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An Affordable Green IoT-Based System for Remote Sensing of PM1, PM2.5 and PM10 Particulate Matter

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ABSTRACT

Particulate matter (PM) possesses the capacity to intrude deeply into the respiratory system, even infiltrating the bloodstream. Prolonged exposure to heightened PM concentrations has been causally associated with a spectrum of respiratory ailments, encompassing asthma, bronchitis, and chronic obstructive pulmonary disease (COPD). This paper endeavours to introduce a remote sensing system tailored for the quantification of particulate matter, underpinned by the principles of the Green Internet of Things (GioT). This framework is rooted in the pursuit of an ecologically harmonious infrastructure and energy sustainability. The devised architecture integrates PM 1, PM 2.5, and PM 10 sensors, seamlessly interfaced with Arduino microcontrollers, thereby facilitating real-time data acquisition. To sustainably energize this system, solar cells are harnessed to furnish a reliable power source. Augmenting this configuration is a data communication infrastructure established upon LoRa (Long Range) technology, a hallmark of the Green Internet of Things. Concomitantly, empirical investigations have been conducted to illuminate system performance. These inquiries were conducted in conditions mirroring low particle deposition scenarios, culminating in an observed average error spectrum spanning 5.64% to 6.95%. Further examinations scrutinized the data transmission process through LoRa, unveiling an impressive maximal transmission range of 281 m while conserving data transmission viability. Additionally, an exploration of energy utilization encompassed both empty and comprehensive data transmissions, divulging a marginal disparity of 0.1 Watt per data transmission event. In the final analysis, the conducted assessments affirm the system's fidelity, disclosing an error quotient below the 10% threshold. Most notably, the discerned operational efficiency of the energy supply substantiates its synergy with sustainable energy paradigms. In summation, this study proffers an innovative remote sensing system, harmonizing the nuanced demands of PM quantification with the virtuous principles of the Green Internet of Things. By merging the acumen of PM sensors, solar-driven power provisions, and the efficiency

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of LoRa communication, the proposed framework establishes a salient benchmark for integrative sensor networks with ecological resonance.

1. Introduction

In recent years, the escalating levels of particulate matter (PM) in the atmosphere have emerged as a critical environmental concern with far-reaching implications for public health and ecological balance [1,2]. These fine particles, categorized based on their aerodynamic diameter into PM1, PM2.5, and PM10, originate from diverse anthropogenic and natural sources such as vehicular emissions, industrial activities, construction, and even natural phenomena like dust storms and wildfires [3,4]. Their diminutive size allows them to remain suspended in the air for prolonged periods, facilitating their dispersion across vast distances and enabling them to penetrate deeply into the respiratory systems of humans and animals alike [5]. The adverse health effects associated with exposure to PM have been extensively documented, ranging from aggravated respiratory diseases to cardiovascular disorders, and even premature mortality [6,7]. Consequently, there is a growing urgency to monitor and manage PM levels, necessitating the development of advanced sensor systems that provide accurate, real-time data for informed decision-making [8-10].

Simultaneously, the paradigm of the Internet of Things (IoT) has gained prominence for its transformative potential in various domains, including environmental monitoring [11,12]. The synergy of IoT and environmental sensing has paved the way for innovative solutions to longstanding challenges [13]. This paper addresses the pressing need for an affordable and eco-conscious system tailored for remote sensing of PM1, PM2.5, and PM10 particulate matter. By harnessing the capabilities of IoT, this proposed system not only offers an efficient means of data collection but also aligns with sustainable practices, contributing to the overarching goal of a greener future [14,15].

Numerous investigations have documented the creation and utilization of sensor systems for air quality assessment, focusing on the monitoring of outdoor air contaminants. Botero-Valencia and colleagues [16] introduced an approach for data reduction in the context of an economical environmental monitoring system based on LoRa technology. Their method encompassed dynamic subsampling of the measured variable, data fusion from multiple sensors for the same variable, and data scaling that considers the range of variables. Jo *et al.,* [17] explored an IoT-driven air quality monitoring framework, comprising the Smart-Air measurement device, an IoT gateway, and a cloud-based web server. Their focus was on monitoring PM10 concentrations within subway tunnels. Marques *et al.,* [18] detailed the creation of an affordable health information system aimed at improved living environments. Their proposal put forth a cost-effective, modular, and easily installable solution for monitoring particulate matter, ensuring scalability. Lee *et al.,* [19] engaged in an investigation centred on a stochastic model operating within environmental dynamics through IoT gas detectors, leveraging artificial intelligence (AI). The model demonstrated the potential to evaluate air quality by assessing the dispersion of fine PM in urban locales. Ghizlane and associates [20] elucidated the application of satellite atmospheric models to decipher spatiotemporal variations in concentrations of PM10 and PM2.5. Their focus encompassed the western Rif region of Morocco, notable for quarrying activity, thereby furnishing an advantageous particle capture system.

The main objective of this paper is to design, implementation, and validation of our IoT-based sensor network, which combines low-cost yet accurate PM sensors with wireless communication technologies. Our system aims to bridge the existing gap between precise air quality monitoring and economic feasibility, making it an accessible tool for a wide range of users, including researchers, policymakers, and local communities. By leveraging the power of IoT, we empower stakeholders with real-time access to crucial air quality data, enabling prompt interventions and informed decision-making to mitigate the impact of elevated PM levels. The subsequent sections of this paper delve into the technical intricacies of our IoT-based PM sensing system. We discuss the hardware components, data acquisition methodologies, communication protocols, and data processing techniques that collectively constitute our innovative solution. Furthermore, we present the results of field tests and comparisons with established reference instruments to validate the accuracy and reliability of our system.

The rest of this paper is organised as follows: First, Section 2 details the sensor setup, hardware integration, sustainable power supply implementation and green internet of things communication. This section also describes implementation low-overhead inline deduplication. Next, Section 3 present accuracy testing, LoRaWAN communication and testing the efficiency of the duplication method. Lastly, Section 4 presents some conclusions and lines for future research.

2. Methodology

2.1 Sensor Setup and Hardware Integration

In this section, we have meticulously constructed an intricate system comprising a 50 Watt-peak photovoltaic panel, concomitant with a Solar Charge Controller (SCC) to adeptly oversee battery charging and power dissemination to the designated load. Augmenting this energy architecture is a battery possessing a substantial capacity of 750 milliampere-hours (mAh), optimally aligning with the requisite energy demands. The central processing unit integral to this configuration entails the deployment of an Arduino Mega, impeccably interfaced with the PM SEN0117 sensor renowned for its precision in particulate matter quantification. This integration of the processing unit and sensor emerges as a pivotal facet of the system's operational nexus, fostering the translation of raw data into discernible insights.

Moreover, for the establishment of seamless and effective communication, we have adroitly harnessed Long Range (LoRa) technology—a conspicuous choice for its laudable energy efficiency and extended communication range. The orchestration of this communication scheme is facilitated by the strategic incorporation of a waveshare shield, as artfully depicted in Figure 1, where the symphony of components harmoniously converges to foster the symbiotic exchange of data, constituting the quintessence of this meticulously devised system.

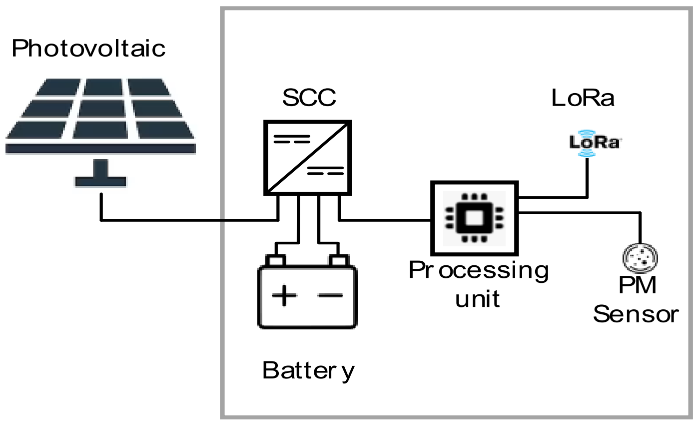


Fig. 1. Particulate matter monitoring system configuration

The PM sensor SEN0117 is a device designed to measure particulate matter (PM) concentrations in the surrounding air. It utilizes a technique called light scattering to estimate the amount of particulate matter present in the sampled air. The SEN0117 PM sensor employs the light scattering principle to determine the concentration of particulate matter. This principle is based on the interaction of light with airborne particles. When light passes through a sample containing particles, some of the light is scattered by these particles in different directions. The sensor module consists of an emitter and a detector. The emitter emits a beam of light, often in the infrared range, across the measurement chamber of the sensor. The detector is positioned at an angle to the emitter, capable of capturing scattered light. The air containing particulate matter is drawn into the sensor's measurement chamber. The particles present in the air intercept the emitted light beam, causing the light to scatter in various directions. The scattered light is detected by the sensor's detector. The intensity of the scattered light is correlated with the concentration of particulate matter in the air sample. Larger and denser particles tend to scatter light more effectively, while smaller particles scatter less. The sensor's internal electronics process the detected scattered light signals. These signals are then converted into a measurable output, typically in terms of PM concentrations. The sensor usually provides an analogue or digital output that can be interfaced with microcontrollers, development boards (e.g., Arduino), or other systems for further processing and display. The block diagram sensor PM SEN0117 can be seen in Figure 2.

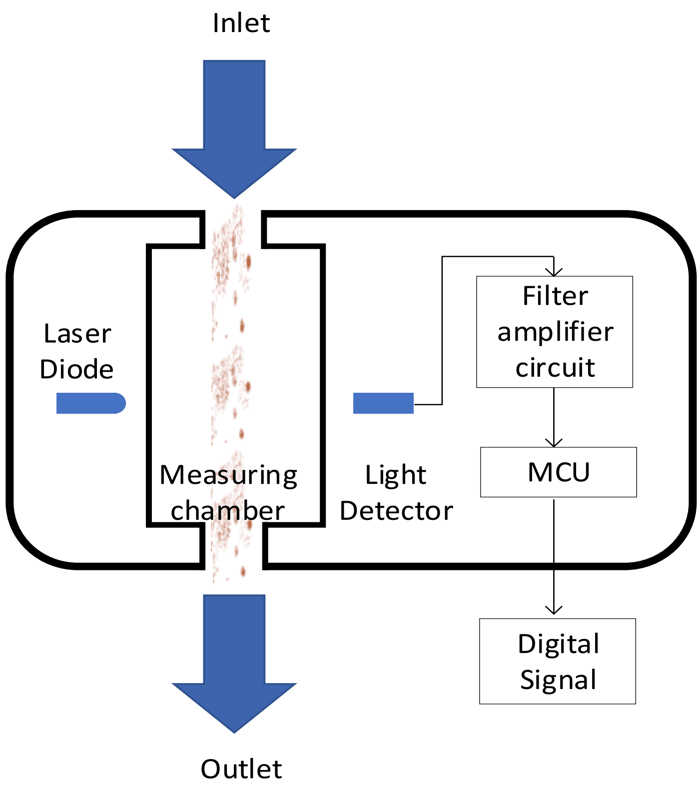


Fig. 2. Block diagram sensor PM SEN0117

2.2 Sustainable Power Supply Implementation

A fundamental tenet encompassed within the purview of Green Internet of Things (IoT) architecture is the paradigm of energy harvesting, a concept inherently predicated on the adept harnessing of ambient energy from the proximate environment. This garnered energy is subsequently channelled into the recharging of batteries, which in turn serve as a direct source of power for the sensor nodes integral to the IoT network. Characterized by the extraction of energy from the immediate milieu, energy harvesting embodies a nuanced process wherein ambient energy is acquired and subsequently stored to cater to the energy requirements of low-power wireless devices1. In effect, this orchestration leverages solar energy as a pivotal source of ambient energy, thereby capitalizing on the principles of Photovoltaics (PV) technology, as evinced in the visual representation delineated in Figure 3.

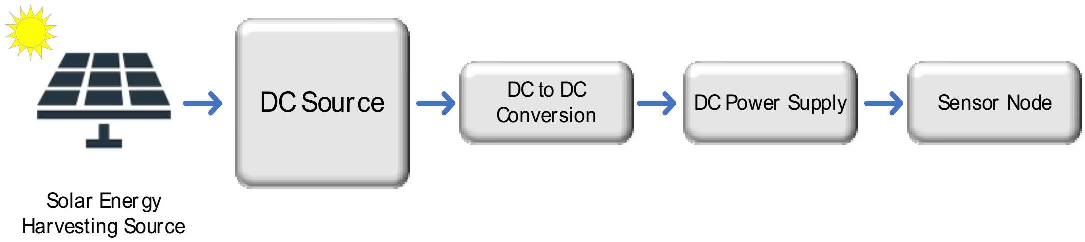


Fig. 3. Solar energy harvesting source

Within the context of our system architecture, we adopt a polycrystalline photovoltaic power supply replete with a commendable capacity of 50 Watts-peak (WP). This power supply, in concert with a Solar Charge Controller (SCC) possessing a 50 Ampere capacity, constitutes a synergistic triad aimed at ensuring optimal energy management within the system. To this cohesive configuration, a battery of substantial capacity, measured at 20 Ampere-hours (AH), is seamlessly integrated. The intricate dynamics underlying the battery's charging and discharging procedures have been meticulously delineated and can be meticulously reviewed in Table 1, encapsulating a comprehensive insight into the interplay of energy storage and release mechanisms governing the system's operation.

Table 1
The process of charging and discharging the battery

Battery discharge rate	
Power load	3 Watt
Strong load current	3/12 = 0.2916 A
Battery Capacity	20AH
Usage time	20/0.2916 = 66.85 hours
Battery Charge Rate	
Maximum solar panel power	50 Watt
Maximum solar panel current	2.78A
Estimated charging time	20/2.78 = 7.194 hours

2.3 Green Internet of Things (GioT) Communication

Green Internet of Things (IoT) is an evolving paradigm that encompasses the integration of Internet of Things technologies with environmental sustainability principles. It seeks to leverage IoT's capabilities to enhance ecological consciousness, energy efficiency, and overall environmental impact. Green IoT aims to create smart systems and solutions that not only provide value through data collection, analysis, and automation but also minimize their carbon footprint and resource consumption.

The data communication architecture employed in this investigation employs Long Range (LoRa) technology [21-25], as elucidated by the network topology diagrammatically presented in Figure 4. Within this contextual framework, the terminal devices encompass the particulate matter (PM) sensors, which are seamlessly integrated with a LoRa shield. As a complementary counterpart, the

LoRa gateways are configured utilizing Raspberry Pi devices, interconnected with a network server by means of mobile cellular connectivity.

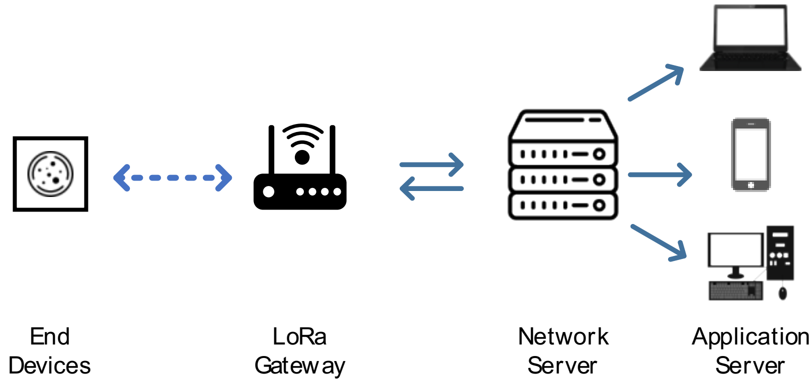


Fig. 4. LoRaWAN architecture

It is pertinent to underscore that the network server serves as the crucible for hosting Internet of Things (IoT) applications that play a pivotal role in the facets of data surveillance and presentation. The said applications, residing within the network server ecosystem, ardently facilitate the real-time monitoring of the acquired data, orchestrating its coherent visualization for perceptive analysis. This symbiotic amalgamation of components within the communication scheme substantiates the overarching objective of seamless, reliable, and intelligible data transmission.

2.4 Implementation Low-Overhead Inline Deduplication

The term "Low-Overhead Inline Deduplication" could imply a deduplication technique that aims to minimize the computational, processing, or resource overhead associated with the deduplication process during real-time data ingestion [26]. This might involve optimizing the algorithms used for comparing data chunks, utilizing efficient data structures for storing unique chunks, or finding ways to reduce the impact of deduplication on system performance. Deduplication is a data compression technique commonly used in storage systems and data management to eliminate redundant copies of data [27]. The primary goal of deduplication is to reduce storage space consumption and improve efficiency by identifying and removing duplicate data instances. This is particularly beneficial in scenarios where the same data is stored in multiple locations, such as backups or shared storage systems. Meanwhile, Inline deduplication is a deduplication process that occurs in real-time as data is ingested or written to storage. In an inline deduplication system, incoming data is examined for duplicates before it is stored. If identical data chunks are detected, only one copy is stored, and subsequent references to the same data point to the existing stored copy. This approach is contrasted with post-process deduplication, where data is first stored and deduplication occurs afterward in scheduled maintenance windows. The deduplication process flowchart in this work can be seen in Figure 5.

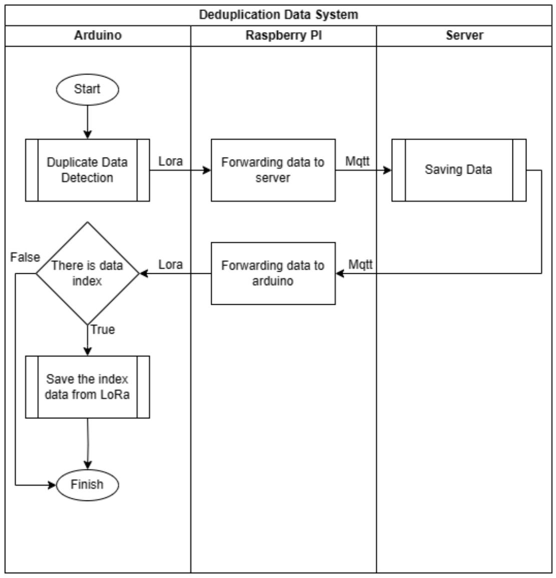


Fig. 5. Deduplication process flowchart

In the context of Low-Overhead Inline Deduplication, a "fingerprint" represents the result of applying the MurMurHash3 algorithm to the original raw data. These fingerprints are categorized into two tiers: weak fingerprints and strong fingerprints. Weak fingerprints are generated at half the length of the original data, while strong fingerprints maintain a length equivalent to that of the original data. The underlying deduplication process entails a systematic comparison between the fingerprint data stored in the metadata and the fingerprint data derived from the current data. The congruence of the current and stored fingerprint data signifies the presence of duplicated data instances.

The comparison procedure unfolds in a structured sequence, commencing with a juxtaposition of each weak fingerprint, followed by a corresponding assessment of strong fingerprints. This iterative comparative process culminates in the identification of duplicate data segments. A visual representation of the sequential workflow intrinsic to the Low-Overhead Inline Deduplication system is elucidated in Figure 6, encapsulating the intricate interplay of components and processes within the deduplication framework.

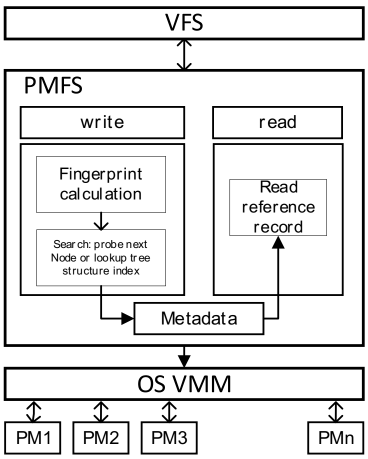


Fig. 6. Low-overhead online application workflow in systems with persistent memory

3. Results and Discussion
3.1 Accuracy Testing

The Sensor hardware testing has been carried out on SEN0177 hardware to determine the level of accuracy of each sensor in the system, compared to a calibrated tool on the market, namely DM106 (See Figure 7).

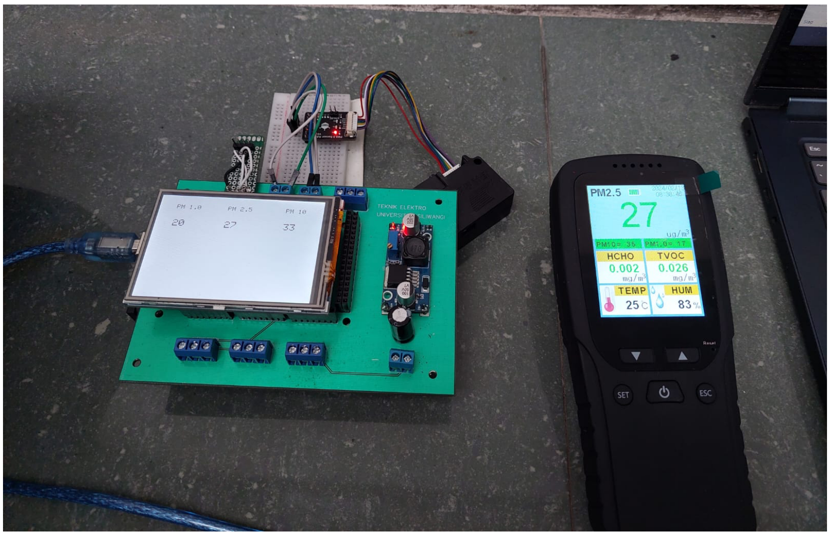


Fig. 7. Hardware of particulate matter and DM106

The experiments were conducted at 20 distinct locations within the Siliwangi University (UNSIL) and city of Tasikmalaya, West Java, Indonesia. The SEN0177 and DM106 sensors were situated near each other, and data retrieval was concurrently executed through simultaneous readings captured via photography. The recorded readings were meticulously documented, enabling the computation of the instrument's error margin based on the observed test outcomes. The outcomes of the precision assessment are itemized in Table 2. The findings show that the comparison between the SEN0177 and DM106 sensors in PM1.0 does not exceed 10%, then for PM2.5 the biggest difference is 9.76% and for PM10 it does not exceed 9.76%.

Table 2
The comparison SEN0177 sensor and DM106 sensor

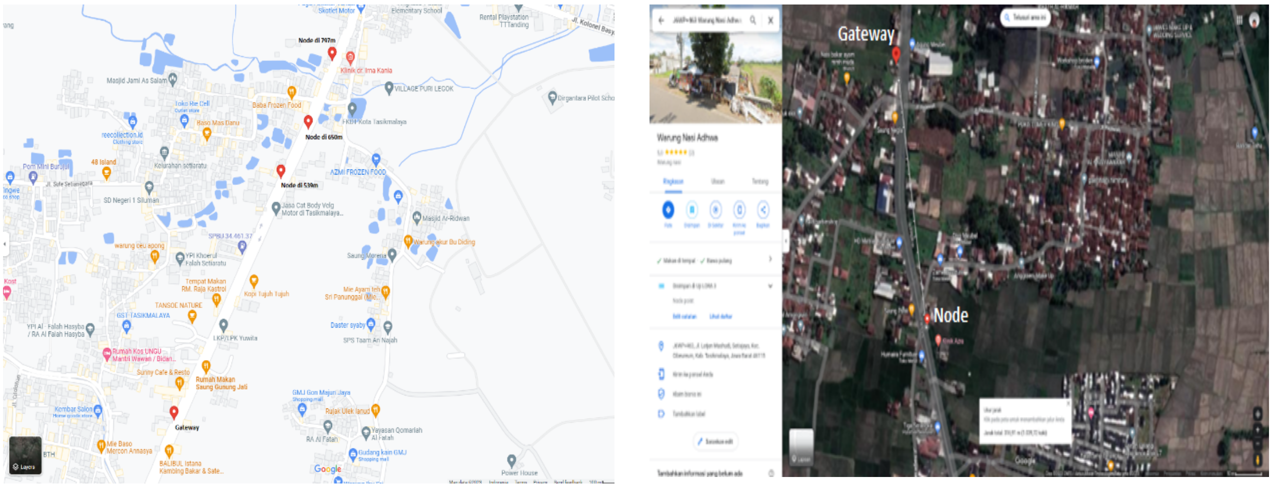
		SEN0177 sensor			DM106 sensor (Calibrator)			Error values		
No	Location	PM 1.0	PM 2.5	PM 10	PM 1.0	PM 2.5	PM 10	PM 1.0	PM 2.5	PM 10
1	UNSIL Laboratory	28	37	49	26	41	54	7.69%	9.76%	9.26%
2	UNSIL Mosque	19	30	38	21	29	38	9.52%	3.45%	0.00%
3	UNSIL Faculty of Economics Park	26	37	49	26	41	54	0.00%	9.76%	9.26%
4	Pondok Asri Hostel	16	23	31	15	25	32	6.67%	8.00%	3.13%
5	Tasco BKR	22	30	40	20	31	41	10.00%	3.23%	2.44%
6	GCC DADAHA	13	19	24	12	19	25	8.3%	0.00%	4.00%
7	Foodcourt Asia Plaza	27	37	49	25	40	52	8.00%	7.50%	5.77%
8	Gor Mashudi UNSIL	16	23	28	15	24	31	6.67%	4.17%	9.68%
9	Tasco Cilolohan	23	33	43	21	34	45	9.52%	2.94%	4.44%
10	SPBU UNSIL	29	41	53	27	44	57	7.41%	6.82%	7.02%
11	Digital Garden, UPI Tasikmalaya	30	43	56	29	46	60	3.45%	6.52%	6.67%

12	Taman Makam Pahlawan Kusuma Bangsa	23	32	41	21	35	45	9.52%	8.57%	8.89%
13	Tasco Cikalang	27	38	49	26	41	54	3.85%	7.32%	9.26%
14	SDN Nyantong	22	31	39	20	34	43	10.00%	8.82%	9.30%
15	Poltekkes Tasikmalaya Mosque	21	29	37	20	31	41	5.00%	6.45%	9.76%
16	Matahari Store Tasikmalaya	17	25	35	17	27	35	0.00%	7.41%	0.00%
17	Foodcourt Mayasasi Plaza	117	161	204	106	173	225	10.38%	6.94%	9.33%
18	Masjid Agung Tasikmalaya	25	35	48	23	37	48	8.70%	5.41%	0.00%
19	Tasikmalaya City Park	24	34	48	23	36	48	4.35%	5.56%	0.00%
20	Cihideung Street, No.62	22	31	41	20	34	43	10.00%	8.82%	4.65%
Average								6.95%	6.37%	5.64%

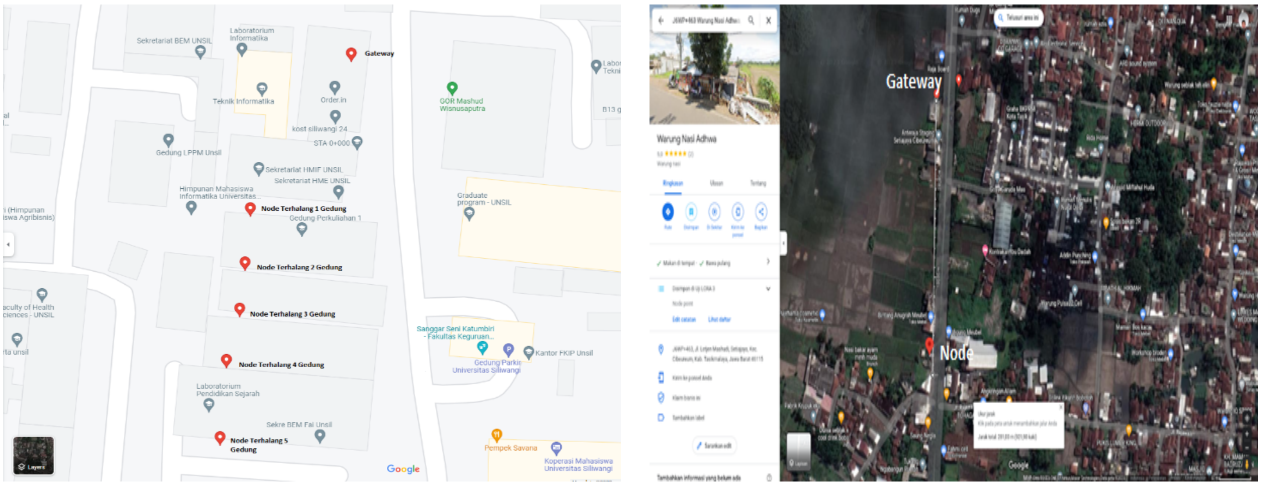
3.2 Sending Distance Test with LoRa

The sending distance test with LoRa is a test to find out the maximum range of LoRa communication that can run in one area. Testing was carried out using Arduino as a node and Raspberry Pi as a gateway. During testing, the node sends random data to the gateway and the gateway receives data sent from the node. The node during the test will record the time the data is sent and the gateway as the recipient will record the time the data is received from the node.

The tests were carried out on two different schemes. The first test scheme is carried out in an open environment so that between nodes and gateways there are no buildings or objects blocking them. The second test scheme is carried out in a dense building environment so that node and gateway communications are blocked by buildings. A map of node and gateway positions in each scheme can be seen in Figure 8.



(a) (b)



(c) (d)

Fig. 8. (a). Node and gateway positions at distances of 539m, 650m and 797m, (b). Position of node and gateway at a distance of 316m, (c). Node and gateway positions at a distance of 218m, (d). Position of node and gateway on the blocked scheme of the building

Table 3 shows that data sent starting from distance 218 can be received well with a latency of approximately 1 second, as well as at distances 316, 539, 650 and 707, the latency is only around 1 second with the same received data. But when tested at a distance above 797, the data sent immediately was not detected. Therefore, LoRA can only transmit data up to a distance of 797 m.

Table 3
Building unobstructed LoRA testing

No	Distance (m)	Node		Gateway	
		Timestamp	Data	Timestamp	Data
1	218	2023-03-24T13:36:19.226	{"id": "bd950176","data": "va|11132.00"}	2023-03-24T13:36:20.213569	{"id": "bd950176","data": "va|11132.00"}
2		2023-03-24T13:36:22.052	{"id": "bd950176","data": "va|8101.00"}	2023-03-24T13:36:23.011668	{"id": "bd950176","data": "va|8101.00"}
3		2023-03-24T13:36:23.479	{"id": "bd950176","data": "va|8100.00"}	2023-03-24T13:36:24.416313	{"id": "bd950176","data": "va|8100.00"}
4	316	2023-03-24T14:09:04.572	{"id": "bd950176","data": "va|8102.00"}	2023-03-24T14:09:05.565584	{"id": "bd950176","data": "va|8102.00"}
5		2023-03-24T14:09:05.998	{"id": "bd950176","data": "va|8103.00"}	2023-03-24T14:09:06.970181	{"id": "bd950176","data": "va|8103.00"}
6		2023-03-24T14:09:07.419	{"id": "bd950176","data": "va|8103.00"}	2023-03-24T14:09:08.374731	{"id": "bd950176","data": "va|8103.00"}
7	539	2023-03-24T14:23:19.366	{"id": "bd950176","data": "va|11138.00"}	2023-03-24T14:23:20.290305	{"id": "bd950176","data": "va|11138.00"}
8		2023-03-24T14:23:20.789	{"id": "bd950176","data": "va|9112.00"}	2023-03-24T14:23:21.683846	{"id": "bd950176","data": "va|9112.00"}

9		2023-03-24T14:23:22.164	{"id": "bd950176","data": "va|8107.00"}	2023-03-24T14:23:23.088423	{"id": "bd950176","data": "va|8107.00"}
10	650	2023-03-24T14:33:20.638	{"id": "bd950176","data": "va|8108.00"}	2023-03-24T14:33:21.563952	{"id": "bd950176","data": "va|8108.00"}
11		2023-03-24T14:33:34.687	{"id": "bd950176","data": "va|8108.00"}	2023-03-24T14:33:35.608367	{"id": "bd950176","data": "va|8108.00"}
12		2023-03-24T14:33:36.110	{"id": "bd950176","data": "va|8107.00"}	2023-03-24T14:33:37.012806	{"id": "bd950176","data": "va|8107.00"}
13	797	2023-03-24T14:38:53.624	{"id": "bd950176","data": "va|787.00"}	2023-03-24T14:38:54.541081	{"id": "bd950176","data": "va|787.00"}
14		2023-03-24T14:39:10.340	{"id": "bd950176","data": "va|787.00"}	2023-03-24T14:39:11.259940	{"id": "bd950176","data": "va|787.00"}
15		2023-03-24T14:39:17.317	{"id": "bd950176","data": "va|685.00"}	2023-03-24T14:39:18.226197	{"id": "bd950176","data": "va|685.00"}

In testing with building blocks, it is not the distance that becomes the test parameter but the number of buildings at a distance below 797 m. Table 4 shows that LoRA signals that are blocked by up to 5 buildings can still transmit data properly with a latency of under 1 second. But upon entering the barrier at the 6th building, the data sent was completely unacceptable.

Table 4
Building obstructed LoRA testing

No	Number of Barrier Buildings	Node		Gateway	
		Timestamp	Data	Timestamp	Data
1	1	2023-04-06T15:52:07.953	{"id": "bd950176","data": "va|10120.23"}	2023-04-06T15:52:07.947349	{"id": "bd950176","data": "va|10120.23"}
2		2023-04-06T15:52:12.984	{"id": "bd950176","data": "va|10119.53"}	2023-04-06T15:52:12.952473	{"id": "bd950176","data": "va|10119.53"}
3		2023-04-06T15:52:17.962	{"id": "bd950176","data": "va|10119.18"}	2023-04-06T15:52:17.957577	{"id": "bd950176","data": "va|10119.18"}
4	2	2023-04-06T15:57:31.347	{"id": "bd950176","data": "va|9114.96"}	2023-04-06T15:57:31.747893	{"id": "bd950176","data": "va|9114.96"}
5		2023-04-06T15:58:31.427	{"id": "bd950176","data": "va|9114.26"}	2023-04-06T15:58:31.805823	{"id": "bd950176","data": "va|9114.26"}
6		2023-04-06T15:59:01.447	{"id": "bd950176","data": "va|9114.26"}	2023-04-06T15:59:01.835071	{"id": "bd950176","data": "va|9114.26"}
7	3	2023-04-06T16:02:48.092	{"id": "bd950176","data": "va|16197.23"}	2023-04-06T16:02:48.523125	{"id": "bd950176","data": "va|16197.23"}

<table>
<tr><td>8</td><td></td><td>2023-04-06T16:03:13.132</td><td>{"id": "bd950176","data": "va|9113.55"}</td><td>2023-04-06T16:03:13.526153</td><td>{"id": "bd950176","data": "va|9113.55"}</td></tr>
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<tr><td>15</td><td></td><td>2023-04-06T16:16:01.063</td><td>{"id": "bd950176","data": "va|9115.31"}</td><td>2023-04-06T16:16:01.427279</td><td>{"id": "bd950176","data": "va|9115.31"}</td></tr>
</table>

3.3 Testing the Efficiency of the Duplication Method

Tests are carried out with the help of the INA219 sensor to measure current and voltage. The measured current and voltage are then calculated into power. INA219 measurements are performed every 500ms. The read voltage and current data are displayed in the serial monitor and the power calculation is carried out. In each scheme, as much as 60 data is sent by the Node to the Gateway. Because the reading data for INA219 is not based on sending Node data, data from INA219 is processed by only taking measurement results that have a timestamp close to the timestamp of the Node when sending data.

In scheme (a), the data sent is in the form of complete data starting from the device id data to the sensor reading result data. In scheme (b), the data sent has been manipulated by the deduplication system so that the data sent is index database data from the server and new data from sensor readings. In scheme (c), the data sent has also been manipulated by the deduplication system, but because the sensor readings are the same, the data sent is index database data from the server. The data sent in the three schemes are as follows:

i. {"id": "759b21ae","data": "ht120v|63,19,19,29,50,0.00,"}
ii. 2178;v|75,28,10,22,54,0,00,"};
iii. 2416;2417;

Database index data is index data where the server stores the data on the server. For data synchronization between servers and nodes, every time data is sent, if there is duplicate data on the node, only the database index is sent, not all data which is duplicate data. The testing efficiency of data transmission power with various schemes can be seen in Table 5.

Table 5
The testing efficiency of data transmission power with various schemes

Testing	Without Deduplication			Random Deduplication			Same Data Deduplication		
	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)
1	4.15	0.1778	0.73787	4.14	0.1774	0.734436	4.05	0.1766	0.71523
2	4.16	0.1782	0.741312	4.14	0.17752	0.7349328	4.04	0.1766	0.713464
3	4.15	0.1778	0.73787	4.14	0.177	0.73278	4.04	0.17672	0.7139488
4	4.16	0.17772	0.7393152	4.14	0.17732	0.7341048	4.04	0.17672	0.7139488
5	4.16	0.17752	0.7384832	4.14	0.17732	0.7341048	4.04	0.17652	0.7131408
6	4.16	0.1778	0.739648	4.14	0.17732	0.7341048	4.04	0.17652	0.7131408
7	4.16	0.17792	0.7401472	4.14	0.1776	0.735264	4.04	0.17652	0.7131408
8	4.16	0.17772	0.7393152	4.14	0.17732	0.7341048	4.04	0.1768	0.714272
9	4.16	0.1776	0.738816	4.14	0.17752	0.7349328	4.04	0.1768	0.714272
10	4.16	0.1778	0.739648	4.14	0.17712	0.7332768	4.03	0.17692	0.7129876
11	4.16	0.1776	0.738816	4.14	0.17752	0.7349328	4.04	0.1764	0.712656
12	4.16	0.1776	0.738816	4.13	0.1774	0.732662	4.04	0.17652	0.7131408
13	4.16	0.17772	0.7393152	4.14	0.17752	0.7349328	4.04	0.1766	0.713464
14	4.16	0.17752	0.7384832	4.14	0.1774	0.734436	4.03	0.17652	0.7113756
15	4.16	0.1776	0.738816	4.14	0.1774	0.734436	4.04	0.17652	0.7131408
16	4.16	0.17772	0.7393152	4.14	0.1776	0.735264	4.03	0.1768	0.712504
17	4.15	0.1776	0.73704	4.13	0.1774	0.732662	4.03	0.1766	0.711698
18	4.15	0.17772	0.737538	4.13	0.17752	0.7331576	4.04	0.1766	0.713464
19	4.16	0.1776	0.738816	4.13	0.1774	0.732662	4.04	0.17612	0.7115248
20	4.16	0.17752	0.7384832	4.13	0.1774	0.732662	4.04	0.17672	0.7139488
21	4.16	0.1776	0.738816	4.13	0.177	0.73101	4.04	0.17672	0.7139488
22	4.16	0.17772	0.7393152	4.13	0.17732	0.7323316	4.04	0.17672	0.7139488
23	4.15	0.1774	0.73621	4.13	0.1776	0.733488	4.04	0.177	0.71508
24	4.16	0.1782	0.741312	4.13	0.17752	0.7331576	4.03	0.1766	0.711698
25	4.16	0.1776	0.738816	4.13	0.1772	0.731836	4.04	0.1764	0.712656
26	4.16	0.17772	0.7393152	4.13	0.1772	0.731836	4.04	0.1766	0.713464
27	4.15	0.1778	0.73787	4.16	0.17772	0.7393152	4.04	0.17652	0.7131408
28	4.16	0.1774	0.737984	4.12	0.1776	0.731712	4.04	0.17712	0.7155648
29	4.16	0.1774	0.737984	4.12	0.1776	0.731712	4.04	0.17652	0.7131408
30	4.16	0.178	0.74048	4.13	0.17752	0.7331576	4.04	0.17652	0.7131408
31	4.16	0.17752	0.7384832	4.13	0.1772	0.731836	4.04	0.1764	0.712656
32	4.16	0.17772	0.7393152	4.13	0.17732	0.7323316	4.04	0.1766	0.713464
33	4.16	0.12792	0.5321472	4.13	0.1774	0.732662	4.04	0.17672	0.7139488
34	4.16	0.1776	0.738816	4.12	0.17752	0.7313824	4.04	0.17652	0.7131408
35	4.15	0.17772	0.737538	4.12	0.1776	0.731712	4.04	0.1766	0.713464
36	4.16	0.17732	0.7376512	4.12	0.1774	0.730888	4.03	0.17672	0.7121816
37	4.15	0.1778	0.73787	4.12	0.1772	0.730064	4.03	0.17652	0.7113756
38	4.16	0.1776	0.738816	4.11	0.1778	0.730758	4.04	0.17632	0.7123328
39	4.16	0.17752	0.7384832	4.12	0.17712	0.7297344	4.04	0.1766	0.713464
40	4.16	0.1772	0.737152	4.12	0.1774	0.730888	4.04	0.17652	0.7131408
41	4.16	0.1778	0.739648	4.12	0.1774	0.730888	4.04	0.1764	0.712656
42	4.16	0.178	0.74048	4.12	0.1774	0.730888	4.04	0.17652	0.7131408
43	4.15	0.1778	0.73787	4.11	0.17752	0.7296072	4.03	0.17652	0.7113756
44	4.15	0.17792	0.738368	4.12	0.1774	0.730888	4.03	0.17632	0.7105696
45	4.15	0.1778	0.73787	4.12	0.1774	0.730888	4.04	0.17672	0.7139488
46	4.16	0.178	0.74048	4.12	0.1774	0.730888	4.04	0.17632	0.7123328
47	4.15	0.178	0.7387	4.12	0.17752	0.7313824	4.04	0.17652	0.7131408
48	4.16	0.1776	0.738816	4.12	0.1774	0.730888	4.04	0.1768	0.714272
49	4.16	0.17772	0.7393152	4.11	0.17752	0.7296072	4.04	0.17652	0.7131408
50	4.15	0.1776	0.73704	4.12	0.1774	0.730888	4.04	0.17692	0.7147568
51	4.15	0.1776	0.73704	4.12	0.1778	0.732536	4.04	0.1766	0.713464

52	4.15	0.17752	0.736708	4.12	0.1774	0.730888	4.04	0.17652	0.7131408
53	4.16	0.178	0.74048	4.12	0.1774	0.730888	4.04	0.17672	0.7139488
54	4.16	0.17772	0.7393152	4.32	0.17472	0.7547904	4.04	0.17652	0.7131408
55	4.15	0.17772	0.737538	4.11	0.17772	0.7304292	4.04	0.1766	0.713464
56	4.15	0.1778	0.73787	4.12	0.17732	0.7305584	4.04	0.1764	0.712656
57	4.15	0.17772	0.737538	4.12	0.1774	0.730888	4.04	0.17672	0.7139488
58	4.15	0.1776	0.73704	4.12	0.1776	0.731712	4.04	0.1768	0.714272
59	4.15	0.17792	0.738368	4.12	0.17732	0.7305584	4.04	0.1764	0.712656
60	4.15	0.17792	0.738368	4.12	0.1774	0.730888	4.04	0.17652	0.7131408
Average	4.1565	0.17688	0.735184	4.13083	0.177378	0.7327102	4.0387	0.17659	0.713209

4. Conclusions

In this paper, we have built a low-cost PM 1, PM 2.5 and PM 10 particulate matter detection system using the SEN0177 sensor, data communication using LoRA and a power supply based on sustainable energy solar cells. The test results show that the power requirement of 3 watts can be supplied by a 50-Watt PV panel with a 20 AH battery and can be used for 66.85 hours. The comparison results with similar low-cost DM016 produces an error below 7% and the LoRa distance can transmit signals even though it is blocked by buildings. Further development is carried out by placing several sensor nodes to communicate with each other and be able to reach server nodes based on various network topologies. Besides that, we will investigate and incorporate advanced sensor technologies for improved accuracy and sensitivity in PM detection in the future research.

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