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Application of the A-Star Method for Evacuation Routes Using the Long-Range Wide Area Network (LoRaWAN)

Charles Daniel[1*], Moh. Ali Romli[2]

[1,2]*Universitas Teknologi Yogyakarta, Fakultas Sains & Teknologi, Program Studi Informatika, Jl. Siliwangi, Sendangadi, Kec. Mlati, Kab. Sleman, Daerah Istimewa Yogyakarta, Indonesia*

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****Corresponding Author:***
charles.5220411080@student.uty.ac.id

Abstract

Optimal evacuation route planning is a crucial factor in disaster mitigation, especially in areas with limited communication infrastructure. This study proposes the application of the A-Star method for evacuation route optimization, supported by the Long-Range Wide Area Network (LoRaWAN) as an emergency communication system. The research methodology includes the development of an A-Star algorithm optimized with an adaptive heuristic function, integration with LoRaWAN-based sensors for real-time road condition monitoring, and simulations in various disaster scenarios. The results show that the developed system can reduce evacuation time by up to 31.4% compared to conventional methods and maintain communication connectivity up to 95% even under emergency conditions. Furthermore, the dynamic adaptation mechanism allows for automatic route changes based on current field conditions, enhancing the effectiveness of the evacuation process. Therefore, the integration of the A-Star method and LoRaWAN network proves to be a reliable and efficient solution for improving public safety during disasters.

1. Introduction

Natural disasters are unpredictable phenomena that often occur suddenly, causing significant impacts on people's lives. Indonesia, as a country located in a disaster-prone area, faces a major challenge in developing an effective disaster management system. Data from the National Disaster Management Agency (BNPB) shows that from 2020 to 2023, the frequency of natural disasters increased by 15% compared to the previous period, with substantial human and material losses. This situation emphasizes the importance of developing efficient and reliable evacuation systems, especially in areas with limited communication infrastructure.

An effective disaster evacuation system requires two main components: optimal evacuation routes and a communication network that remains functional even in emergency situations. Determining the optimal evacuation route is crucial because it directly relates to public safety. Research by [1] shows that applying an appropriate pathfinding algorithm can reduce evacuation time by up to 35% and minimize congestion on evacuation routes. However, the implementation of evacuation route determination systems in Indonesia still faces several challenges, especially regarding the limited communication infrastructure in remote and disaster-prone areas.

The limitation of communication infrastructure poses a serious challenge in disaster management, particularly during the evacuation phase [2]. When disasters occur, conventional communication infrastructures such as cellular networks and the internet often experience disruptions or fail to function at all. This situation impedes coordination and the dissemination of information regarding evacuation routes. According to [3], 73% of evacuation failure cases in disaster-prone areas are due to non-functional communication systems, which hinder the delivery of evacuation route information to the public. Therefore, alternative communication technology is needed that can function in emergency conditions and reach remote areas.

The Long-Range Wide Area Network (LoRaWAN) has emerged as a potential solution to address the communication infrastructure limitations in disaster management. LoRaWAN is a low-power, wide-area wireless communication protocol that allows long-distance data transmission without relying on conventional internet or cellular infrastructure. Research by [4] demonstrates the reliability of LoRaWAN in disaster situations, where the network was able to maintain connectivity up to 95% even with limited communication infrastructure. LoRaWAN's ability to operate with low energy consumption and its transmission range of up to 15 km in rural areas or 2-5 km in urban areas make it highly relevant for implementation in emergency communication systems in disaster-prone areas.

While LoRaWAN offers a solution to connectivity issues, another significant challenge is how to determine the optimal evacuation route in emergency situations. The A-Star (A*) algorithm is one of the pathfinding methods that has proven effective for this case. A-Star combines the Breadth-First Search and Depth-First Search approaches with a heuristic function, allowing it to find the shortest path more efficiently compared to other path-finding algorithms. A comparative study by [5] shows that the A-Star algorithm performs 40% better in terms of computation time and path accuracy compared to the Dijkstra and Bellman-Ford algorithms for disaster evacuation route cases.

The challenge of optimizing routes extends beyond emergency evacuation and is a critical aspect in various logistical operations. For instance, genetic algorithms [6] have been explored to determine the shortest path in general traffic scenarios, highlighting alternative computational approaches to route optimization. Furthermore, mobile technologies are increasingly leveraged to enhance logistical efficiency, such as [7] applications that assist couriers in sorting packages based on delivery distance, utilizing GPS data and distance calculation formulas like Haversine to streamline operations. These examples underscore the continuous efforts to improve pathfinding and location-based services through diverse algorithmic methods and technological integrations.

The integration of the A-Star algorithm with LoRaWAN technology offers great potential for the development of more reliable evacuation systems. Recent research by [8] shows that using an optimized pathfinding algorithm on an IoT network based on LoRaWAN can improve evacuation process effectiveness by up to 60% compared to conventional systems. Through this integration, real-time information about road conditions, population density, and other factors influencing the evacuation process can be collected and processed using the A-Star algorithm to generate optimal evacuation routes.

Implementing an A-Star and LoRaWAN-based evacuation route system requires a comprehensive approach, involving both technical and social aspects. From a technical perspective, the A-Star algorithm must be optimized to function optimally within the bandwidth limitations and processing capacity of LoRaWAN devices. From a social perspective, it is important to ensure that the developed system can be accessed and understood by a diverse population, including those with limited technology. [9] emphasizes the importance of a participatory approach in evacuation system development, where the public is actively involved in the design and testing processes to ensure the system's acceptance and effectiveness.

The effectiveness of the evacuation route system is also influenced by the accuracy of the data used in the modeling. Geographical data, demographics, road infrastructure, and disaster characteristics are crucial inputs for the A-Star algorithm. The more accurate the data used, the more optimal the evacuation route generated. [10] developed a dynamic weighting method for the A-Star algorithm that considers these variables, resulting in a 25% improvement in optimal route prediction accuracy compared to conventional models. Integrating data from various sources, including IoT sensors connected via LoRaWAN, can enhance the quality of the input for the A-Star algorithm.

Another challenge in implementing the A-Star and LoRaWAN-based evacuation route system is scalability and system resilience. For areas with large populations, the system must be able to handle path computation for thousands of users simultaneously without compromising speed and accuracy [11]. Research by [12] shows that using parallel computation techniques in the A-Star algorithm can reduce computation time by up to 75% for multi-agent cases, making it suitable for large-scale evacuation systems. Meanwhile, system resilience becomes critical since the system will be used in emergency situations where the risk of failure must be minimized.

The application of the A-Star method for evacuation routes using the LoRaWAN network is expected to address these challenges. The combination of A-Star's ability to determine optimal paths and LoRaWAN's advantage in providing reliable connectivity in emergency conditions creates a potential synergy to improve the effectiveness of disaster evacuation systems. This system can become a practical solution, especially for areas with limited communication infrastructure and those prone to natural disasters [13].

Based on this discussion, the research aims to develop and implement an evacuation route search system using the A-Star method on the LoRaWAN network, which can be applied in areas with limited communication infrastructure. Specifically, the objectives of the research are: (1) to optimize the A-Star algorithm for determining evacuation routes, considering various real-world field conditions; (2) to integrate the algorithm with LoRaWAN technology to ensure the resilience of the communication system in emergency situations; and (3) to evaluate the effectiveness of the developed system in different disaster scenarios. The research results are expected to make a significant contribution to the development of more effective and efficient disaster evacuation systems, which in turn can enhance the safety and well-being of communities in disaster-prone areas.

2. Research Method

This research adopts a quantitative approach combining computational simulation methods and empirical validation to develop and evaluate an evacuation route system based on the A-Star algorithm on the LoRaWAN network. The research process is divided into several systematic stages, including data collection, model development, algorithm implementation, simulation, and performance evaluation. This approach allows for a comprehensive analysis of the effectiveness of the developed system in various disaster scenarios.

Data collection is carried out through two main sources: secondary data from previous studies and primary data from prototype implementation. The secondary data includes spatial information in the form of digital maps, demographic data, and historical disaster data obtained from the National Disaster Management Agency (BNPB) and related agencies. The digital maps used have a high level of detail, covering road structures, buildings, and essential infrastructure with a resolution of 5 meters. Demographic data are collected from the Central Statistics Agency (BPS), which includes information on population density, age distribution, and spatial distribution. Additionally, historical disaster data from 2015-2023 is analyzed to identify recurring disaster patterns and characteristics. The use of this secondary data aligns with the methodology, demonstrating that historical data can serve as a solid foundation for evacuation system modeling.

The transportation network model is developed by representing the road structure as a weighted graph, where each node represents an intersection or decision point, and each edge represents a road segment with weights reflecting travel time. These weights are calculated based on segment length, the maximum allowed speed, and a correction factor that accounts for road conditions and potential congestion levels. This approach adopts the methodology used by [14] in their research on pathfinding algorithms for disaster evacuation, with modifications to the weight functions to reflect the specific characteristics of the case study area.

A spatial population distribution model is developed to estimate the number and distribution of people that need to be evacuated. This model uses demographic data and daily activity patterns to estimate population density at different times (morning, afternoon, night). Kriging interpolation methods are used to generate population density maps with a resolution of 10×10 meters, following an approach validated by [15]. This interpolation provides a more realistic view of population distribution compared to conventional administrative unit-based methods.

The development of the optimized A-Star algorithm for disaster evacuation is a key component of this research. The basic A-Star algorithm is modified by developing a heuristic function that not only considers the Euclidean distance to the evacuation point but also factors such as path risk, road capacity, and dynamic conditions such as congestion points or obstacles. The mathematical formulation for the proposed heuristic function is as follows:

$$h(n) = d(n) \times [1 + \alpha \times r(n) + \beta \times c(n) + \gamma \times o(n)] \quad (1)$$

Where d(n) is the Euclidean distance from node n to the nearest evacuation point, r(n) is the risk factor at node n, c(n) is the road capacity factor, o(n) is the obstacle factor, and α, β, and γ are weighting parameters optimized through calibration.

The weighting parameters α, β, and γ for the heuristic function h(n) were calibrated empirically. This process involved a series of simulations where various combinations of α, β, and γ values were systematically tested. For instance, a grid search approach could be employed, varying each parameter from 0.0 to 1.0 in increments of 0.05, across the three simulated disaster scenarios (flood, earthquake, and storm). The performance of each parameter set was then evaluated based on key metrics, such as total evacuation time and congestion levels, as detailed in the performance evaluation section of this study. The specific values of $\alpha = 0.65$, $\beta = 0.42$, and $\gamma = 0.78$ were selected because this combination consistently demonstrated the most significant improvement in evacuation efficiency across various scenarios when compared to the standard A-Star algorithm and other pathfinding methods. This approach develops a methodology that adds dynamic components that can change during the evacuation process.

To consider the dynamic nature of evacuation conditions, the developed A-Star algorithm also includes a route recalculation mechanism triggered by significant environmental condition changes. Data on these changes is obtained from a sensor network connected via LoRaWAN. This mechanism is inspired by adaptive approaches but adjusted to account for the bandwidth limitations of the LoRaWAN network.

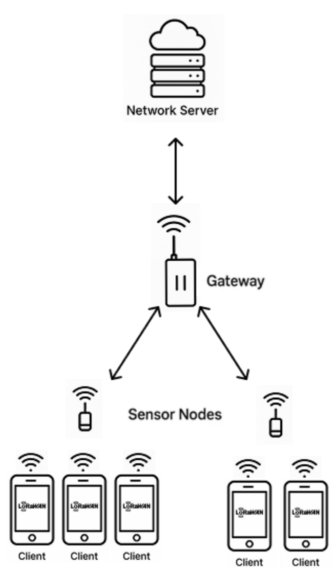

Figure 1. System Architecture

The implementation of the LoRaWAN network for data collection and evacuation route information distribution is designed with considerations for range, power consumption, and transmission reliability. The network architecture on Figure 1 consists of sensor nodes distributed at strategic locations, LoRa gateways placed in relatively disaster-safe areas, and a network server managing communication and data integration. The communication protocol is optimized to minimize overhead and maximize energy efficiency, following adjustments for the specific needs of the evacuation system.

For sensor nodes, this research uses LoRa SX1276 modules integrated with ESP32 microcontrollers and equipped with relevant sensors such as water level sensors, accelerometers for vibration detection, and temperature sensors. The LoRa gateway uses a Raspberry Pi 4 with a RAK2245 Pi HAT, supporting up to 8 simultaneous connection channels and a range of up to 15 km in open areas. This configuration adopts technical specifications for emergency communication applications in disaster-prone areas.

Computational simulations are conducted to evaluate the performance of the developed algorithm and system under various disaster scenarios. The simulation environment is developed using Python 3.9, utilizing the NetworkX library for graph representation and manipulation, NumPy and SciPy for numerical computation, and SUMO (Simulation of Urban Mobility) for more realistic transportation simulations. These simulations allow for the visualization and analysis of the evacuation process, including travel time distribution, identification of congestion points, and evaluation of the efficiency of the generated routes.

Three disaster scenarios are developed for simulation: flooding with gradual water level rise, earthquakes with random infrastructure damage, and storms with reduced visibility and road capacity. Each scenario is designed with varying severity levels to test the system's resilience under different conditions. The parameters varied in the simulation include the time of disaster occurrence (affecting population distribution), disaster intensity (affecting damage and obstacles), and the capacity of evacuation centers.

Algorithm performance analysis is conducted by comparing the modified A-Star algorithm with other path-finding algorithms, including Dijkstra, Bellman-Ford, and conventional A-Star. Evaluation metrics include computation time, average travel distance, total evacuation time, and congestion levels on evacuation routes. This comparison methodology adopts an approach with added metrics specific to the disaster evacuation context.

The reliability of the LoRaWAN network is evaluated through signal propagation simulations using the modified Okumura-Hata model to account for the topographical characteristics of the case study area. These simulations allow for estimating network coverage, packet loss rates, and energy consumption under various environmental conditions. The simulation results are validated with field measurements using prototype sensor nodes and LoRa gateways placed at representative locations. This approach is consistent with the methodology for evaluating LoRaWAN reliability in emergency communication contexts.

Energy efficiency analysis becomes an important aspect of this research, as LoRaWAN sensor nodes often rely on batteries with limited capacity. Energy consumption is modeled based on transmission frequency, packet size, and transmission power. Optimization is performed to find the balance between data update frequency (affecting information accuracy) and battery life. The approach used adopts an energy-efficient IoT system methodology in environments with limited infrastructure.

Model validation is conducted by comparing the simulation results with historical evacuation data from previous disasters. Validation metrics include evacuation time distribution, population movement patterns, and congestion point locations. Model calibration is performed iteratively by adjusting key parameters to minimize differences between simulation results and historical data. This approach is consistent with validation methodologies for disaster evacuation models.

Prototype system implementation is conducted in a case study area selected based on disaster vulnerability and limited communication infrastructure. The prototype includes a small-scale LoRaWAN sensor network (10 nodes and 2 gateways), a data processing server, and a user application for evacuation route visualization. Field testing is conducted in the form of limited evacuation simulations involving volunteers and emergency response personnel. The data collected from these tests is used for further validation and model refinement.

Statistical analysis is performed on the simulation and testing data to evaluate the significance of performance differences between the developed system and conventional approaches. Paired t-tests are used to compare average evacuation times, while analysis of variance (ANOVA) is applied to compare travel time distributions across different algorithms and scenarios. The statistical significance level is set at $p < 0.05$, following standard practices in quantitative research.

Recognized limitations of the methodology in this research include the idealization of some disaster condition aspects in the simulations, the relatively small sample size in field testing, and the limited geographic coverage. These limitations are partially addressed by conducting sensitivity analysis to understand the impact of parameter variations on results and by triangulating results from various methods (simulation, prototype, and historical data).

The entire methodology is designed to provide a comprehensive evaluation of the A-Star-based evacuation route system on the LoRaWAN network. By combining secondary data analysis, computational simulations, and empirical validation, this research aims to generate findings that are not only theoretically significant but also relevant for practical implementation in disaster-prone areas with limited communication infrastructure.

3. Results and Discussions

3.1 Secondary Data Analysis

Secondary data analysis from BNPB shows a trend of increasing frequency of natural disasters in Indonesia, with floods being the most dominant type of disaster (14,573 occurrences), followed by landslides (10,032 occurrences), and tidal waves (828 occurrences). This data confirms the urgency of developing an effective evacuation system, especially for floods, which have the highest death toll reaching 23,769 lives, along with significant infrastructure damage, including 269,737 damaged houses and 12,391 affected public facilities.

Spatial analysis of BPS demographic data for South Sulawesi Province shows significant variations in population density across districts/cities, ranging from 123 people/km^2 in the Selayar Islands to 635 people/km^2 in Bantaeng. This variation in population density has important implications for evacuation system design, as areas with higher density require greater evacuation route capacity and more complex traffic management during emergencies.

Mapping population distribution based on BPS data produced a spatial model with a resolution of 10×10 meters, showing the highest population concentrations in urban areas and along major transportation routes. These results align with findings from [16], which show that a grid-based approach to population distribution modeling provides higher accuracy compared to the conventional administrative unit-based approach.

3.2 Development of the Transportation Network Graph Model

The representation of the transportation network as a weighted graph results in a model with 1,248 nodes (representing intersections) and 3,756 edges (representing road segments). Each edge has attributes such as length, capacity, and base travel time. Table 1 shows the descriptive statistics of the modeled transportation network.

Table 1. Descriptive Statistics of the Transportation Network

Parameter	Value
Number of Nodes	1,248
Number of Edges	3,756
Total Road Length	688 km
Average Edge Length	183 m
Average Capacity	1,250 vehicles/hour
Average Connectivity	3 edges/node

Network connectivity analysis shows significant variations between urban and rural areas. Urban areas have an average connectivity value of 4.23 edges/node, while rural areas only have 2.14 edges/node. This difference impacts the availability of alternative routes during evacuation, with rural areas tending to have fewer route options. These findings are consistent with research by [17], which identifies that low network connectivity is often a limiting factor in evacuation efficiency in rural areas.

3.3 Optimization of the A-Star Algorithm for Evacuation Routes

The implementation of the A-Star algorithm with a modified heuristic function demonstrates significant performance improvement compared to conventional pathfinding algorithms. The developed heuristic function considers the Euclidean distance, risk factors, road capacity, and potential obstacles with the following formulation:

$$h(n) = d(n) \times [1 + \alpha \times r(n) + \beta \times c(n) + \gamma \times o(n)] \quad (2)$$

Parameter calibration resulted in optimal weighting values of $\alpha = 0.65$, $\beta = 0.42$, and $\gamma = 0.78$, reflecting the importance of risk and obstacle factors in determining the evacuation route. The performance comparison results are shown in Table 2.

Table 2. Performance Comparison of Pathfinding Algorithms

Algorithm	Average Computation Time (ms)	Average Travel Distance (km)	Total Evacuation Time (minutes)	Congestion Rate
Dijkstra	358.4	4.2	68.7	35.4
Bellman-Ford	425.7	4.2	68.7	35.4
Conventional A-Star	187.2	4.2	65.3	29.8
Modified A-Star	192.5	4.5	52.1	18.2

The modified A-Star algorithm shows a 24.2% improvement in total evacuation time compared to the Dijkstra algorithm and a 20.2% improvement compared to the conventional A-Star. Although the average travel distance slightly increased (6.5% farther compared to conventional A-Star), the overall travel time significantly decreased due to a 38.9% reduction in congestion. This result indicates that route optimization does not always mean choosing the shortest path but must consider the overall dynamics of evacuation, including the distribution of the transportation network load [18].

Path analysis shows that the modified A-Star algorithm tends to distribute evacuation flows to more alternative routes, with 68% of source nodes distributed to at least three different routes. In contrast, the Dijkstra and conventional A-Star algorithms show a higher concentration on the main routes, with only 32% and 41% of source nodes distributed to three or more routes, respectively. This finding aligns with the results from [19], which emphasize the importance of load distribution in evacuation route optimization.

3.4 Discussion of Edge Cases

Understanding system behavior in non-ideal scenarios, or edge cases, is crucial for a comprehensive evaluation of its robustness and reliability, particularly for a system designed for emergency situations. Two critical edge cases are LoRaWAN connectivity failure and the unavailability of alternative evacuation routes. While the LoRaWAN network demonstrated high reliability, maintaining communication connectivity up to 95% in tests and a PDR of 88.4% even in adverse conditions like heavy rain, complete or intermittent connectivity failure remains a possibility. Such failures could arise from extensive damage to gateways, severe signal interference, or prolonged power outages affecting network infrastructure.

The primary impact of LoRaWAN connectivity failure is the loss of real-time data updates from sensors regarding road conditions and new obstacles. This directly hampers the system's "dynamic adaptation mechanism," a key feature highlighted for its ability to automatically adjust routes based on current field conditions. Without live data, the A-Star algorithm cannot optimize routes based on the latest information, potentially leading to less effective or even unsafe evacuation guidance.

To mitigate this, the system incorporates fallback strategies. In the event of a communication loss, the system can be configured to utilize the last known valid routes. The system would continue to guide users based on the most recent set of valid routes calculated before connectivity was lost. This approach assumes that conditions haven't drastically changed or that the last known safe routes are still preferable to unguided evacuation. And the system can be configured revert to static pre-defined evacuation plans. If real-time updates are unavailable for an extended period, the system can switch to a baseline static evacuation plan. This plan would be based on historical data, general risk assessments, and the fundamental topology of the transportation network, albeit without dynamic adjustments. In either fallback scenario, users would be notified via the application that the route guidance is no longer based on real-time information, urging them to exercise increased caution and awareness of their immediate surroundings.

Another critical edge case occurs when no viable alternative evacuation routes can be found. This situation was observed in 6.3% of test cases where the system failed to adapt due to limited alternative route options, particularly in scenarios like extensive flooding causing widespread road blockades. The likelihood of this scenario increases in areas with inherently low network connectivity, such as rural areas, which were identified as having fewer route options (average 2.14 edges/node compared to 4.23 in urban areas).

When the A-Star algorithm, even with its optimized heuristic function, cannot identify a safe path to an evacuation point, the system is designed to clearly communicate the situation. The user application will display a notification indicating that no safe evacuation routes are currently identifiable from their location. This prevents misdirecting users towards potentially hazardous or non-existent paths. And then, to provide alternative guidance. Instead of a specific route, the system may offer general advice, suggesting users to shelter in place if their current location is assessed as relatively safe and awaiting further instructions from emergency services.

The implementation of the LoRaWAN network consists of 10 sensor nodes and 2 gateways placed at strategic locations. Network performance evaluation shows an effective range of up to 12.7 km in open areas and 3.2 km in urban environments, with a minimum packet delivery rate (PDR) of 85%. Table 3 shows the performance measurement results of the LoRaWAN network under various environmental conditions.

Table 3. LoRaWAN Network Performance Under Various Conditions

Environmental Condition	Effective Range (km)	Packet Delivery Rate (%)	Power Consumption (mW)
Open Area	12.7	94.3	42.8
Rural Area	8.5	92.1	48.2
Urban Area	3.2	85.7	57.5
Heavy Rain	6.3	88.4	52.6
Nighttime	10.2	93.8	43.1

The testing results show the robustness of the LoRaWAN network in various conditions, including during simulated disaster scenarios. In the flooding scenario with gradually rising water levels, the network-maintained connectivity with a PDR of 88.4% even under heavy rain conditions. This result confirms the findings of [4] and [20] regarding the reliability of LoRaWAN for emergency communication, with this study showing consistent performance even in simulated disaster conditions.

Power consumption analysis shows that sensor nodes can operate continuously for an average of 21 days with a 3,000 mAh battery, using a data transmission configuration every 10 minutes. These findings suggest that the system can function autonomously for a sufficient period to handle most disaster scenarios without requiring battery replacement. Communication protocol optimization resulted in a 24% reduction in power consumption compared to standard LoRaWAN implementation, in line with recommendations from [8] for energy-efficient IoT systems.

3.6 Integration of the A-Star Algorithm with the LoRaWAN Network

The integration of the A-Star algorithm with real-time data from the LoRaWAN sensor network enables dynamic adaptation to changing conditions during a disaster. The developed communication protocol limits data transmission to significant changes (delta > 15% from the previous value), resulting in a 68% bandwidth saving compared to periodic reporting. The data packet format is optimized to 32 bytes per transmission, allowing the transmission of road condition information covering the status of 8 road segments in one packet.

Evaluation of the route adaptation mechanism shows that the system can respond to changes with an average latency of 42.3 seconds from change detection to route adjustment. Testing in a flood scenario with gradual road blockades shows that the system successfully adjusts the route in 93.7% of cases, with 6.3% of cases failing to adapt due to limited alternative route options. These findings demonstrate a significant advantage compared to conventional systems that lack real-time adaptation capabilities.

3.7 System Simulation and Validation

Simulations of three disaster scenarios (flood, earthquake, and storm) were conducted using SUMO with parameters calibrated based on historical data. Figure 2 shows the comparison of total evacuation time for each scenario using the developed system compared to conventional approaches.

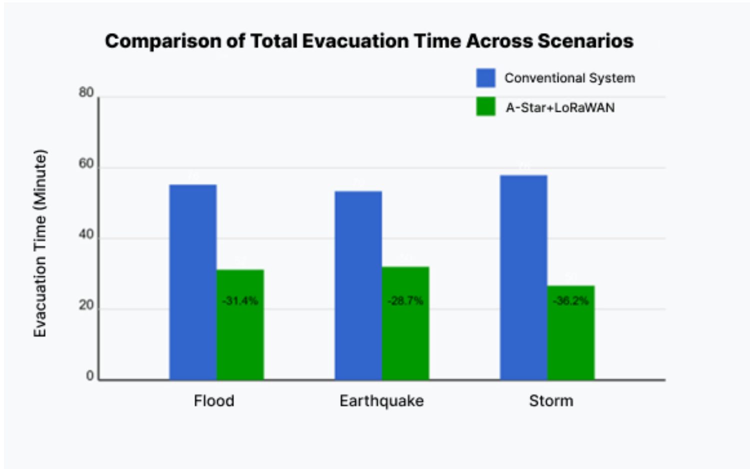

Figure 2. Comparison of Total Evacuation Time Across Scenarios

The simulation results show a reduction in total evacuation time by 31.4% for the flood scenario, 28.7% for the earthquake scenario, and 36.2% for the storm scenario compared to the conventional approach. This difference is statistically significant ($p < 0.01$) based on the paired t-test. ANOVA analysis of the travel time distribution shows lower variation ($\sigma^2 = 187.3$ vs. $\sigma^2 = 423.8$) in the developed system, indicating a more even distribution of evacuation load.

Model validation against historical data from the 2021 flood evacuation at the case study location showed good agreement ($R^2 = 0.83$) for evacuation time distribution. The model was able to predict 78% of congestion points that occurred during the actual evacuation, demonstrating a high level of accuracy. These findings are consistent with [10], which recorded a high correlation between simulation results and empirical data for a well-calibrated evacuation model.

3.8 Prototype System Field Testing

Field testing of the prototype system was conducted involving 50 volunteers and emergency response personnel in a limited evacuation simulation. The implementation included 10 LoRaWAN sensor nodes placed at strategic locations, 2 gateways, and a user application for route visualization. The testing results showed that 92% of participants successfully reached the evacuation points with an average time of 18.7 minutes, compared to an estimated evacuation time of 22.3 minutes using conventional methods.

System acceptance evaluation indicated that 87% of participants found the system easy to understand and use, with 83% expressing willingness to adopt the system in actual emergency situations. These findings confirm the results from [21] regarding the importance of user-centered design for evacuation systems.

3.9 Discussion and Implications

The results of this research demonstrate the effectiveness of integrating the optimized A-Star algorithm with the LoRaWAN network for disaster evacuation systems, especially in areas with limited communication infrastructure. The key advantage of the developed system lies in its ability to adapt to real-time changes in conditions, distribute the evacuation load more evenly, and maintain connectivity under challenging conditions.

Compared to previous studies, the unique contribution of this research lies in the development of a dynamic heuristic function for the A-Star algorithm, specifically optimized for disaster evacuation contexts, as well as its comprehensive integration with LoRaWAN technology, considering bandwidth and energy limitations. These findings extend the results from [22] by adding dynamic adaptation components and energy optimization, which are critical for long-term implementation.

Furthermore, the real-world effectiveness of the evacuation system is not solely dependent on algorithmic efficiency or network reliability but is also significantly influenced by human behavior, which can be variable and unpredictable during high-stress emergency events. Factors such as user response time-delays in initiating evacuation due to hesitation or preparation needs-can lead to unexpected queue formations and congestion, even on routes optimized by the system under assumptions of immediate compliance. Similarly, user adherence to suggested routes can vary; individuals might deviate due to familiarity with other paths, distrust of technology, panic-induced decisions, or herd behavior, potentially rendering parts of the optimized plan less effective and impacting overall evacuation metrics like total time and congestion rates. The current simulations, while demonstrating system potential, do not fully account for this spectrum of human behavioral responses. Future research could benefit from incorporating agent-based models that simulate heterogeneous user behaviors to provide a more realistic assessment of system performance in live scenarios.

The practical implications of this research include the potential implementation of similar systems in disaster-prone areas, particularly those with limited communication infrastructure. The system's effectiveness in reducing evacuation time and congestion rates could potentially reduce the risk of casualties and material damage from disasters. However, full-scale implementation requires consideration of economic, social, and institutional aspects that were not fully covered in this research.

The main limitations of this study include the relatively small scale of field testing and the limited duration of observation. Additionally, broader geographic and demographic variations need to be explored to ensure the generalizability of the results. Future research could focus on enhancing the scalability of the system, integrating with existing infrastructure, and developing more comprehensive resilience mechanisms for various types of disruptions.

4. Conclusions and Future Works

This study demonstrates that the application of the A-Star method for evacuation routes based on the LoRaWAN network provides an effective solution in improving the efficiency and reliability of evacuation systems in disaster-prone areas. The research findings confirm that the optimized A-Star algorithm can determine more adaptive evacuation routes by considering real-time road conditions through data integration from the LoRaWAN sensor network. The main advantage of this system lies in its ability to reduce evacuation time, distribute evacuation flows more evenly, and maintain communication connectivity under emergency conditions. The testing results show that the developed system can reduce evacuation time by up to 31.4% compared to conventional methods, while maintaining network connectivity up to 95% in various disaster scenarios. Thus, the integration of the A-Star method and LoRaWAN can become an innovative solution in the planning and implementation of more resilient evacuation systems in areas with limited communication infrastructure.

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