A Low-Cost, Off-the-Shelf Prototyping Platform for Molecular Communications Research

1st Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address or ORCID

2nd Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address or ORCID

3rd Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address or ORCID

4th Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address or ORCID

5th Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address or ORCID

6th Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address or ORCID

***Abstract*—While electromagnetic waves dominate the data communication arena in modern computing systems, they are unsuitable in environments requiring stringent electromagnetic interference control, such as covert operations, medical facilities, and sensitive research settings. Molecular communication (MC) is an alternative data communication paradigm that utilises the propagation of chemical molecules to carry modulated data. Implementation of MC systems demand expertise in specialised hardware and chemicals, thereby limiting its accessibility for researchers in communication and networks. This study addresses these challenges by developing a low-cost, ready-to-use research platform for rapid prototyping and experimentation. Utilizing Ethanol and Turpentine as the chemical agents and off-the-shelf gas sensors as receivers, the study explores the feasibility of establishing a wireless diffusion-based MC channel between computers. Through a series of experiments, the response of sensors to chemical molecules under various conditions were evaluated, demonstrating the effectiveness of the platform. The proposed platform, suitable for indoor environments, provides a foundational tool for further research in molecular data communication.**

***Index Terms*—Molecular Communication, Diffusion-based Propagation, Low-cost MC Platform, Off-the-shelf MC, On-Off Keying.**

I. Introduction

Communication is paramount to the sustainability of a society. Thereby, substantial amount of research followed by technical and technological enhancements can be found in the communication realm. Use of electromagnetic (EM) waves is the most dominant medium for communication in modern systems. However, there are environments where the use of EM waves is not suitable, such as covert operations, medical facilities, highly sensitive research experiment facilities, implant communication. Such environments require strict EM interference control [1]. Therefore, there has been a growing emphasis on finding alternative communication technologies among the stakeholders where molecular communication (MC) has drawn significant attention among researchers [2].

Inspired by the nature and observing how different biological organisms communicate, MC can be seen as a viable substitute for EM communication for specific needs and environments [2]. MC primarily resembles how biological organisms such as microbes, plants, etc. communicate by using compositions of different molecules (i.e., chemical signals) to exchange information [3]. This interdisciplinary field lies at the crossroads of engineering, communication technologies, biology, biochemistry, biotechnology, nanotechnology, and microfluidics, drawing contributions from each specialized area [4], [5].

MC can be classified into different subdomains and applications based on communication channel, propagation mechanism, and range. The establishment of any kind of physical connectivity between the transmitter and receiver is identified as a wiring mechanism where absence of such a guided channel is considered wireless communication [6]. Further, different propagation mechanisms would be employed based on the nature of the application requirements. The communication range of MC is identified to be short-range (nano) if the distance is measured in *nm*, mid-range (micro) if measured in μm to *cm*, and long-range (macro) if measured in *cm* to *m* [7].

The primary propagation mechanisms of MC include diffusion-based, flow-based, and active transport-based propagation mechanisms [8]. Diffusion-based communication relies on the passive movement of molecules from high to low concentration, making it suitable for short-range interactions [9]. Flow-based communication employs the directed movement of fluids to transport information-carrying molecules, offering enhanced control and stability in controlled environments [10]. Active transport mechanisms utilize molecular motors or biological machinery to actively deliver molecules to specific destinations, providing greater precision and timing control in molecular delivery [7].

Identify applicable funding agency here. If none, delete this.

Building MC channels require specialised hardware and chemicals. Unlike traditional wireless communication equipment, these hardware are bulky and requires careful handling. Furthermore, the use of hardware and chemicals in MC channels requires expertise on embedded systems development. Due to this reason, it is not straightforward for communication and networks researchers to conduct research on using MC for data communication. Under these circumstances, it is necessary to have ready-to-use research hardware platforms that facilitates the rapid prototyping and experimentation under a lower cost.

Towards this goal, this study aims at exploring the possibilities of establishing MC between two computers using a wireless diffusion mechanism using low-cost, off-the-shelf hardware components. As the target chemical agents in the proposed MC, Ethanol and Turpentine are used along with a collection of gas sensors. In order to explore the nature of the molecules in diffusion, a series of experiments were conducted to see how each sensor responds to the chemical molecules under varying conditions. The work presented in this paper makes the following contributions:

- Tests the effectiveness of off-the-shelf and low-cost chemical sensors to act as receivers in an MC channel, which will enable the large-scale deployment of MC receivers in real-world application scenarios.
- Empirically evaluates the capability of chemical molecules to carry information through diffusion. Ethanol and Turpentine, being volatile chemical agents that spread through diffusion, present the opportunity to be used as carriers of information in a diffusion-based molecular communication channel, which can be easily sourced from off-the-shelf market.
- Presents the design of a diffusion-based MC platform that is usable in indoor environments. The proposed platform uses off-the-shelf hardware and can be used as the basis for further research in molecular data communication.

II. Background and Related Work

A. Background

Recently, there is an inclination among researchers to explore the possibilities of communicating information using molecular communication to address the needs of sensitive environments [11]–[15]. Traditional communication relies on EM waves, enabling high-speed data transfer by encoding encoding them to the properties of EM waves. However, EM-based communication comes with drawbacks, such as high energy consumption [2]. In contrast, MC uses chemical substances as signals, encodes information through chemical states and processes, operates at slower speeds, and is much more energy-efficient. The noise of molecular communication channels arises from molecules and particles in the environment rather than from EM sources [2].

Initially, data is encoded into molecular signals according to a specific encoding scheme [2]. These molecules are then released into a transport medium, such as air or water, where they propagate through the medium via various transport mechanisms [16]. The variations in the concentration and distribution of the molecules convey the transmitted information. At the receiving end, sensors detect the molecular signals, measuring their concentration and spatial distribution. This data is then decoded to reconstruct the original information, utilizing the properties of molecular interactions with the sensors to enable effective communication [16].

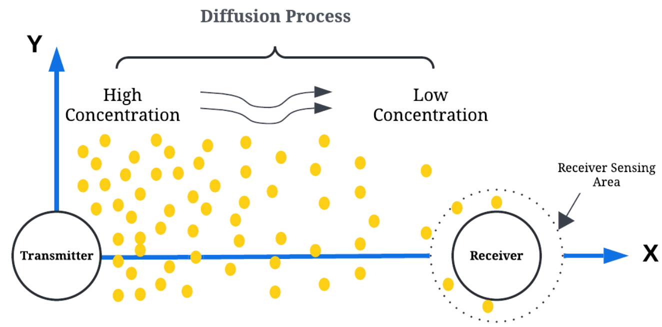


Fig. 1: Diffusion-based MC model that consists of a transmitter and receiver between which, molecules travel from high to low concentration. (adapted from [17])

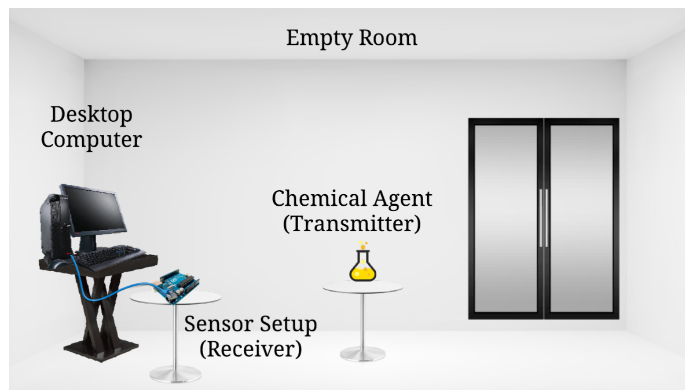


Fig. 2: Placement of hardware components in the experimental environment. The diffusive chemical agent, i.e., transmitter, is placed away from the sensor setup, i.e., receiver, attached to a computer.

Diffusion-based MC is the most widely used model for molecular transport mechanisms. This process, similar to radio communication in nature, enables the transmission of information in any direction without needing extra energy sources or communication infrastructure [9]. Free diffusion describes the movement of molecules from regions of high concentration to those of low concentration until equilibrium is reached, all occurring without chemical reactions [9]. Figure 1 illustrates the basic model of diffusion-based propagation of information in MC.

Alcohol, which includes various substances, such as Methanol (methyl alcohol), Ethanol (ethyl alcohol), Isopropanol (isopropyl alcohol), etc., has frequently been used as the chemical agent in diffusion-based molecular data communication studies [11], [18]–[21]. Capacity for rapid vaporization and stable vapor phase formation in Alcohols render as exceptionally favourable diffusion properties for enabling molecular data transmission through diffusion.

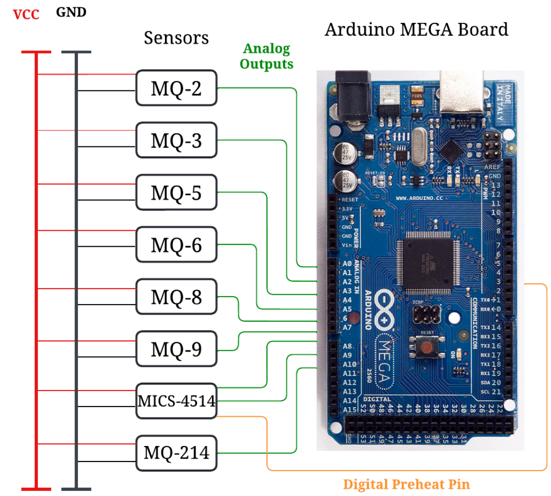
Modulation techniques in MC involve various strategies to encode and transmit information through chemical signals. Concentration-based modulation uses the concentration levels of molecules in the medium to represent different data values [8]. Type-based modulation differentiates between data symbols by utilizing distinct types of molecules [8]. Timing-based modulation encodes information based on the time intervals between the release of molecular signals [8]. Spatial modulation involves the position or movement of molecules within a given space to convey data. Meanwhile, higher-order modulation techniques combine these basic methods to enhance the capacity and reliability of molecular communication systems, enabling more complex and efficient data transmission.

B. Related Work

MC is quite challenging due to the influence of many different factors that the two communication end points may not have control of, i.e. within the communication channel alone, molecule diffusion may result in adding a number of variables in to the equation such as Brownian motion, advection factors, degradation and other affects through chemical reactions, etc. [22]. Therefore, most of the studies on MC are conducted in controlled and confined environments to minimize such affects on communication by using tubes, cylinders, or similar structures connecting sender and receiver, limiting the free-space spread of the chemical molecules in use. However, a few studies have used free diffusion of the chemical to the environment with air flow assisted propagation using electrical motor driven fans and were able to successfully send a text message to the receiver at a macro range [11].

Shakya et al. [14] have been able to identify transmitted molecules at meter-scale distances, using modulation rates as fast as 100 Hz using a tube guided flow of molecules which proves the possibility of information communication at significantly higher rates using MC. Daniel [12] has carried out a study to successfully increase the throughput of communication using multi-chemical transmission together with quadrature amplitude modulation on molecules. However, the studies used a confined tube analogous to a cable in a wired communication channel, such as Ethernet, where the molecule propagation happens through the flow flow of air inside the tube.

This work focuses on building an experimental setup in an indoor environment with atmospheric air without using any guided media or air flow control mechanism thus working only with the chemical's properties of diffusion and atmospheric conditions to study the possibilities of building an MC. Therefore, the conditions in this experimental setup is challenging but closely resembling a real-world application scenario. Thereby, this study reveal new avenues of using MC for information communication under realistic conditions.



(a) Connectivity of sensors to the Arduino MEGA board.

(b) Models of MQ series sensors used for experiments.

Fig. 3: Receiver hardware setup consisting of various sensors in the MQ series that are sensitive to various gases.

III. Proposed Approach

The research study aims to build a platform to systematically investigate the transmission of bit patterns through a chemical medium using diffusion-based MC in indoor environments. The initial phase involved an extensive literature review to identify appropriate methodologies and materials for the experiments. For preliminary experiments, Ethanol was selected as the primary chemical medium based on its established use in previous studies as an effective transmitter in MC systems [11], [18], [21]. In subsequent experiments, Turpentine was chosen due to its cost-effectiveness and widespread availability in the off-shelf market, making it a practical and accessible option. Turpentine typically includes a mixture of chemicals such as Acetone, Toluene, Xylene, and various Alcohols and Ketones [23].

The experimental setup included the deployment of an array of sensors at the receiving end to detect the transmitted chemical signals. The selection of these sensors was guided by a review of relevant literature and other scholarly sources to ensure they were capable of accurately capturing the transmitted data. Multiple experimental trials were conducted to test the transmission of data through the chosen chemical medium. During each trial, detailed data from the sensors was logged to record signal reception and transmission performance.

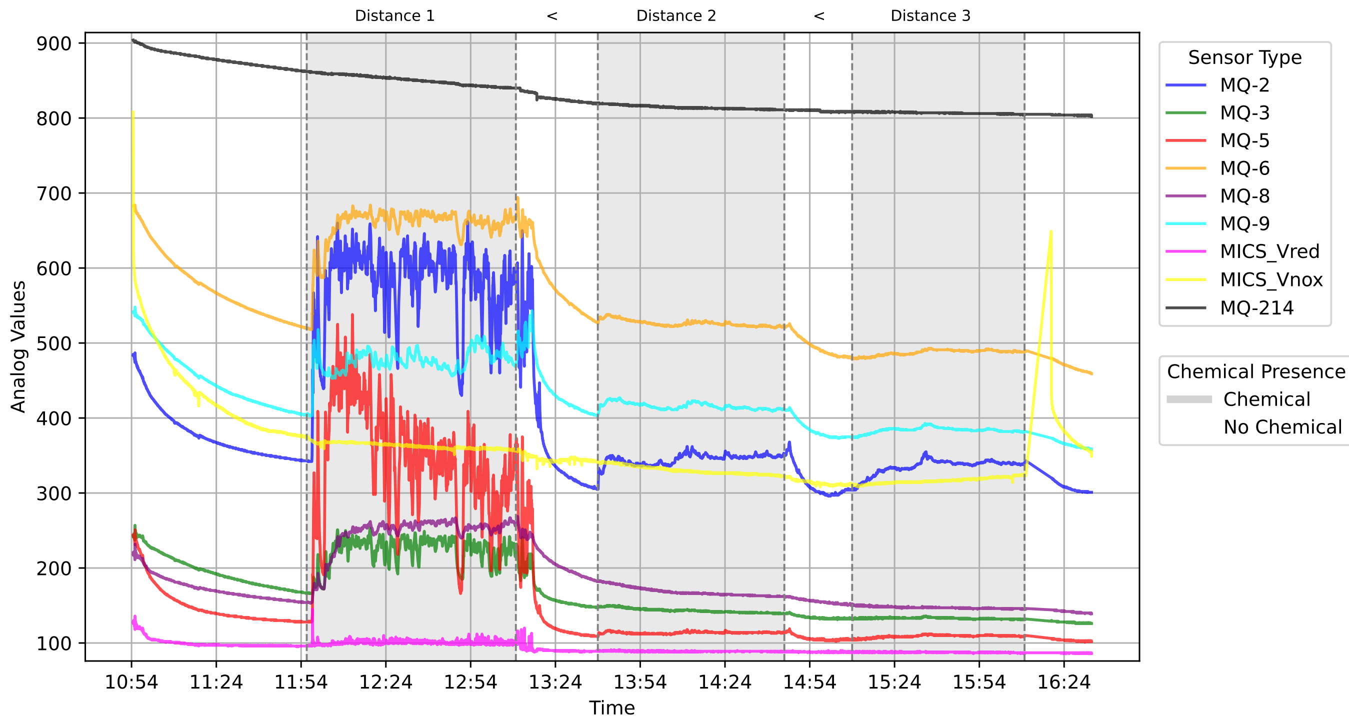


Fig. 4: Readings of sensor data with and without Ethanol exposure in hourly intervals and at varying distances. The sensors MQ-2, MQ-6, and MQ-9 are exhibiting strong sensitivity to Ethanol at longer distances in contrast to others.

Subsequent to data collection, a thorough analysis was performed to assess the efficacy and reliability of the diffusion-based MC system. This analysis encompassed evaluating parameters such as bit rate, transmission consistency, and overall system efficiency.

A. Experimental Setup

The overall experimental setup involved storing the chemical of interest in an isolated space, equipped with a sensor array capable of detecting it's presence in the atmosphere. The sensors were connected to a computer system that continuously recorded data from each sensor. Two primary modes of experimentation were conducted with the chemical: continuous exposure to assess sensor sensitivity and intermittent exposure to study diffusion patterns over time. Both the chemical source and the sensor array were positioned at identical heights to ensure the measurement of horizontal communication, as depicted in Figure 2.

1) Receiver: The sensor setup comprised 8 sensors: MQ-1, MQ-214, MQ-3, MQ-5, MQ-6, MQ-8, MQ-9, and MICS-4514, as shown in Figure 3b. With the exception of the MICS-4514, all sensors belong to the MQ series sensors. Previous in the literature indicates common usage of the MQ-3 sensor in Ethanol detection, prompting inclusion of other MQ series sensors to broaden the dataset and assess their respective sensitivities. Their wide sensitivity to volatile organic compounds (VOCs), as shown in Table I, enables them to detect substances such as Turpentine as well. The operational principle of MQ sensors are based on the detection of changes in electrical conductivity upon interaction with specific gases [24]. In contrast, the MiCS-4514 utilizes a compact metal oxide (MOS) sensor design with two independent sensing elements, Vnox and Vred, integrated into a single package. This sensor uses micro electro mechanical system (MEMS) technology that enables the detection of concentration of a range of gases including CO, C_2H_5OH (alcohol), H_2, NO_2, and NH_3 [25].

Each of these sensors are producing analog outputs that can be read through a microcontroller platform for processing. For this purpose, an Arduino MEGA2560 embedded device featuring an ATmega2560 microcontroller was used. Figure 3a illustrates the wiring of the sensors to the embedded device where their analog output are directly read by the Arduino device's general-purpose input and output (GPIO) ports. A

TABLE I: The considered sensors of the MQ series and the gases they are capable of detecting. (adapted from [24])

Sensors	Detectable Gases
MQ-2	LPG, i-butane, propane, methane (CH_4), alcohol, hydrogen (H_2), smoke
MQ-214	methane (CH_4), LPG, i-butane, propane
MQ-3	alcohol, benzene, methane (CH_4), hexane, LPG, carbon monoxide (CO)
MQ-5	LPG, natural gas, town gas
MQ-6	LPG, iso-butane, propane, LNG
MQ-8	Hydrogen (H_2)
MQ-9	Carbon Monoxide (CO) and methane (CH_4), LPG

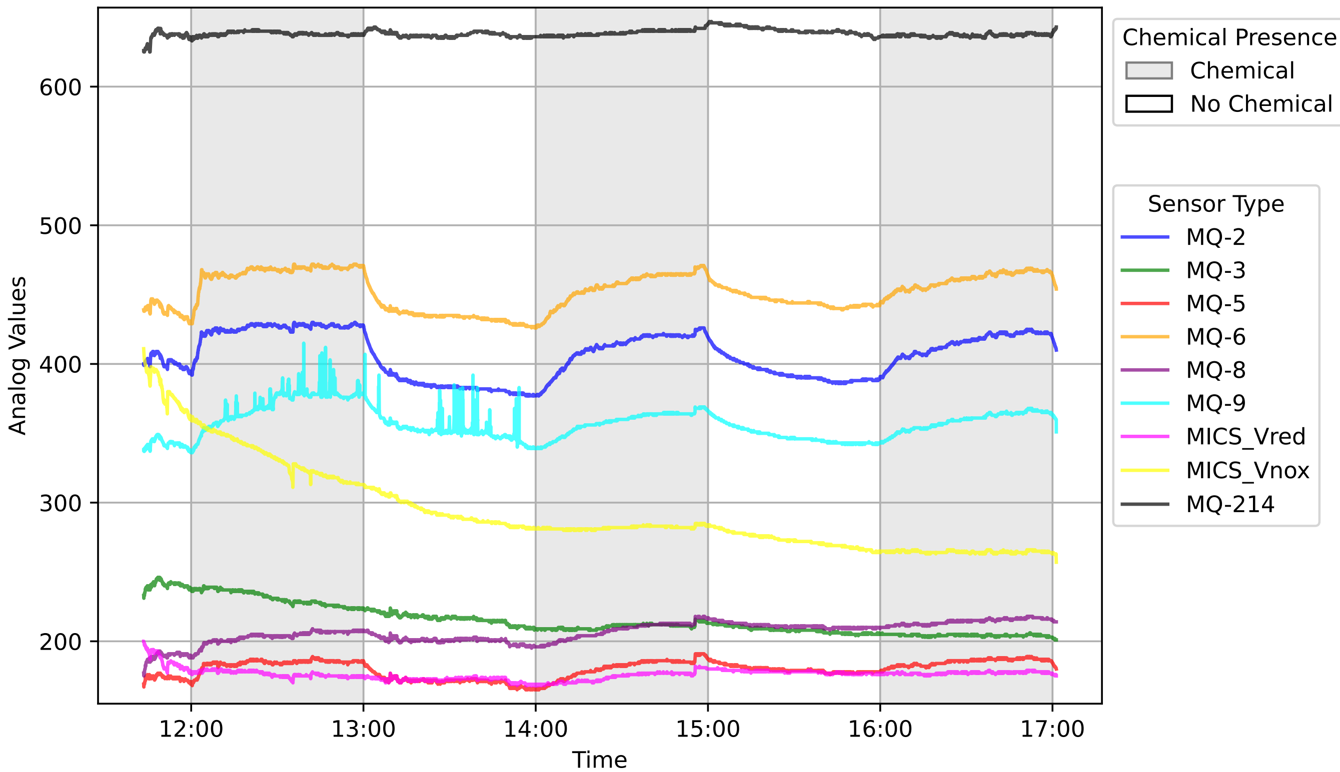


Fig. 5: Readings of sensor data at hourly time intervals capturing an alternative 1 and 0 pattern using Ethanol. The sensors MQ-2, MQ-6, and MQ-9 continues to demonstrate a consistent sensitivity across time.

firmware written for the Arduino device is deployed to continuously read sensor output and transfer data to the connected computer through its USB port. A Python script running on the computer captures the incoming stream of data through the USB port and saves them to a log file along with time stamps in comma-separated value (CSV) format.

2) Transmitter: The role of the transmitter is to release chemical molecules in a controlled manner to represent data in the MC medium. In order to keep the experimental setup easy to handle under low data rate transmissions, a simple mechanical procedure was used to control the opening and closing of the lid of chemical container. No force, such as air flow or heat, was used to induce the diffusion; thus, natural chemical diffusion occurred at room temperature when the container lid was open.

3) Channel: No specific channel or flowing mechanism is assembled, thus the chemical diffuses freely into the open air of the confined room without any induced force.

IV. Evaluation and Results

A. Sensitivity of Gas Sensors

To determine the sensitivity of the receiver hardware to the presence of the chemical molecules, Ethanol was diffused from the transmitter to the atmosphere at hourly intervals. Furthermore, the distance between the chemical transmitter and the sensor receiver was varied to observe its impact to the detectability of the molecules.

Initially, the chemical was diffused from about 30cm away from the sensor receiver setup (by opening the container lid) in a closed room for approximately one hour. After this exposure, the chemical diffusion was stopped (by closing the container lid) and the room was ventilated. Afterwards, the chemical was placed further away from the sensor, and the experiment was repeated. This process was carried out multiple times to ensure the accuracy and consistency of the results.

The overall results indicate that most sensors are sensitive to Ethanol, and their readings vary with distance, as illustrated in Figure 4. The sensors MQ-2, MQ-6, and MQ-9 exhibit clear changes in sensitivity to the chemical at different distances in contrast to the other sensors. Conversely, the sensor MQ-5 demonstrates sensitivity primarily at close ranges The MICS-4514 and MQ-214 sensors did not show satisfactory sensitivity to Ethanol.

B. Slow-rate Data Transmission

Based on the insights gained by the previous experiment, an attempt was made to transfer a fixed bit pattern of alternating 1s and 0s through the MC. For this purpose, a modulation scheme of on-off keying (OOK) was used where digit 1 was represented by the emission of chemical molecules for a time period of 1 hour, and the digit 0 was represented using the absence of chemical molecule emission for a time period of

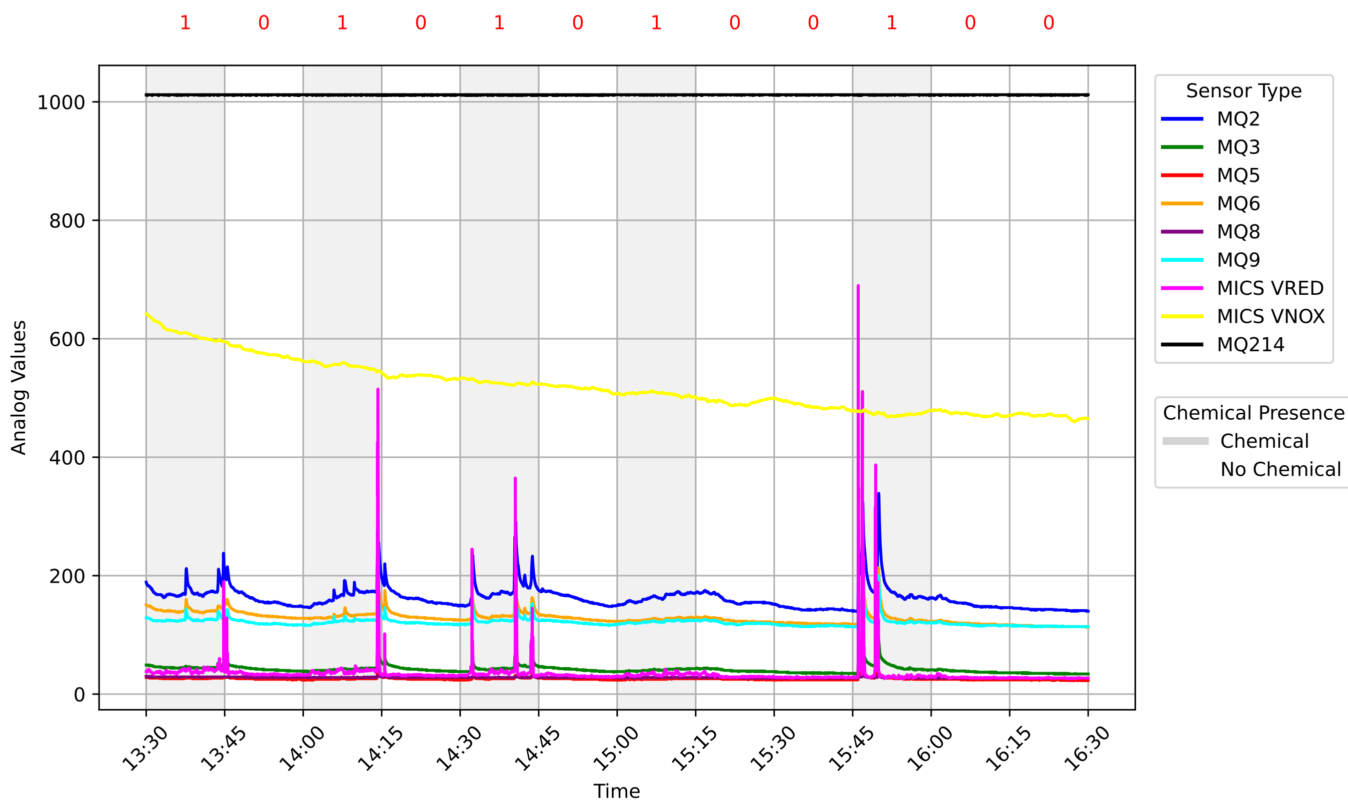


Fig. 6: Readings of sensor data when transmitting Hamming-encoded data using Turpentine molecular signals.

1 hour. Effectively, the channel was supposed to transfer bits in the physical medium at a rate of 1 bit per hour.

This experiment was conducted by positioning the Ethanol-diffusing transmitter at a fixed distance from the sensor setup in a closed room for approximately one hour, during which the sensor monitored and recorded any changes induced by the chemical. After this observation period, the chemical was removed, and the room was ventilated to eliminate any remaining traces. Following ventilation, the chemical was reintroduced into the environment at the same distance from the sensor, and the experiment was repeated. This process aimed to evaluate the feasibility of transmitting a bit pattern through the chemical medium, assessing the sensors' ability to detect and interpret these signals effectively.

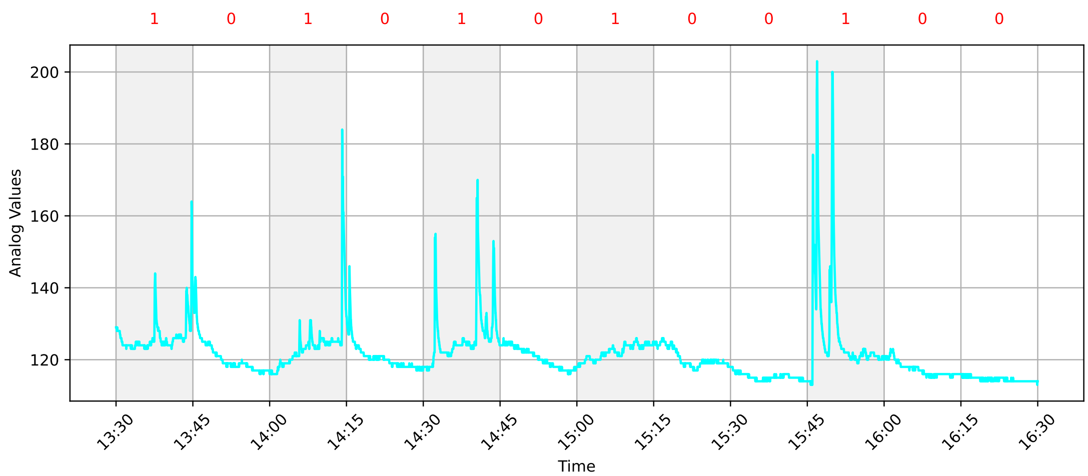
The results gained by this experiment were promising and demonstrated a significant elevation in sensor readings when the chemical is introduced to the medium in alternating time periods as illustrated in Figure 5. Notably MQ-2 and MQ-6 sensors as showing discernible patterns in their output. Although with rapid variations, MQ-9 sensor is also continuing to demonstrate its capability to detect Ethanol cross time windows.

C. Fast-rate Data Transmission

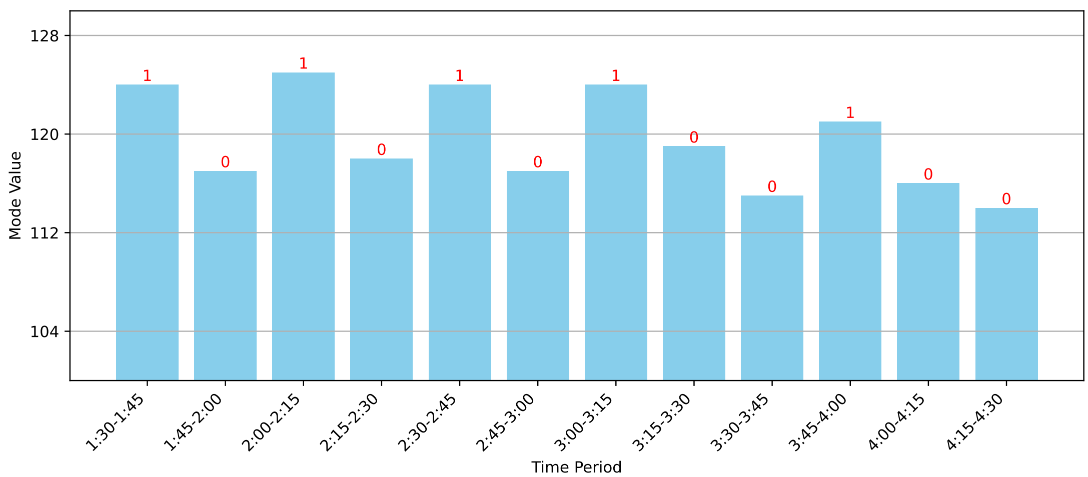
The results from the previous experiment indicates that it is possible to transfer data with OOK modulation, as long as the rate is maintained at a significant low value, such as 1 bits per hour. In order to transfer data in faster rates, it is necessary to reduce the time duration of chemical emission from 1 hour to smaller windows. Furthermore, attempting to achieve faster data rates can increase the possibility of erroneous detection of bits at the receiver. Mechanisms to mitigate such errors by detecting and correcting them is necessary when building faster MC channels. Towards this goal, in this experiment, a faster data transmission was tested with error detection and correction using Hamming codes.

An alternating sequence of 1s and 0s, similar to the previous experiment was considered, with a length of 8 bits as the data to be transmitted, i.e., `10101010`. By using $Hamming(12, 8)$ coding scheme, the original data were converted to a sequence of 12 bits which consists of the original 8 bits of data and additional 4 parity bits for error check, i.e., `101010100100`. When these bits are transmitted through the MC and received at the other end, it is possible to correct single bit errors and, at least, detect multiple bit errors. It helps to improve the robustness of the MC under noisy and uncertain conditions.

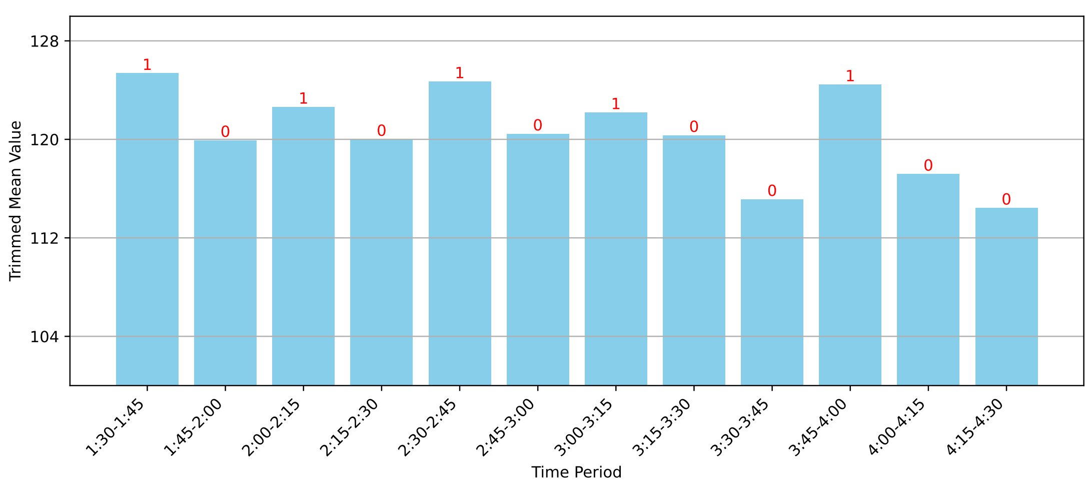
For the purpose of this experiment, Turpentine purchased from the off-the-shelf market was chosen, which is available in larger quantities for cheaper cost, hence more applicable in real-world large-scale MC implementations. Preliminary observations were conducted to confirm that the sensor setup was capable of detecting Turpentine, similar to Ethanol-based experiments. To make the experimental setup even more real-



(a) Analog values of MQ-9 sensor when transmitting hamming-encoded bit pattern using thinner.



(b) Mode values of MQ-9 sensor when transmitting hamming-encoded bit pattern using thinner.



(c) Trimmed mean values of MQ-9 sensor when transmitting hamming-encoded bit pattern using thinner.

Fig. 7: Readings of MQ-9 sensor when transmitting hamming-encoded bit pattern using thinner.

istic, this experiment was conducted in an indoor environment where doors and windows were kept open throughout the experimental procedure to allow external factors, such as wind, temperature, and humidity conditions change freely without any control.

The time window for a single bit transmission was set to an ambitious 15 minutes, which is significantly slower than the 1-hour window in the previous experiments. During the experimental procedure, Turpentine was diffused into the air to represent a bit value of `1`, while diffusion was halted to signify a bit value of `0`. The Turpentine diffused passively into the air whenever the lid of the transmitter was opened, with no additional force applied to control the process. A fixed distance of approximately 1 meter was maintained between the chemical transmitter and the sensor receiver setup throughout the entire procedure.

Overall, it was observed that the majority of sensor readings increased during the period when the thinner was diffused, with some readings showing significant increases while others showed slight increases as illustrated in Figure 6. However, the exact transmitted bit pattern is not visibly observable in the detected chemical signals on the sensors. Upon cessation of the diffusion, these readings generally decreased. Notable exceptions to this pattern were the MQ-214 sensor and the Vnox sensor within the MiCS-4514. The MQ-9 sensor, in particular, demonstrated exceptionally impressive results, as depicted in Figure 7. Even with the MQ-9 sensor, due its noisy nature of the output signal, it was not straightforward to extract the modulated bits out of it. Therefore, the following strategy was used. For each time window of data transmission, the received data samples were aggregated separately to obtain different statistical properties as representatives for each time window. Among these representatives, the mode and trimmed mode[1] proved to be ideal representatives of the samples in each time window as it was discovered empirically. Based on these values, it was possible to distinguish the individual data bits that are received at each time window based on the received value's amplitude.

Although the transmitted data consisted of a Hamming-encoded bit sequence, the extracted data by visual observation at the receiving end indicates that all bits can be successfully received for MQ-9 sensor without any errors. However, if the bit extraction procedure was to be automated, a threshold value should have defined to filter out the mode and trimmed mean values in the resulting graphs to determine a particular bit is either `0` or `1`. The closeness of the values in the resulting graphs indicate that this threshold value need to be carefully selected to distinguish bits with minimum errors. Once the bit pattern is recovered, if any errors present, they can be detected and corrected due to the use of Hamming codes. In this particular preliminary experiment, it was not required as all the original 8 bits, i.e., `10101010`, could be retrieved straightforwardly.

[1]A technique for averaging that eliminates a small proportion of both the highest and lowest values before computing the mean.

D. Discussion

Wireless communication systems that uses EM spectrum as the medium can operate simply using a supply of electricity without any other resources. In contrast, systems that uses MC channels for data transfer depletes chemical resources that are carrying information from a transmitter to the receiver. Due to this reason, it is necessary for MC channels to use chemicals that are lower in cost and easy source for refilling transmitter endpoint; use of an expensive or difficult to find chemical means, the MC system becomes unsustainable in the long run. In this work, the initial use of Ethanol proved to be effective in transferring data through the diffusion-based channel. However, since Ethanol is relatively expensive and difficult to obtain in sufficiently large quantities, the later focus was laid on Turpentine, which is readily available in off-the-shelf markets for a significantly lower cost.

Gas sensors of the MQ series (and many other similar sensors) does not become fully functional as soon as they are powered up. These devices require a pre-head time period during which, their internal components are heated up to a particular temperature, before they become usable. During experiments, it was notes that different sensors have different pre-heat time periods; without providing thse required pre-heat times, the output of sensors are less reliable and mostly erroneous. As a workaround, experimentation in this work were preceded by a long pre-heat time period provided to the entire collection of sensors, often amounting to a 1 hour. In real-world deployments of MC systems that uses similar gas sensors, it would be necessary to precisely time the required pre-heat time period before they are used.

The sensors of the MQ series available in the market may not always be coming from its original manufacturer. There are various counterfeit components available in the market that are indistinguishable from the original components. Due to this reason, there is no guarantee that different samples of the same sensor model will exhibit the same sensitivity and chemical detection behaviour as discovered through experimentation. Therefore, it is necessary to ensure the authenticity of sensors used in an implementation of an MC system. Another workaround to this issue of behavioural diversity of components can be to employ a fleet of sensors of the same model at the receiver, and then, extracting a collective representation of their readings, such as statistical average or other value.

When a transmitted signal consists of multiple consecutive `1` or `0` values, it has the possibility to affect the detectability of the next different bit transmitted by the channel. For example, consider a situation where two consecutive `0` bits are transmitted by the absence of any chemical emissions in two consecutive time intervals. This depletes the atmosphere of the carrier molecules due to a longer time period of non-emission. When a digit `1` is transmitted next by emitting chemical molecules, the receiving end expects to see a larger dose of molecules for detecting that signal. The opposite of this phenomena is also possible where a digit `0` would be indistinguishable if multiple consecutive digit 1s have filled the atmosphere with a large quantity of chemical molecules. This phenomena, called inter-symbol interference (ISI) is a challenge that requires sophisticated data encoding and modulation techniques at the physical layer of MC channels for effective mitigation.

The key focus of this was on evaluating the diffusion-based propagation and the detectability of molecular signals at the receiving end. An aspect that was not explored in this work is the design and functionality of the molecular transmitter endpoint. Due to the use of relatively slow data rates in this work, the molecular transmitter could be mechanically controlled by opening and closing the lid of chemical container at a manageable speed. However, going forward to higher data rates, it is necessary to build diffusion-based molecular transmitters that can automatically release and block molecular diffusion to the atmosphere with fine-grained quantities and time intervals.

V. Conclusion

Molecular communication has gained attention as a viable alternative to traditional electromagnetic wave-based communication, particularly in environments where electromagnetic signals face interference or attenuation, such as areas with high noise or obstructive materials. Implementing MC often requires specialized hardware, embedded systems expertise, and a background in chemistry, which can complicate research efforts for network researchers. To address these challenges, our study introduced a ready-to-use and cost-effective research platform that simplifies the exploration of MC. This platform utilizes inexpensive sensors as receivers and common chemical agents like ethanol and thinner, employing free diffusion as the primary propagation method. We conducted experiments to assess sensor sensitivity to chemicals at various distances, transmitted binary data through chemical diffusion, and tested Hamming-encoded ASCII data transmission. The results demonstrated successful reception of the transmitted bit patterns, and the experiments effectively simulated real-world conditions by allowing free diffusion at room temperature.

Acknowledgment

References

[1] L. Felicetti, M. Femminella, G. Reali, and P. Lio, "Applications of molecular communications to medicine: A survey," *Nano Communication Networks*, vol. 7, pp. 27–45, Mar. 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1878778915000411

[2] T. Nakano, A. W. Eckford, and T. Haraguchi, *Molecular Communication*. Cambridge: Cambridge University Press, 2013. [Online]. Available: https://www.cambridge.org/core/books/molecular-communication/D3888016ED63B605D25B48406C68DAC3

[3] D. Bi, A. Almpanis, A. Noel, Y. Deng, and R. Schober, "A Survey of Molecular Communication in Cell Biology: Establishing a New Hierarchy for Interdisciplinary Applications," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 3, pp. 1494–1545, 2021. [Online]. Available: https://ieeexplore.ieee.org/document/9378780/

[4] D. Bi, Y. Deng, M. Pierobon, and A. Nallanathan, "Chemical Reactions-Based Microfluidic Transmitter and Receiver Design for Molecular Communication," *IEEE Transactions on Communications*, vol. 68, no. 9, pp. 5590–5605, Sep. 2020. [Online]. Available: https://ieeexplore.ieee.org/document/9090868/

[5] T. Stefanic, "Molecular communication a new nanotechnology health frontier," Jun. 2024. [Online]. Available: https://eng.unimelb.edu.au/ingenium/health-technologies/molecular-communication-a-new-nanotechnology-health-frontier

[6] L. Parcerisa Giné and I. F. Akyildiz, "Molecular communication options for long range nanonetworks," *Computer Networks*, vol. 53, no. 16, pp. 2753–2766, 2009. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1389128609002540

[7] N. Farsad, H. B. Yilmaz, A. Eckford, C.-B. Chae, and W. Guo, "A Comprehensive Survey of Recent Advancements in Molecular Communication," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 3, pp. 1887–1919, 2016. [Online]. Available: http://ieeexplore.ieee.org/document/7405285/

[8] M. S. Kuran, H. B. Yilmaz, I. Demirkol, N. Farsad, and A. Goldsmith, "A Survey on Modulation Techniques in Molecular Communication via Diffusion," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 1, pp. 7–28, 2021. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/9311804

[9] J. Wang, B. Yin, and M. Peng, "Diffusion based molecular communication: principle, key technologies, and challenges," *China Communications*, vol. 14, no. 2, pp. 1–18, Feb. 2017. [Online]. Available: https://ieeexplore.ieee.org/document/7868158/

[10] W. Wicke, T. Schwering, A. Ahmadzadeh, V. Jamali, A. Noel, and R. Schober, "Modeling Duct Flow for Molecular Communication," in *2018 IEEE Global Communications Conference (GLOBECOM)*, Dec. 2018, pp. 206–212, iSSN: 2576-6813. [Online]. Available: https://ieeexplore.ieee.org/document/8647632

[11] N. Farsad, W. Guo, and A. W. Eckford, "Tabletop Molecular Communication: Text Messages through Chemical Signals," *PLoS ONE*, vol. 8, no. 12, p. e82935, Dec. 2013. [Online]. Available: https://dx.plos.org/10.1371/journal.pone.0082935

[12] D. T. McGuiness, "Macro-scale molecular communications," Ph.D. dissertation, 2020, aAI28179553.

[13] M. Ozmen, E. Kennedy, J. Rose, P. Shakya, J. K. Rosenstein, and C. Rose, "High Speed Chemical Vapor Communication Using Photoionization Detectors," in *2018 IEEE Global Communications Conference (GLOBECOM)*. Abu Dhabi, United Arab Emirates: IEEE, Dec. 2018, pp. 1–6. [Online]. Available: https://ieeexplore.ieee.org/document/8647736/

[14] P. Shakya, E. Kennedy, C. Rose, and J. K. Rosenstein, "Correlated Transmission and Detection of Concentration-Modulated Chemical Vapor Plumes," *IEEE Sensors Journal*, vol. 18, no. 16, pp. 6504–6509, Aug. 2018. [Online]. Available: https://ieeexplore.ieee.org/document/8395272/

[15] W. Guo, M. Abbaszadeh, L. Lin, J. Charmet, P. Thomas, Z. Wei, B. Li, and C. Zhao, "Molecular Physical Layer for 6G in Wave-Denied Environments," *IEEE Communications Magazine*, vol. 59, no. 5, pp. 33–39, May 2021. [Online]. Available: https://ieeexplore.ieee.org/document/9446692/

[16] Y. Moritani, S. Hiyama, and T. Suda, "A Molecular Communication System," in *Natural Computing*, F. Peper, H. Umeo, N. Matsui, and T. Isokawa, Eds. Tokyo: Springer Japan, 2010, vol. 2, pp. 82–89. [Online]. Available: https://link.springer.com/10.1007/978-4-431-53868-4_9

[17] H. ShahMohammadian, G. G. Messier, and S. Magierowski, "Optimum receiver for molecule shift keying modulation in diffusion-based molecular communication channels," *Nano Communication Networks*, vol. 3, no. 3, pp. 183–195, Sep. 2012. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S187877891200035X

[18] M. Dash and T. Panigrahi, "Molecular Communication via Diffusion—An Experimental Setup using Alcohol Molecule," in *Advances in Intelligent Computing and Communication*, M. N. Mohanty and S. Das, Eds. Singapore: Springer Nature Singapore, 2022, vol. 430, pp. 299–307. [Online]. Available: https://link.springer.com/10.1007/978-981-19-0825-5_32

[19] B.-H. Koo, C. Lee, H. B. Yilmaz, N. Farsad, A. Eckford, and C.-B. Chae, "Molecular MIMO: From Theory to Prototype," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 3, pp. 600–614, Mar. 2016. [Online]. Available: http://ieeexplore.ieee.org/document/7397863/

[20] S. Giannoukos, D. T. McGuiness, A. Marshall, J. Smith, and S. Taylor, "A Chemical Alphabet for Macromolecular Communications," *Analytical Chemistry*, vol. 90, no. 12, pp. 7739–7746, Jun. 2018. [Online]. Available: https://pubs.acs.org/doi/10.1021/acs.analchem.8b01716

[21] A. O. Kislal, B. C. Akdeniz, C. Lee, A. E. Pusane, T. Tugcu, and C.-B. Chae, "ISI-Mitigating Channel Codes for Molecular Communication Via Diffusion," *IEEE Access*, vol. 8, pp. 24 588–24 599, 2020. [Online]. Available: https://ieeexplore.ieee.org/document/8972472

[22] V. Jamali, A. Ahmadzadeh, W. Wicke, A. Noel, and R. Schober, "Channel Modeling for Diffusive Molecular Communication—A Tutorial Review," *Proceedings of the IEEE*, vol. 107, no. 7, pp. 1256–1301, Jul. 2019. [Online]. Available: https://ieeexplore.ieee.org/document/8742793/

[23] "Paint Thinner - an overview | ScienceDirect Topics." [Online]. Available: https://www.sciencedirect.com/topics/materials-science/paint-thinner

[24] "All About MQ Series Gas Sensor," Jun. 2024. [Online]. Available: https://robocraze.com/blogs/post/mq-series-gas-sensor

[25] "MiCS 4514 Gas Sensor." [Online]. Available: https://esphome.io/components/sensor/mics_4514.html