Air Purifier with Thermoelectric Cooling and Advanced Air Monitoring Sensors

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Global air pollution presents a pressing concern impacting human well-being. The growing emphasis on indoor air quality (IAQ) and heightened demands for enhanced home comfort have fueled interest in innovative solutions. This research introduces a comprehensive system integrating real-time monitoring, air purification, and cooling technologies using sensors, filters, Ultraviolet light, and a Peltier Module. Effectively eliminating indoor pollutants like dust and microparticles, the device is equipped to detect smoke, methane, LPG, and carbon monoxide, while monitoring temperature and humidity. Post-purification, the air undergoes partial chilling for improved interior temperatures. Operated through a manual remote control and the 'BLYNK I. O. T. ' Android application, The system enables remote operation over long distances, extending its functionality to operate seamlessly through the internet. Assessments indicate a temperature decrease of 5.7 ^{0}C in real-time monitoring accuracy. Furthermore, the project incorporates automated control functions for the cooling system, humidifier activation, and alarm notifications, responding from the output of the sensors. This holistic approach showcases the potential for future advancements in IAQ solutions and Heating, Ventilation, and Air Conditioning (HVAC) technologies.

Keywords: air purifier, BLYNK I. O. T., Peltier Module, thermoelectric coolers.

1. Introduction

The increasing demand to ensure an appealing indoor atmosphere is vital for general welfare, particularly in areas characterized by significant temperature fluctuations. Indoor air pollution presents a substantial risk to human health, as it contains a range of harmful substances including particulate matter, volatile organic compounds (VOCs), and allergens. These pollutants can lead to respiratory problems and other health issues. This leads to the rise in indoor air pollution that has led to severe concerns for elderly people, infants, and asthmatic patients even if they stay back at home [1], [2].

Additionally, Modern air purification systems and cooling technologies often function separately, requiring the use of numerous devices and energy sources [3]. This can result in inefficiency and inconvenience. To tackle these challenges, the integration of these systems into a single, efficient solution has become a priority for many researchers and engineers. Innovative air filtration and cooling systems can enhance home comfort and energy efficiency.

Panicker et al. [4] created a prototype for filtering the air in confined spaces. They used an Arduino UNO microprocessor and optical dust sensors to automatically purify the air according to predetermined air quality levels. The system comprises pre-filter, dust filter, and fine filter components housed in a wooden body created specifically for filtering purposes. This study primarily emphasized air filtration and did not consider other variables such as temperature or humidity regulation. Similarly, Al Talib et.al. [5] studied a prototype for a solar-powered air purifier, equipped with HEPA and carbon filters, demonstrating its self-sustainability and air purification capabilities.

The study of Bielinski [6] entitled “Thermoelectric cooling system” explores the involvement of a control assembly and a direct current power source, facilitating thermal flow across a module with heat sinks and sources. Relay and thermocouple were employed to prevent thermal reversal, and moisture control measures like metal straps or pads to manage humidity and optimize cooling efficiency. Despite moisture control measures like metal straps and pads integration in these devices, the water-cooling system was still an advantage for it is efficient heat dissipation and precision temperature control is essential for overclocked or high-performance computing systems, as it ensures components stay within optimal temperature ranges.

Salsabila et al. [7] conducted an experiment of the Thermoelectric Cooler Module, observing its performance under varying input power levels. Their findings revealed a positive correlation between input power and both the performance coefficient value and cooling capacity. This suggests that the thermoelectric module exhibits favorable characteristics, particularly for applications requiring cooling below ambient temperatures.

Furthermore, Chein and Huang [8] discuss the utilization of thermoelectric coolers (TECs) for electronic cooling purposes. They proposed that to fulfill the demand for low thermal resistance heat sinks when TECs are operating at their maximum cooling capacity, it is advisable to employ a heat sink incorporating either water or air as the cooling medium.

Mahesh [9] explores the integration of a self-sustainable air purifier and integrated air-cooling system, focusing on its sustainability and efficiency. Mahesh's study on the self-sustainable air purifier with an integrated air-cooling system incorporates air purification technologies like HEPA filters, UV-C light, or activated carbon, combined with a thermoelectric cooling system utilizing the Peltier effect and E’SHWASA. However, akin to other research studies, the constrained computational capabilities of Arduino render it unsuitable for intricate applications such as a self-sustainable air purifier and integrated air-cooling system. Choudhary et al. [10] demonstrate in the study that they have created an air purifier for the Internet of Things (IoT) that uses a High Efficiency Particulate Air (HEPA) filter and ultraviolet (UV) radiation to purify indoor air. By providing a mobile phone platform that operates over Wi-Fi, customizing IoT technology simplifies the process of manually operating the purifier.

This study aims to build on the attributes found in those earlier studies while adding filtration, cooling, gas monitoring, and an Internet of Things (IoT) using Raspberry Pi as a microcontroller. The objectives of this study are (1) to design, build, and test an integrated air purifier based on HEPA filter and Activated Carbon filter; (2) to design, build, and test the cooling system using a thermoelectric cooling system; (3) to test and evaluate its performance by measuring how quickly it responds to changes in temperature, humidity, and gas detection.

2. METHODOLOGY

This part offers a detailed summary of the advanced air purification system that incorporates thermoelectric cooling and advanced air monitoring sensor technology.

A. System Flow

Fig. 1 Illustrates the conceptual framework for improving indoor air quality and comfort through an integrated air purification system with thermoelectric cooling and advanced air monitoring sensor technology. A smart control unit processes the air quality data that this system incorporates from sensors and environmental inputs. The control unit communicates with air purification components and thermoelectric cooling systems.

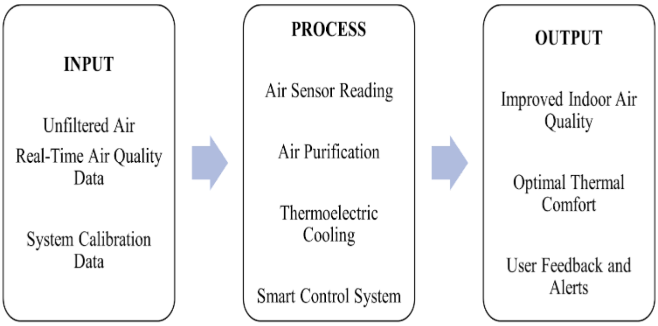

Fig. 1. System Flow

B. Feedback and Control Block Diagram

In Fig. 2, it is shown that the air enters the air inlet, where it is monitored by the Temperature sensor and gas sensor. The air then passes through integrated filters consisting of a pre-dust filter, activated carbon filter, and HEPA filter. Subsequently, the air undergoes the UV purification process and proceeds to the cooling stages before reaching the air outlet.

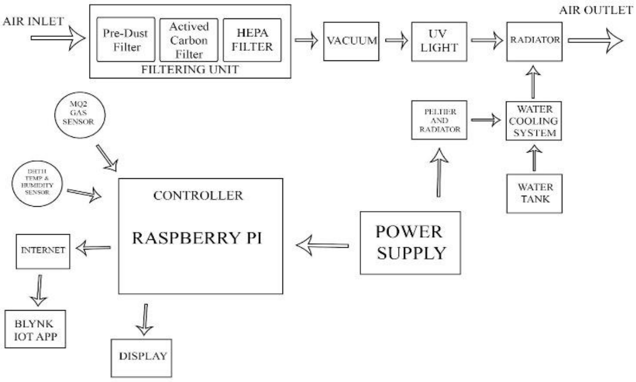

Fig. 2. Detailed Block Diagram

C. Hardware Design

As illustrated in Fig. 3, this study utilized a Raspberry Pi as the brain of the system, controlling the system and sending data to the IoT Blynk app through the internet. The device frame was constructed from aluminum with dimensions of 15 3inches in length, 13.5 inches in width, and 23.4 inches in height. The Temperature sensor and gas sensors are positioned on the front side of the device where the integrated filter is located. The vacuum fan is responsible for drawing air from the air inlet through the UV purification and cooling stages to the air outlet.

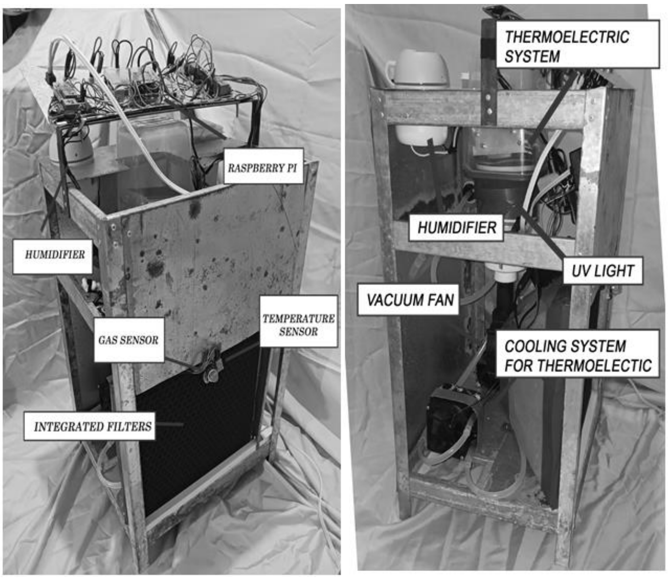

Fig. 3. The Design of the Device

D. Electronic Heat Dispersal Mechanism

Inspired by recent research findings [7], The heat sink's thermal resistance is acknowledged as a pivotal parameter in thermoelectric cooler design. [8], [12].

In Figure 4, the Electronic Heat Dispersal Mechanism is depicted in action: a water pump actively moves water from the water tank to cool the Peltier module. Subsequently, the water traverses to the heat side of the Peltier module and progresses through cooling stages 1 and 2. In these stages, two silent blowers aid in dissipating heat as the water flows through a radiator. The now-cooled water is then rerouted back to the water tank for recirculation.

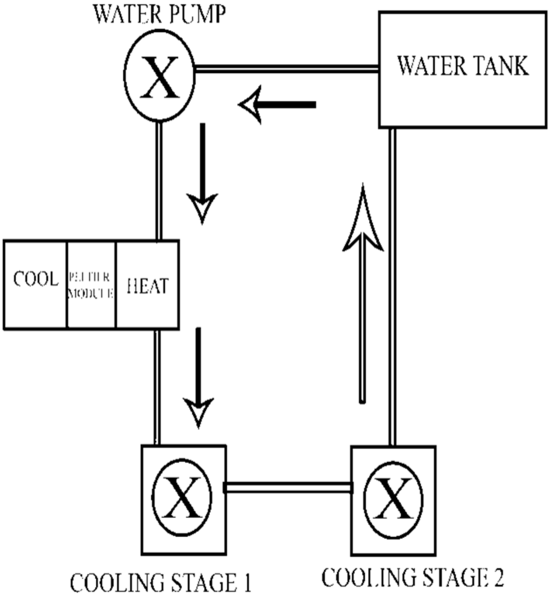

Fig. 4. Water Cooling

E. Filtering Unit and Purification Process

The air purification system's filtering unit comprises multiple layers designed to efficiently eliminate various particles and enhance indoor air quality and comfort. The sequential layers include:

Pre-Dust Filter: The pre-dust filter is the initial layer responsible for trapping larger dust particles present in the air. It acts as a preliminary barrier, preventing large particulate matter from progressing further into the filtration process.

Activated Carbon Filter: The activated carbon filter consists of highly porous carbon particles designed to absorb household chemicals, volatile organic compounds (VOCs), and odors. Effectively removes chlorine, sediment, VOCs, and other impurities, enhancing the overall quality of the purified air and eliminating undesirable odors.

HEPA (High-Efficiency Particulate Air) Filter: HEPA filters are high-performance filters with the ability to capture particles as small as 0.3 micrometers, providing exceptional efficiency in removing minute particles and bacteria from the air. According to Bhagwat et al. [11], this layer is crucial in ensuring thorough purification because it achieves efficiency levels of up to 99.97%. HEPA filters help make indoor air cleaner by getting rid of tiny particles and pollutants.

UV Light Sterilization: UV light is employed for sterilization purposes, targeting and neutralizing microorganisms like bacteria and viruses. UV light boosts the effectiveness of the air purification system by adding another level of protection against airborne pathogens, contributing to a healthier indoor environment.

F. Testing Procedure of the Developed Air Purifier

A program on the Arduino is used to operate two dust sensors connected to a laptop, serving as measuring tools. The first dust sensor is placed in the air inlet of the device, and the second dust sensor is positioned in the air outlet. The second test involves the smoke sensor, utilizing a gas sensor programmed in the Arduino and connected to the laptop to display the sensor readings. The measuring unit reads in micrograms (one-millionth of a gram) per cubic meter air or µg/m3. A total of 50 different readings on the air inlet are taken to execute the study trials and observe the results.

G. Testing Procedure of the Developed Thermoelectric Cooling System

The device is tested in a room with dimensions of 151.4 inches in length, 68.3 inches in width, and 60.2 inches in height. Two Temperature sensors are employed as measuring tools to monitor the ambient temperature of the room. The temperature is measured in degrees Celsius. The cooling system is activated when the temperature falls below 22 degrees Celsius [12]. A total of 50 temperature readings are taken during the study trials to observe the results. Data collection occurs after a 1-hour activation period.

H. Testing Procedure of the Reaction Time of the Smart Control System

The device operates at fan speed level 1 in normal mode if the temperature is below 22 degrees Celsius [13], and the gas sensor does not detect smoke, methane, LPG (liquefied petroleum gas), or carbon monoxide (CO2). In cooling mode, the controller activates the cooling system, turns on the humidifier if the Temperature sensor reading is above 22 degrees Celsius [12], and increases the fan speed to Level 2.

In turbo mode, if the gas sensor detects smoke, methane, LPG (liquefied petroleum gas), or carbon monoxide (CO2), the controller sets the fan speed to Level 3, tripling the air circulation speed [14]. The controller collects data from the sensors and uploads it to the internet, where it is displayed on the IoT Blynk app. Fifty trials were conducted to measure the reaction time of the Smart Control System. Users can manually or remotely switch the device on or off using the IoT Blynk app. Fig. 5 shows the display on the Blynk IoT mobile app.

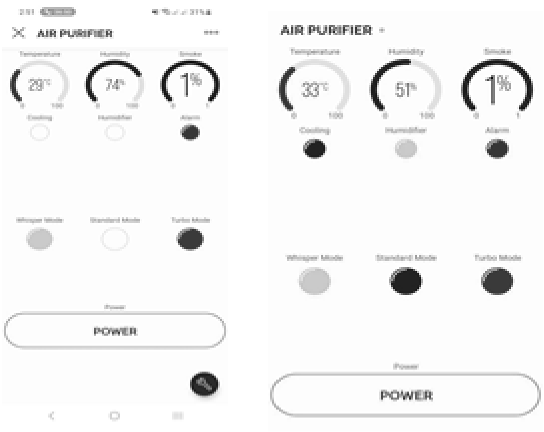

Fig. 5. The Actual Photo of the Device in Activation

3. RESULTS AND DISCUSSION

A. Performance analysis of Air Purifier based on HEPA Filter and Activated Carbon filter

A paired T-test is employed in this study to determine whether there is a significant difference in gas and smoke concentrations before and after a specific event. The paired T-test is utilized to evaluate the existence of a significant difference between two distinct tests. The collected data is pre-processed by calculating the means of gas and smoke values collected at the inlet and outlet, resulting in 50 mean data points. The resulting values from the two different test procedures are then used as inputs for the paired T-test.

Table 1 present the two-sided p-value results indicating the significance of pre and post dust concentration in micrograms per cubic meter.

Table 1. Paired T-test Result on Dust Concentration

	Inlet Dust Concentration (µg/m³)	Outlet Dust Concentration (µg/m³)
Mean	196.0460	102.2160
Standard Deviation	79.62314	37.58221
Observation (N)	50	50
t Stat	15.703	
Significance Two-Sided p value	9.3458E-21	

Table 2 present the two-sided p-value results indicating the significance of pre and post smoke concentration in micrograms per cubic meter.

Table 2. Paired T-test Result on Smoke Concentration

	Inlet Smoke Concentration (µg/m³)	Outlet Smoke Concentration (µg/m³)
Mean	168.6680	127.7320
Standard Deviation	72.46859	56.02859
Observation (N)	50	50
t Stat	9.245	
Significance Two-Sided p value	2.5477E-12	

B. Result Data of the Developed Cooling System

A paired T-test is employed in this study to determine whether there is a significant difference in ambient temperature before and after the trials. The paired T-test is utilized to evaluate the existence of a significant difference between two distinct tests. The collected data is pre-processed by calculating the means of temperature in Celsius values collected at room temperature with the interval of 1 hour per trial, resulting in 50 mean data points. The resulting values from the two test procedures are then used as inputs for the paired T-test.

Table 3 presents the two-sided p-value results indicating the significance of pre- and post-room temperature in Celsius.

Table 3. Temperature Sensor Paired t-Test Analysis

	Pre-Measurement Temperature (Celsuis)	Post-Measurement Temperature (Celsuis)
Mean	31.2940	25.5920
Standard Deviation	5.72030	5.57084
Observation (N)	50	50
t Stat	47.618	
Significance Two-Sided p value	1.0729E-42	

C. Result Data of the Developed Cooling System

During the test, experiments were carried out in an enclosed space with consistent airflow specifically directed at the device. The distance between the fan and the apparatus remained constant at 2 meters throughout the entire trial. The measured distance plays a vital role in evaluating the ability of the device to respond and efficiently adjust to the directed airflow within the specified range. Table 4 shows the result of the average reaction time.

Table 4. Average Result of Reaction time

Sensor	Reaction Time (seconds)
Temperature Sensor	5.99 seconds
Gas Sensor	2.26 econds

4. CONCLUSION AND RECOMENDATIONS

Performance analysis of air purifiers based on HEPA filters and activated carbon filters shows a statistically significant difference. According to the paired t-test analysis, the calculated t-statistic for dust is 15.703, and for smoke concentration, it is 9.245. The two-sided p-values were determined to be 2.5477E-12 for dust and 1.0729E-42 for smoke, both of which are less than the significance level of 0.05. These results indicate that there is a significant difference in the effectiveness of air purifiers equipped with HEPA filters and activated carbon filters in reducing both dust and smoke concentrations. The low p-values suggest that the observed differences are unlikely to occur by chance, further supporting the conclusion that these two types of filters have distinct impacts on air purification. This suggests a statistically significant difference between pre- and post-test dust and smoke concentrations. Consequently, it can be inferred that the developed air purifier, based on a HEPA filter and activated carbon filter, enables the user to use the purifier simply and efficiently [9].

According to the paired t-test analysis, the calculated t-statistic for temperature is 47.618. The two-sided p-values were determined to be 1.0729E-42, which is less than the significance level of 0.05. This suggests a statistically significant difference between the pre- and post-test temperatures. As the result computed in temperature decreases to 5.7 C (Celsius) from the current temperature, it can be inferred that the developed cooling system is efficient. The temperature sensor requires around 5.99 seconds to respond and adjust its temperature when there is a sudden change in temperature and humidity. The gas sensor requires around 2.26 seconds to respond when it is exposed to smoke within a certain range. These response times indicate that both the temperature and gas sensors are capable of quickly detecting and adjusting to changes in their respective environments. This quick response time is crucial for maintaining accurate and reliable data for monitoring purposes.

Based on the provided data and analysis, it can be recommended that the developed air purifier, utilizing an HEPA filter and an activated carbon filter, be effective in reducing both dust and smoke concentrations significantly. The results from the paired T-tests indicate a statistically significant difference between pre- and post-test concentrations, with p-values well below the significance level of 0.05. Balbin, De Guzman, and Rambuyon [15] investigated the efficacy of an air purifier across various household locations. The findings indicated a substantial reduction in air pollutants following air purification, as observed from the recorded data before and after the purification process. This suggests that the air purifier successfully removes contaminants from the air, making it suitable for improving indoor air quality.

Similarly, the developed cooling system also demonstrates effectiveness in reducing ambient temperature significantly. The paired T-test results show a statistically significant difference between pre- and post-test temperatures, with a decrease of 5.7 degrees Celsius observed. This reduction indicates the cooling system's efficiency in providing a comfortable environment, which is crucial for various applications, such as residential, commercial, or industrial cooling.

In conclusion, both the air purifier and cooling system have shown promising results in their respective performance evaluations. The air purifier effectively reduces dust and smoke concentrations, while the cooling system efficiently decreases ambient temperature. These findings indicate the potential of these technologies to contribute positively to indoor air quality and thermal comfort. Further optimization and validation may be necessary, but the initial results suggest that these developed systems have practical applications in enhancing environmental conditions and promoting human well-being.

References

1. G. Liu, “A review of air filtration technologies for sustainable and healthy building ventilation,” A review of air filtration technologies for sustainable and healthy building ventilation - ScienceDirect, Apr. 26, 2017. [Online].Available: https://www.sciencedirect.com/science/article/abs /pii/S221067071630734X. [Accessed: Jan. 12, 2024]
2. R. Y. Powar & B. VD, “Solar Powered Outdoor Air Purifier with Air Quality Monitor.,” International Research Journal of Innovations in Engineering and Technology. vol. 6, no. 4, pp. 68, 2022
3. M. Rashad, N. Khordehgah, A. Żabnieńska-Góra, L. Ahmad, and H. Jouhara, “The utilization of useful ambient energy in residential dwellings to improve thermal comfort and reduce energy consumption.,” International Journal of Thermofluids, pp. 100059–100059, Feb. 2021.
4. D. Panicker, “Smart Air Purifier with Air Quality Monitoring System,” International Journal for Research in Applied Science and Engineering Technology, vol. 8, no. 5, pp. 1511–1515, May 2020, Doi: 10.22214/ijraset.2020.5244.
5. A. A. Al-Talib, I. C. Aung, N. I. M.Tahir, and S. ‘Atifah Saruchi, “Solar Powered Outdoor Air Purifier with Air Quality Monitoring,” Proceedings of International Conference on Artificial Life and Robotics, vol. 28, pp. 683–688, Feb. 2023, Doi: 10.5954/icarob.2023.os27-2.
6. A. Belinski. “Thermoelectric cooling system.,” A review of air filtration technologies for sustainable and healthy building ventilation - ScienceDirect, Jun. 2022. https://patents.google.com/patent/US3125860A/en [Accessed: Jan. 12, 2024].
7. S. E., A. T.A. and S. A., "Performance Evaluation of TEC1-12706 Thermoelectric Cooler Module at Low Temperature Experimentally," 2019 International Conference on

Information and Communications Technology (ICOIACT), Yogyakarta, Indonesia, 2019, pp. 835-838, doi: 10.1109/ICOIACT46704.2019.8938437.

8. R. Chein and G. Huang, “Thermoelectric cooler application in electronic cooling,” Applied Thermal Engineering, vol. 24, no. 14–15, pp. 2207–2217, Oct. 2004, Doi: https://doi.org/10.1016/j.applthermaleng.2004.03.001.
9. D. S. Mahesh, “Self-sustainable air purifier with air cooling system.,” International Journal of Engineering Research & Technology (IJERT), vol. 7, no. 10, pp. 1-4, 2019.
10. A. Choudhary, L. Saini, A. Ahmad, H. Banerjee, and F. Gazi, "Design and Fabrication of an IoT based Air Purifier using HEPA Filter," 2023 11th International Conference on Internet of Everything, Microwave Engineering, Communication and Networks (IEMECON), Jaipur, India, 2023, pp. 1-6, Doi: 10.1109/IEMECON56962.2023.10092366
11. A. N. Bhagwat, S. N. Teli, P. Gunaki, and V. S. Majali, "Review paper on energy efficiency technologies for heating, ventilation and air conditioning (HVAC)," International Journal of Scientific & Engineering Research, vol. 6, no. 12, pp. 106-116, 2015.
12. B. J. Huang, C. J. Chin, and C. L. Duang, “A design method of thermoelectric cooler,” International Journal of Refrigeration, vol. 23, no. 3, pp. 208–218, May 2000, Doi: https://doi.org/10.1016/s0140-7007(99)00046-8.
13. J. F. Nicol and M. A. Humphreys, “Adaptive thermal comfort and sustainable thermal standards for buildings,” Energy and Buildings, vol. 34, no. 6, pp. 563–572, Jul. 2002, Doi: https://doi.org/10.1016/s0378-7788(02)00006-3.
14. R. L. Peck, S. A. Grinshpun, M. Yermakov, M. B. Rao, J. Kim, and T. Reponen, “Efficiency of portable HEPA air purifiers against traffic related combustion particles,” Building and Environment, vol. 98, pp. 21–29, Mar. 2016, Doi: https://doi.org/10.1016/j.buildenv.2015.12.018
15. J. J. R. Balbin, A. J. G. De Guzman and C. J. C. Rambuyon, "Air Pollutant Detection System Utilizing an IoT-based Electronic Nose for Air Purifier," 2022 6th International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM), Medan, Indonesia, 2022, pp. 136-140, Doi: 10.1109/ELTICOM57747.2022.10037913.