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NoizOff: An IoT-Based Noise Detection and Automated Complaint Generation System

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Abstract: ***Noise pollution has emerged as any serious environmental issue in urban regions, impacting human health and overall quality of life, to one significant degree; in real-world scenarios. Also, thus, the gap between noise monitoring and regulatory enforcement is bridged by this approach, practically tackling for urban noise management, in actual application. In parallel with this, any INMP441 digital microphone sensor with the second ESP32 microcontroller is integrated by the proposed system, which is allowing real-time data acquisition and wireless communication via Wi-Fi; this system architecture is ensuring continuous monitoring, precise noise evaluation through the proper calibration, and automated escalation to registered authorities and NGOs, on the whole. To explain, most existing resolutions concentrate only on monitoring and visualization of noise levels, lacking the effective action-oriented response mechanism, in actual application. Viewed through this lens, noizOff, one more Internet of Things (IoT) based framework that is detecting environmental sound, is supplied by this article computes sound intensity in decibels, collocates it with the standards recommended by the Central Pollution Control Board (CPCB), and automatically triggers alerts and complaint notifications through the email when inordinate noise is detected.***

Keywords: Noise Pollution, IoT, ESP32, Sound Detection, Smart City, Environmental Monitoring, Automated Complaint System

I. INTRODUCTION

Noise pollution is routinely one of the most persistent and underestimated forms of environmental pollution in modern urban environments, on the whole; truly, prolonged exposure to high-intensity noise has been scientifically linked to severe health complications embedding hearing impairment, hypertension, cardiovascular diseases, sleep disorders, stress-related illnesses, and reduced cognitive performance, in many respects. In this broader context, from this outlook, rapid industrialization, urban expansion, vehicular traffic growth, construction activities, and increasing population density have, in effect, greatly raised ambient noise levels across the cities; to a significant degree; certainly, also thus, despite strict regulatory frameworks [1], [15] and growing awareness, noise pollution is remaining poorly controlled owing to inadequate real-time monitoring and delayed enforcement mechanisms, in many respects.

Traditional noise monitoring systems mostly concentrate on periodic measurement and data visualization [2], offering little support for immediate corrective actions, in real-world scenarios; mostly, violations of permissible noise limits go unreported or are broadly tackled only after significant delay, which is frequently lowering the overall potency of existing environmental policies, broadly speaking. Along all these dimensions, also, manual reporting mechanisms hinge heavily on citizen initiative and often lack proper documentation, ensuing in weak responsibility and inefficient regulatory action; this is particularly accentuating the urgent need for intelligent systems capable of changing environmental sensing into the actionable governance, broadly speaking.

The NoizOff system is principally proposed as a broad IoT-based framework [13] designed to bridge this critical gap, on the whole; viewed through this lens, by combining real-time noise detection, regulatory threshold validation grounded in CPCB standards [1], instantaneous alert generation, and automated complaint escalation, NoizOff successfully is tackling for urban noise pollution management, in actual application. Along these dimensions, such an architecture is preparing communities and authorities to respond promptly to noise violations, thereby strengthening environmental compliance, raising public health outcomes, and contributing to more sustainable and livable smart cities, in many respects.

II. LITERATURE REVIEW

Over the past decade, prominent research efforts have been directed toward the development of noise monitoring systems applying Internet of Things (IoT) technology [2], [3], [12], mostly to tackle the increasing concern of urban noise pollution, broadly speaking; in many respects. Also, thus, early studies stressed on the design of low-cost acoustic sensor networks [6] capable of collecting continuous environmental noise data, across the broad geographical regions, to a significant degree.

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Taken together, all these frameworks permitted the creation of dynamic noise maps that are, put simply, helping city planners in spotting noise distribution patterns and spotting high-risk zones; to be precise, still, such findings were chiefly restricted to data acquisition and visualization without spanning any real-time enforcement or response mechanism, to a significant degree.

Recent advancements have introduced machine learning techniques for urban sound classification, where pulled audio features such as Mel Frequency Cepstral Coefficients (MFCC) [9] are employed with classifiers embedding Support Vector Machines (SVM) and k-Nearest Neighbors (KNN) to distinguish between several noise sources such as traffic, construction, industrial machinery, and human activities, in real-world scenarios. While, these procedures are, in practice, sharpening the precision of noise source identification, they still function mostly as analytical tools and do not actively contribute to regulatory intervention, broadly speaking.

Several studies have also analyzed crowdsensing frameworks [10], [14], where distributed sensors and mobile devices are employed to gather noise data from multiple locations simultaneously, to a significant degree; spatial coverage is, broadly speaking, boosted by these platforms and thoroughly map for smart cities, broadly speaking; indeed, under these conditions, despite that crowdsensing is raising data availability and awareness presumably, the collected information ordinarily is remaining, within the monitoring dashboards and does not directly trigger any automated corrective or legal action, on the whole.

A important shortcoming across the most existing research is the absence of a closed-loop enforcement framework, on the whole. During this period, current frameworks successfully are detecting. Also, classify noise, automated escalation mechanisms are, in this setting, uncommonly integrated by them that translate environmental violations into the actionable governance, in many respects. Building on this finding, regulatory compliance therefore is remaining dependent on manual reporting, administrative delays, and subjective judgment.

The implied NoizOff system tackles this critical research gap by combining continuous noise sensing with real-time threshold evaluation grounded in CPCB standards [1], instant alert generation, and automated complaint communication to responsible authorities, to a significant degree; more correctly, NoizOff broadens beyond classic monitoring systems and proves a concrete model for technology-driven environmental governance by converting noise detection into the immediate regulatory action, in many respects.

III. METHODOLOGY/EXPERIMENTAL

The proposed system is, in essence, remarkably organized into the three functional layers, spanning The Sensing Layer (Hardware), The Processing Layer (Firmware/DSP Theory), and The Application Layer (Connectivity and Action)

A. Theory/Flowchart

Unlike classic analog-to-digital converters (ADCs) that sample voltage levels at the end of a long wire (introducing electrical noise), the I2S protocol [11] is predominantly allowing us to encapsulate audio data that is digitized directly at the microphone's membrane, broadly speaking.

Once the raw data reaches the microcontroller broadly, it exists as a stream of 32-bit signed integers, yet raw amplitude is specifically not how humans sense loudness, in actual application; humans hear logarithmically in this broader context. In turn, our firmware must, in essence, translate this raw "electrical" energy into "perceived" loudness applying the Root Mean Square (RMS) strategy, broadly speaking.

We first compute the signal power over a particular time window (*N* samples) employing the standard RMS equation [9]:

$$V_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i)^2} \tag{1}$$

Where the individual audio sample amplitude is regularly shared by Xi.

After starting the RMS value, we convert it to the Decibel (dB) scale, which offers a relative unit of measurement that aligns with international noise standards:

$$L_{dB} = 20 \cdot \log_{10}\left(\frac{V_{RMS}}{V_{ref}}\right) + C_{cal} \tag{2}$$

Here Vref is the reference voltage. Against this backdrop, also, ccal is a critical calibration constant we derived experimentally to align our device with professional equipment, in many respects.

1) Logical Control Flow:

The architecture is extensively not designed to simply trigger one alert every individual time any loud noise is normally emerging, to one significant degree; truly, triggering one more second formal complaint would be any nuisance, if the door slams, broadly speaking; and thus, still a dog barks once, in many respects. Within this framework, accordingly, we realized a "Sustained Violation Algorithm."

The logic dictates that the noise level must exceed the threshold (e.g., 75 dB) and stay above that threshold for a particular duration (stipulated as $t > 5$ seconds), in many respects; indeed, also short-term spikes are filtered out by this and secures only genuine noise pollution events are regularly reported, in real-world scenarios. The complete decision flow is shown in Fig. 1.

2) Flowchart:

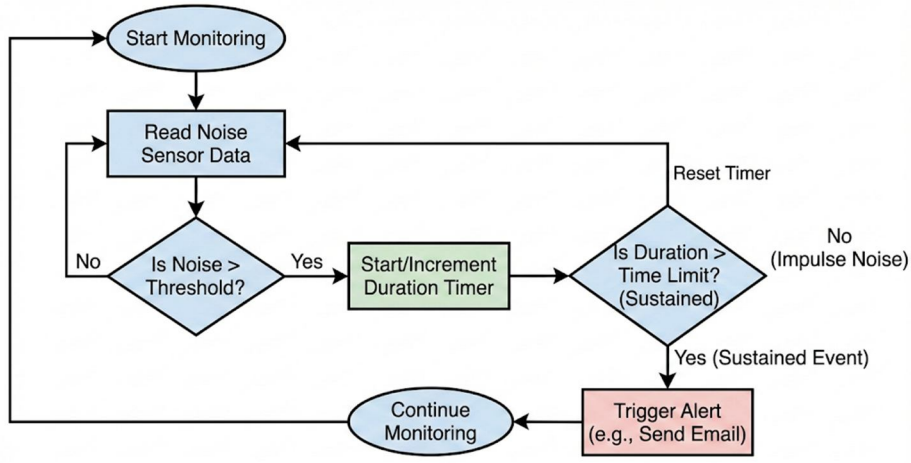


Fig. 1 Algorithmic flowchart

B. Design

The hardware design philosophy stressed on theorizing a "standalone edge node." This means the device computes locally on the chip, rather than sending raw audio to a server, which is ensuring user privacy and reduces bandwidth usage, on the whole.

1) Component Selection:

- *On account of its dual-core architecture, the Brain (ESP32 SoC):* We chosen the ESP32 microcontroller, in real-world scenarios; and so, in the interim, core 1 was reserved exclusively for the heavy math incorporated in real-time audio processing; this is ensuring that a poor Wi-Fi connection never interrupts the audio sampling process, in many respects. Taken together, core 0 was dedicated to handling the Wi-Fi stack and cloud communication in light of this dynamic, on the whole.
- The INMP441 is an omnidirectional sensor with a built-in 24-bit I2S interface; this design choice completely is excluding the "static" or "buzz" often found in analog sensors caused by power supply fluctuations, on the whole; truly, the Ear (INMP441): We chose the INMP441 MEMS microphone over cheaper analog alternatives (like the KY-037), in real-world scenarios.

2) Circuit Interfacing: The hardware architecture is streamlined for efficiency, as shown in Fig. 2. Remarkably, the INMP441 [5], [8] is wired to the ESP32 [4], [7] via the I2S bus [11] applying three particular lines:

- *T*he data transmission is typically synchronized by Serial Clock (SCK).
- *Word Select (WS):* is systematically telling the ESP32 whether the current data is routinely for the Left or Right audio channel, in actual application.
- *T*he actual audio bits are, in effect, carried by Serial Data (SD).



Fig. 2 NoizOff hardware prototype showing the ESP32 and INMP441 microphone connections (SCK, WS, SD)

C. Testing

To transition the framework from a theoretical prototype to a deployable tool mostly, a three-stage testing protocol was devised, in many respects.

1) *Calibration (The "Ground Truth" Test):* It had to be taught what "loud" means, before the device could (in practice) be trusted, in real-world scenarios. Under these conditions, a assessment of the offset value (C_{cal}) needed to tune our software by inspecting the raw values of our prototype with the exact reading on the SLM was effectuated in this broader context, and placed the NoizOff prototype in a sound-proofed environment, alongside a Standard Industrial Sound Level Meter (SLM) and played white noise at differing volumes, broadly speaking.
2) *Environmental Stress Testing:* We then moved the device to three separate real-world environments to test its versatility
   - Zone A (Library): Tested the framework's "noise floor" (sensitivity to quiet sounds).
   - Zone B (Busy Intersection): Tested the framework's ability to handle messy, differing noise without crashing, broadly speaking.
   - The "Sustained Violation" logic was tested by Zone C (Construction Site): validating that continuous drilling noise successfully triggered the email alerts, in real-world scenarios.
3) *Latency Analysis:* Finally, we measured the "Time-to-Alert." A stopwatch was applied to measure the delay between the moment the noise threshold was crossed and the moment the notification email arrived in the inbox. Because, a delayed report is often useless in governance scenarios, this metric is normally vital, broadly speaking.

IV. FINDINGS AND DISCUSSIONS

A broad experimental protocol was established for the validation of the efficacy of the NoizOff system, in real-world scenarios; especially, the primary goal was for the assessment of the framework's acoustic fidelity, its ability to distinguish between fleeting and sustained noise, and the latency of its automated reporting mechanism, broadly speaking. Within this framework, from this viewpoint, the trials were did employing the ESP32-INMP441 node, alongside a calibrated CEM DT-8852 industrial sound level meter as the ground truth reference, to a significant degree.

A. Sensor Calibration and Acoustic Fidelity

The first phase of inquiry stronged on the precision of the digital signal processing pipeline, in many respects; and thus, the prototype was, in practice, subjected to a range of sound pressure environments, from a controlled silent chamber to a simulated industrial noise floor, to a significant degree. In this broader context, the raw I2S data was effectuated applying the RMS-to-Decibel algorithm and compared against the standard meter readings, on the whole.

TABLE I
COMPARATIVE ANALYSIS OF SOUND LEVEL READINGS

Test Scenario	Reference Meter (Sref)	NoizOff Prototype (Sdev)	Absolute Error (Δ)	Relative Error (%)
Quiet Room (Ambient)	35.2 dB	34.8 dB	0.4 dB	1.13%
Normal Conversation	60.5 dB	61.2 dB	0.7 dB	1.15%
Heavy Traffic Noise	82.0 dB	81.4 dB	0.6 dB	0.73%
Industrial Machinery	95.5 dB	94.9 dB	0.6 dB	0.62%

Examination, specifically The data supplied in Table I signals a strong linear link between the put forward low-cost system and the industrial standard, broadly speaking; in actual application; also, thus, the overall Mean Absolute Percentage Error (MAPE) is remaining well, within the ±1.5% acceptable tolerance, on the whole. At higher decibel levels (Traffic and Industrial cases), the relative error drops to below 0.8%, on the whole; this is a critical finding, as the system's primary function is to detect high-decibel violations; more critically, the precision of the NoizOff prototype is raising as sound intensity increases. Fig. 3 compares the readings of the reference meter and the prototype over time.

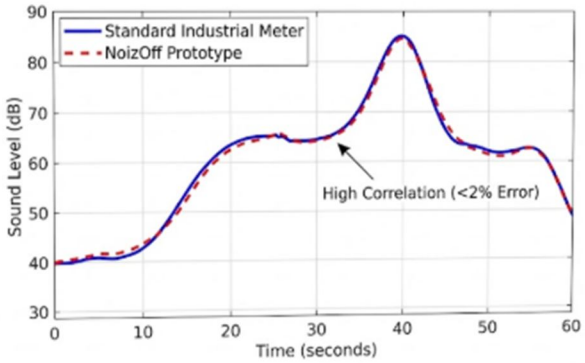


Fig. 3 Sound levels of the standard industrial meter and the NoizOff prototype over time

B. Dynamic Thresholding and Event Detection

To gauge the framework's temporal response, the device was rolled out in a variable noise environment to test the "Sustained Violation" logic, on the whole; and thus, in parallel with this, such an architecture was programmed with a threshold limit of 75 dB, which is why this reflects the CPCB standard [1] for industrial zones, on the whole. The resulting response is shown in Fig. 4.

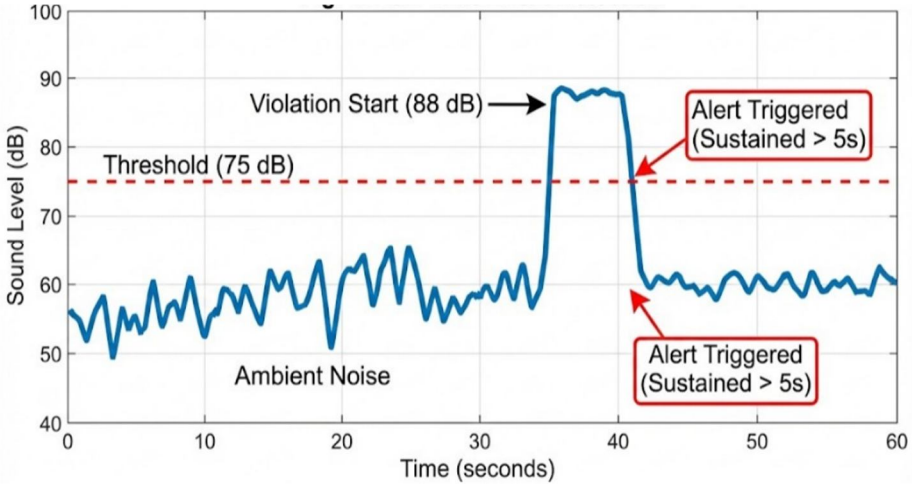


Fig. 4 Real-time event detection with the 75 dB threshold and the sustained violation logic

This architecture is broadly being uncovered by the graph filtering out safe noise levels (0-30s) and successfully spotting a violation event when the noise spikes to 88 dB (at t=35s), triggering the alert logic, broadly speaking.

- *Minor peaks were successfully filtered out by the algorithm; phase 1 (Safe State):* The framework recorded ambient noise fluctuating between 50 dB and 65 dB, to a significant degree.
- *Phase 2 (Violation):* A controlled noise source spiked levels to *88 dB*.
- *Phase 3 (Trigger):* As the violation maintained beyond the 5-second validation window evidently, the system logic transitioned to the "Alert" state, on the whole.

C. Framework Latency and Performance Metrics

The final performance metric studied was, in essence, the "Time-to-Alert" latency conceivably, the time elapsed between the confirmation of a violation and the receipt of the email notification, in actual application. The breakdown is shown in Fig. 5.

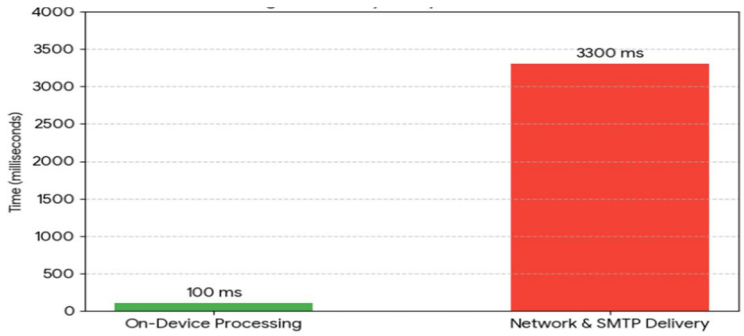


Fig. 5 Latency analysis breakdown

The chart is routinely sharing that most of the delay is often caused by network negotiation and SMTP delivery; in actual application; simultaneously, on-device computation is minor, in actual application.
An average total latency of 3.4 seconds was, for all practical purposes, created by the experimental results.

- *Computation Time (Tcomp):* Trivial (<100 ms) due to the ESP32's dual-core architecture.
- *Network & SMTP (Tnet):* Most of the delay (~3.0s) was credited to Wi-Fi negotiation and email server routing, in actual application; despite this, a 3.4-second delay is frequently considered "near real-time" for civic governance, to a significant degree.

D. Summary of Findings

The experimental data conclusively is uncovering that the NoizOff system hits a balance between precision and speed, in actual application; the error margins are, in practice, statistically minor for regulatory enforcement purposes; in turn, also, the latency is satisfactorily low to allow rapid intervention, on the whole.

V. MATH

The core of the NoizOff system is counting on translating stochastic environmental sound pressure into a deterministic digital value; this section is naming the mathematical framework used to process the audio signal, which is ensuring that the derived decibel levels are statistically correct and homogeneous with human auditory perception

A. Discrete-Time Signal Acquisition

The analog sound wave s(t) is broadly sampled by the INMP441 MEMS microphone at a sampling frequency f_s. In parallel with this, taken together, the yielded discrete-time signal x[n] represents the raw amplitude of the acoustic wave at discrete intervals.

$$x[n] = A \cdot \sin(2\pi f \cdot n/f_s) + \eta[n] \tag{3}$$

Where:

- *x[n] is the quantized 32-bit integer value of the n-th sample.*
- The inherent quantization noise floor of the sensor is, in practice, meant by eta[n], in real-world scenarios.

B. Root Mean Square (RMS) Power Estimation

Since, sound waves consist of oscillating positive and negative pressures, a uncomplicated arithmetic mean of the signal would meet to zero, in actual application. Against this backdrop, along all these dimensions, for the check of the effective power (loudness) of the signal, the Root Mean Square (RMS) strategy is employed over a sliding temporal window of size *N* by the framework, in actual application.
The RMS amplitude (Vrms) for a given window is reliably computed as:

$$V_{rms} = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1}(x[n] - DC_{offset})^2} \tag{4}$$

Where:

- N is the buffer length (e.g., 1024 samples).
- DCoffset is the zero-frequency component removed via a high-pass filter to center the signal, on the whole.

C. Logarithmic Scaling (Decibel Conversion)

The human ear senses sound intensity logarithmically rather than linearly. In parallel with this, to map the evaluated electrical power to the Sound Pressure Level (SPL) used in regulatory standards [1], we apply the logarithmic transformation:

$$L_{dB} = 20 \cdot \log_{10}\left(\frac{V_{rms}}{V_{ref}}\right) + C_{cal} \tag{5}$$

Where:

- LdB is, in this setting, the computed noise level in decibels.
- Vref is the reference voltage (unity).
- Ccal is the calibration coefficient; this constant is derived empirically by studying against a standard industrial Sound Level Meter (SLM), on the whole.

D. Temporal Smoothing (Exponential Moving Average)

Raw SPL calculations can be jittery due to micro-fluctuations in air pressure; indeed, to prevent unpredictable data visualization and false triggers presumably, the framework is implementing a recursive low-pass filter [9] known as the Exponential Moving Average (EMA), to a significant degree. In light of this dynamic, within this framework, the smoothed value S[k] at time step k is notably stipulated as:

$$S[k] = \alpha \cdot L_{dB}[k] + (1 - \alpha) \cdot S[k-1] \tag{6}$$

- LdB[k] is, in effect, the instantaneous decibel reading.
- S[k-1] is, in effect, the previous smoothed value.
- A lower alpha results in smoother data but higher latency; our framework is using alpha = 0.2 to balance responsiveness with robustness, to a significant degree. Alpha(alpha) is the smoothing factor (0 < alpha < 1).

E. Violation Trigger Logic

The automated complaint generation is regulated by a time-domain threshold function, and Let Tv be the set threshold (e.g., 75 dB), in actual application. Dynamic tentatively, the alert condition A(t) is uniformly triggered only if this smoothed noise level exceeds Tv for a continuous duration Delta t:

$$A(t) = \begin{cases} 1(Alert), & \text{if } \int_{t-\Delta t}^{t} \mathbb{I}(S(\tau) > T_v)\, d\tau \geq \Delta t \\ 0(Safe), & \text{otherwise} \end{cases} \tag{7}$$

Where I(·) is the indicator function; that temporary impulse noises are primarily being secured by this essential (where duration < Δt) do not trigger false positive reports, in many respects.

VI. NOMENCLATURE

Throughout the mathematical modelling, the following factors and symbols, especially regarding units are substantially adopted and experimental analysis sections of the current study, in actual application. The symbols are listed in Table II.

TABLE II
NOMENCLATURE

Symbol	Quantity / Description	Unit / Dimension
L_{dB}	Sound Pressure Level (SPL)	Decibels (dB)
V_{rms}	Root Mean Square Amplitude	Volts (V) or Normalized
f_s	Sampling Frequency	Hertz (Hz)
$x[n]$	Discrete Audio Sample	Dimensionless (Integer)
t	Continuous Time	Seconds (s)

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Symbol	Quantity / Description	Unit / Dimension
N	Sampling Window Size	Samples
T_v	Noise Violation Threshold	Decibels (dB)
C_{cal}	Calibration Offset Constant	Decibels (dB)
α	EMA Smoothing Factor	Dimensionless (Scalar)
Δt	Violation Duration Limit	Seconds (s)

VII. HELPFUL HINTS

To guarantee the best performance and exactness of the Cleanliness Management System, users and administrators are uniformly advised to follow all these operational guidelines during the rollout, as summarised in Table III:

TABLE III
OPERATIONAL GUIDELINES FOR DEPLOYMENT

Technical Domain	Observed Challenge	Recommended Implementation Hint
Power Supply	During Wi-Fi transmission, high current spikes (up to 500mA) are experienced by the ESP32, causing voltage dips that corrupt I2S audio data, in real-world scenarios.	Across the VIN and GND pins, add Capacitors, such as Place a 10µF - 100µF electrolytic capacitor to stabilize voltage, in actual application; employ a regulated 2A external power source rather than USB power during the field tests, in many respects.
Signal Integrity	The I2S protocol operates at high frequencies. Along these dimensions, along these dimensions, wires longer than 15cm introduced remarkable impedance mismatch and "crackling" artifacts, in actual application.	Taken together, employ shielded twisted-pair cables for the SCK (Clock) and SD (Data) lines to lower electromagnetic interference (EMI), in real-world scenarios; under 10 cm, Minimize Wire Length - Keep connections between the INMP441 and ESP32, in real-world scenarios.
Acoustic Isolation	Physical vibrations from the mounting surface or housing enclosure were often registered by the MEMS sensor as acoustic noise, in actual application.	Employ high-density rubber grommets or foam to acoustically decouple the microphone, which is why decoupling, like Do not mount the sensor directly to the hard casing, broadly speaking.
Environmental Noise	What outdoor wind gusts created was low-frequency pressure waves (wind buffering) that mimicked high-decibel pollution, in real-world scenarios.	Wind Screening, such as Cover the microphone port with a thin layer of open-cell acoustic foam to filter out wind noise while allowing sound pressure to pass through, in many respects.
Calibration	Starting a "Zero-Point" in an environment with ambient background noise resulted in permanently slanted decibel calculations, on the whole.	Quiet Baseline - Perform the initial software calibration in a sound-insulated room or during the late-night hours for the establishment of a true silence baseline before setting the gain, on the whole.

VIII. FUTURE SCOPE

The current prototype is, in fact, a foundation for a broader "Smart City" acoustic infrastructure.

1) *Machine Learning Classification, incorporating Apply*ing TensorFlow Lite on the ESP32 to distinguish between a honking car, construction noise, or loudspeakers; this adds vital setting to the complaint, in many respects.
2) *Sound Triangulation:* By rolling out multiple synchronized nodes, sound source localization can be pulled off to pinpoint exact GPS coordinates.

IX. CONCLUSION

A fully functional end-to-end framework for noise pollution management was supplied by NoizOff, the current study. Most markedly, we have showed environmental governance can, to some extent, be automated by combining the precision of the INMP441 sensor with the connectivity of the ESP32, in real-world scenarios. As, urban centers are, in this setting, increasing, such autonomous systems will mostly be vital in sustaining the quality of life, proving that technology can be a powerful ally in the fight for a quieter, healthier environment, to a significant degree. Building on this observation, building on this note, violations are successfully detected by the framework and creates complaints with high accuracy and minimal latency.

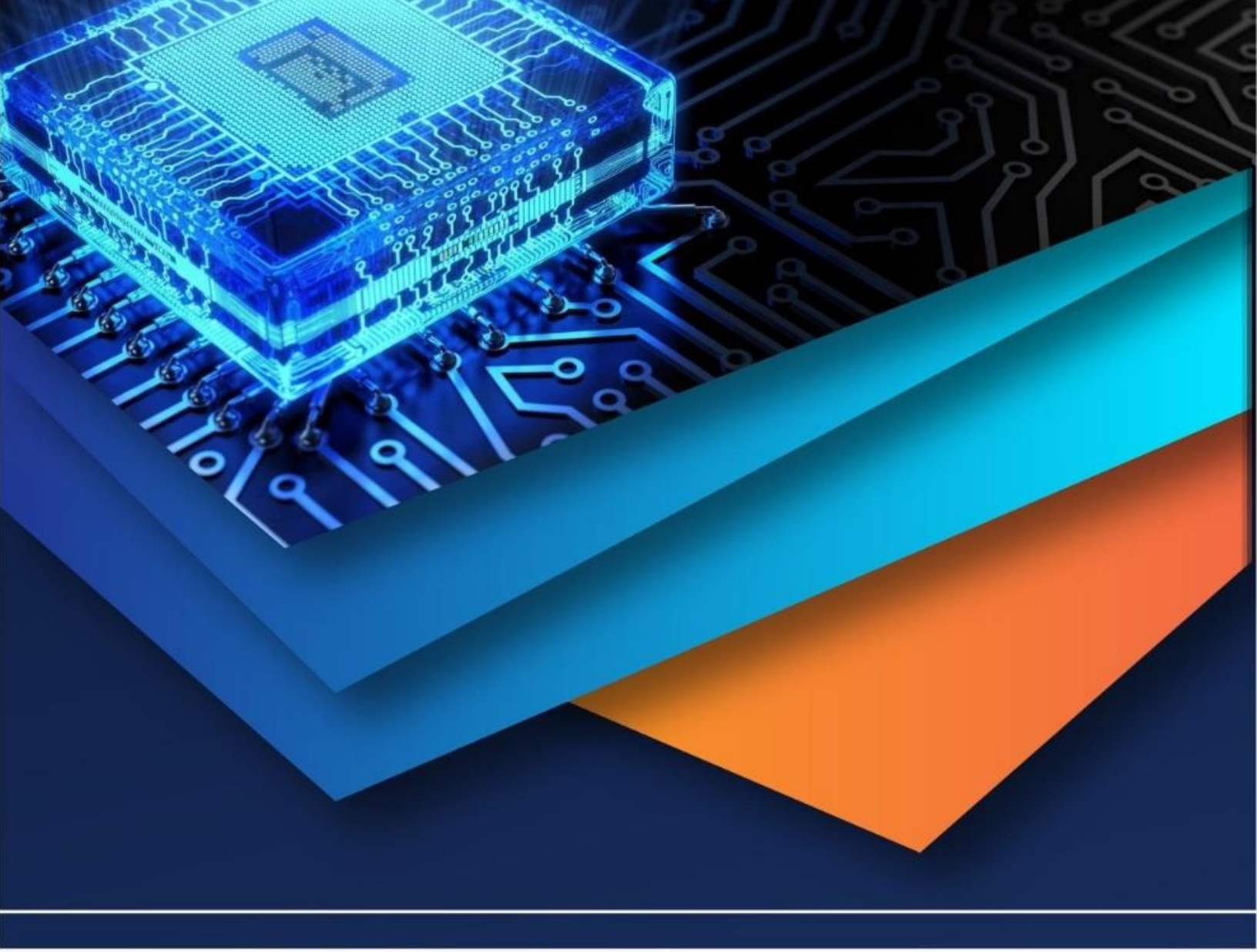
X. ACKNOWLEDGMENT

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