54. Ahsan, M.; Based, M.A.; Haider, J.; Rodrigues, E.M. Smart monitoring and controlling of appliances using LoRa based IoT system. *Designs* **2021**, *5*, 17. [CrossRef]
55. Sherazi, H.H.R.; Grieco, L.A.; Imran, M.A.; Boggia, G. Energy-Efficient LoRaWAN for Industry 4.0 Applications. *IEEE Trans. Ind. Inform.* **2020**, *17*, 891–902. [CrossRef]
56. Yang, Y.; Wang, H.; Jiang, R.; Guo, X.; Cheng, J.; Chen, Y. A review of IoT-enabled mobile healthcare: Technologies, challenges, and future trends. *IEEE Internet Things J.* **2022**, *9*, 9478–9502. [CrossRef]

57. Aix, M.L.; Claitte, M.; Bicout, D. A Low-Cost Sensors Study Measuring Exposure to Particulate Matter in Mobility Situations. In Proceedings of the 12th International Conference on Sensor Networks SENSORNETS, Lisbon, Portugal, 23–24 February 2023; SCITEPRESS-Science and Technology Publications: Setúbal, Portugal, 2023. [CrossRef]
58. HabitatMap. AirCasting Is an Open-Source Environmental Data Visualization Platform That Consists of a Smartphone App and Online Mapping System. 2023. Available online: https://www.habitatmap.org/aircasting (accessed on 1 July 2023).
59. District, T.C.; Jackson, W.Y.; Wright, P. Brake Emissions at the Base of Teton Pass, Wyoming. *White Paper* 2019. Available online: http://inversionlabs.com/pdfs/TCD_Brake_Emissions_White_Paper.pdf (accessed on 1 July 2023).
60. Castell, N.; Dauge, F.R.; Schneider, P.; Vogt, M.; Lerner, U.; Fishbain, B.; Broday, D.; Bartonova, A. Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? *Environ. Int.* **2017**, *99*, 293–302. [CrossRef] [PubMed]
61. Environmental Instruments Ltd. AQMesh Air Quality Monitoring System. 2023. Available online: https://www.aqmesh.com/products/aqmesh/ (accessed on 1 July 2023).
62. PM Monitor, Division of GAC. Near Fem Outdoor Particulate Monitor. 2023. Available online: http://imonpm.com/ (accessed on 1 July 2023).
63. South Coast Air Quality Management District. PM Monitor— iMonPM. *Sensor Details*. 2023. Available online: https://www.aqmd.gov/aq-spec/sensordetail/pm-monitor---imonpm (accessed on 1 July 2023).
64. Oizom, Ambient Air Quality Monitoring System. Polludrone. Available online: https://oizom.com/product/polludrone-air-pollution-monitoring/ (accessed on 28 March 2020).
65. Gulia, S.; Prasad, P.; Goyal, S.K.; Kumar, R. Sensor-based Wireless Air Quality Monitoring Network (SWAQMN)-A smart tool for urban air quality management. *Atmos. Polluti. Res.* **2020**, *11*, 1588–1597. [CrossRef]
66. Pica, A.Ș. Building a Low-Cost Electric Device for Ambiental Monitoring. *Sci. Bull. Electr. Eng. Fac.* **2022** *22*, 70–74. [CrossRef]
67. Bainomugisha, E.; Ssematimba, J.; Okure, D. Design Considerations for a Distributed Low-Cost Air Quality Sensing System for Urban Environments in Low-Resource Settings. *Atmosphere* **2023**, *14*, 354. [CrossRef]