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Development of IoT-Based Automated Dynamic Emergency Response System Against Fire Incidents in Academic Building

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ABSTRACT
The ongoing advancement of architectural and structural designs, high-ceiling spaces, special spaces have made fire disasters increasingly diverse and difficult to predict. It is demanding the need for improved firefighting systems. This study aims to address the need for improved firefighting systems in academic building by proposing the development of an IoT-based automated emergency response website. The proposed system leverages IoT technology, wireless and bluetooth sensor networks to gather real-time data from various sensors and devices installed in the site and uses machine learning algorithms to predict and prevent potential fire incidents. The system also includes an emergency response website that allows users to access real-time information about the fire incident, location, severity, and evacuation instructions. Additionally, the proposed system incorporates Building Information Modelling (BIM) to optimize evacuation and rescue routes, providing early detection and accurate alarm capabilities, evacuation guidance for endangered individuals, and guidance for firefighters. The integration of BIM allows the system to provide a three-dimensional visualization of the site, enabling a more efficient and effective response to fire incidents. Overall, the proposed system aims to improve the safety and security through real-time monitoring and response capabilities. By leveraging the power of IoT technology, machine learning algorithms and BIM, the proposed system aims to reduce the impact of fire disasters by providing accurate and timely information, route optimization and facilitating effective evacuation and rescue efforts.
Keywords: Building Information Modeling, IoT, Sensor, Dijkstra Algorithm, Simulation

1 Introduction
Around the world, modern industrial sites, office sites and academic buildings have grown more complex and augmented. Given the structural characteristics of these sites, quick evacuation such as through emergency exits or evacuee guidance markers during blackouts caused by fire, building collapse, earthquakes, or building aging is a critical issue. Uniform evacuation guidance, such as exit light is insufficient for guiding evacuees during a fire, causing them to take incorrect exits while buildings are on fire. Existing emergency exit guides do not take the location of the fire in and out of the account and simply direct people to the nearest exit, which may result in significant secondary casualties if a fire occurs at the exit and evacuees are directed towards it. As a result, we must pay special attention to implementing new technology to combat fire disasters. The Internet of Things (IoT), in conjunction with Building Information Modelling (BIM) and wireless sensor networks (WSN), is ideal for firefighting. IoT has a high level of intelligence for maintaining many product categories, quantities, complex fire danger factors, and a wide range of fire monitoring and fighting equipment. IoT has high scalability and resource-sharing capabilities for handling various complex business information. IoT in conjunction with the Wireless Sensor Network (WSN) plays an important role in fire alarm, fire control facility monitoring, and fire equipment management. The fire department's emergency response & rescue capabilities are effectively improved by it. This research will propose an IoT-based intelligent fire emergency response system with decentralized control which is far more effective than the traditional non-communicative signal-based evacuation technology. It can intelligently guide evacuees based on the location and time of a fire to reduce human life loss.

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2 Literature Review

The recent surge of technological advancement in sensor-based networking systems has enriched studies based on IoT systems and their mechanisms. Most IoT-based studies on firefighting in the last decade have discussed the following topics: general firefighting systematic plan, technological sensor development, improvement in sensor sensitivity and mechanism, and use of different parameters in fire identification (such as temperature, pressure, moisture content, etc.).

2.1 Development of IoT-based Fire Hazard Solutions

The "Internet of Things for Smart Cities" discussed only general IoT features that can be implemented in Smart City networks, but no recommendations for Firefighting were given in it whereas Folea and Mois discussed low-power wireless sensors for online environmental monitoring, which combines Wi-Fi connectivity with ambient sensors, used for remote data collection and processing [1]. The use of narrowband IoT (NB-IoT) in Intelligent Fire Protection Systems, can significantly improve firefighting forces combat capability [2]. Combined application features of IoT technology based on fire-fighting business requirements discuss the fire-fighting IoT systematic frame, planning of society fire-fighting safety management, and propose priority development points of society fire-fighting safety management, thereby providing a reference for technology research and development of IoT technology in the field of society fire-fighting safety management [3]. An IoT-based novel fire extinguishing monitoring and control system is proposed to acquire real-time information on fire extinguishing working conditions and improve the reliable prediction mechanism in a traditional fire monitoring system [4]. The novel system can obtain real-time data on the operation of fire extinguishing facilities, such as pipe flow, pressure, temperature, and humidity of the environment, current and voltage of the electric equipment, valve switch, relay action, and an alarming message [5]. The investigation of the design and implementation of a VOC monitoring system using a ZigBee wireless sensor network [6].

The consideration of Gator tech smart house to be a programmable pervasive space [7]. The detailed discussion on the current state of smart homes and the discussion on the WSN-based smart sensors and actuators for intelligent building power management [8-9]. There are some investigations were conducted on the intelligent self-adjusting sensor based on ZigBee communications for smart home services where the structure composition, design concept, and implementation approach has described [10]. Byun, et al. [11] have made an investigation on a Zigbee-based simulation process on a safeguarding sensor system for the real-time monitoring of wireless fire detection nodes. Intelligent-based bridging components in the space where the distributed services have been working seamlessly and where the robots are sharing the missing information in the intelligent space [12]. The use of blockchain technology in an IoT-based automated dynamic emergency response system for energy distribution can improve the efficiency, reliability, and security of energy distribution, leading to a more sustainable and resilient energy ecosystem [13]. A computer-aided visualization of rescue operations was applied, and the investigation novel concept of a fire hazard ranking distribution system based on multisensory technology [14]. The challenges of integrating a Wireless Sensor Network and the Internet of Things for Environmental Monitoring can be improved by using wireless sensors in network-based forest-fire surveillance systems [15-16].

2.2 BIM Model Development in Fire Hazard Situations

In recent years, Building Information Models (BIM) have been widely used in building disaster prevention and relief management, and not only does it provide three-dimensional space for visualizing fire conditions and other emergencies [17-19]. The uncertainty of a building fire makes every second of the fire scene critical and the users can quickly determine the best escape route to deal with the fire using this information [20]. BIM-based construction safety management system using AR and 4D simulation technologies. Advances in Civil Engineering [21-22]. Most of the current research on building fire escape focuses on path planning based on the current fire situation. However, due to many floors and complex internal space in high-rise buildings and large complex buildings, it is difficult to obtain the overall optimal escape path that carries on path planning only through the current location data and situation of a fire, lacking fire spreading and using the fire spreading data to correct the path [23-24]. Although there have been some studies on escape paths in the case of fire spreading, they have primarily focused on fire rendering but the research on the emergency evacuation management system of a museum based on BIM and virtual reality with little research on dynamically changing escape paths based on fire spreading simulation [25-27]

2.3 Dijkstra's Algorithm in a Fire Escape Situation

The fire is sprawling and uncertain, and the trapped people are in constant motion. If the escape route planning was performed only by real-time personnel location and fire information, it may cause the current route to be opposite to the previous route with the fire spread and the escape proceeded [28-30]. As a result, it is hard to escape quickly from the fire scene for the problem of partial route detour. Although there has been research on fire spread and path planning based on simulation data [31], there is a lack of processing to dynamically correct the escape path according to the fire spread data, so it is impossible to ensure the real-time escape path is optimal in the overall escape process [28]. Moreover, people often escape at the same time in a real fire. And it will be more difficult to escape if people are in a panic. Congestion and stampede tend to occur on stairs, resulting in unnecessary casualties [32].

Cheng et al. used Bluetooth and smoke sensors to obtain information about the fire scene in their study of building fire escape paths [33]. and then used the Dijkstra algorithm for dynamic evacuation/rescue path planning, which successfully realized real-time dynamic path planning and navigation of building fires. Similarly, Chou et al. developed an integrated fire protection system with multiple scenarios for evacuation and rescue by employing the Dijkstra algorithm to perform real-time dynamic path planning and constantly update the location nodes of trapped and rescuers [34].

In response to this problems, this paper is going to make a further study on the quick and safe escape from a building fire, and it will adopt IOT based system for an effective escape path. For this effective communication a website is created using the BIM model in conjunction with Dijkstra's algorithm, integrating fire information to simulate fire spread, the data of fire spread can be obtained and adjusted dynamically according to the real-time situation. This dynamic path analysis of the escape path for complex building fires can be realized and displayed in the BIM model, which helps trapped people escape quickly.

3 Methodology

This proposal is divided into three phases that will be implemented simultaneously to achieve the main objectives. The execution of this research can be categorized as follows:

1. Analyzing fire load and fuel arrangements in a typical building, investigating possible worst-case scenarios of fire phenomena in buildings during a fire.
2. Examining the efficiency of dynamic exit signage during an emergency using a demo device, modeling a soft computing-based simulation process that can predict the level of emergency due to fire and occupants' flow.
3. Integrating the main results from previous studies to produce an automated dynamic emergency response system that will be further developed to meet commercialization goals.

3.1 Factors Identification

A concept is developed through a comprehensive literature review and the identification and evaluation of various components of an IOT-based Fire Fighting System. It also aids in the extraction of preliminary factors that are widely used in various types of buildings, structures, and large areas shown in Figure 1.

3.2 Data Collection and Organization

To create a Building Information Modelling (BIM), fire system sensor data and building planning data were collected. The General Mustafiz Tower at the Military Institute of Science and Technology, located in Mirpur Cantonment, Bangladesh, was selected as the study site which has been shown in Figures 2, 3 , and 4. This academic building comprises 10 floors, with the first floor being a lobby. Participants were instructed to evacuate from the 3rd floor. As depicted in the figure, the building features one staircase, three elevators, one emergency exit, and a connecting bridge with the adjacent tower. To eliminate any issues with elevator scheduling, occupants on other floors were not permitted to use elevators during the experiments. Participants were only allowed to use the staircases, emergency exit, and connecting bridge for the duration of the experiment.

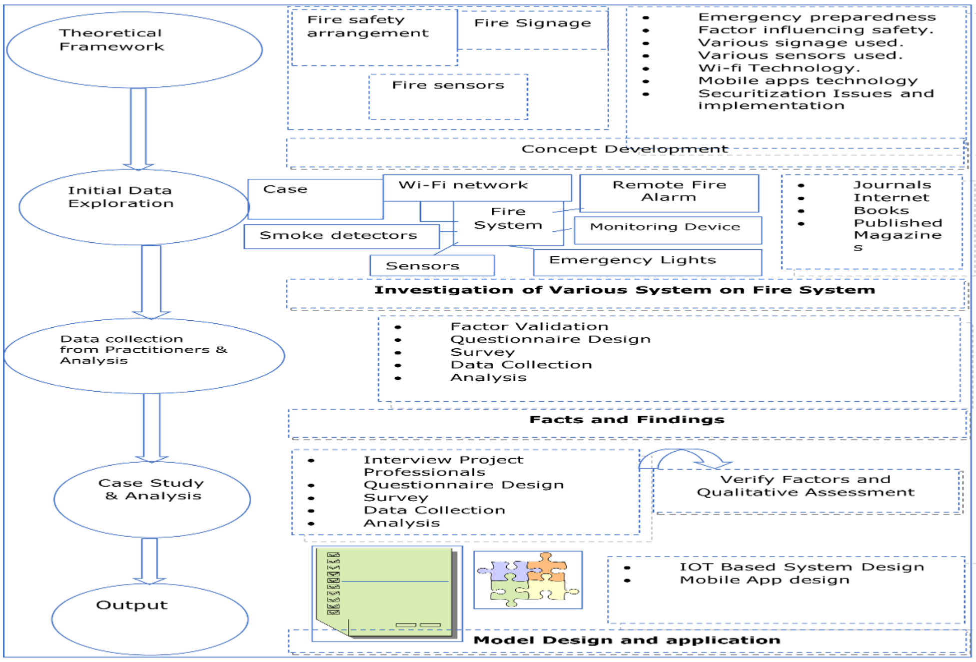

Figure 1: Research framework

3.3 Plan Layout

The floor and node plan diagram are drawn according to the building layout and fire system placements which are shown in Figures 5, 6, and 7. The measurement of the classrooms, corridor, and washroom was taken physically during the experiment.

Figure 2: General Mustafiz Tower, MIST, Mirpur Cantonment, Bangladesh

Figure 3: Student classroom

Figure 4: Common Space of the MIST academic building

Figure 5: Emergency exit and staircase

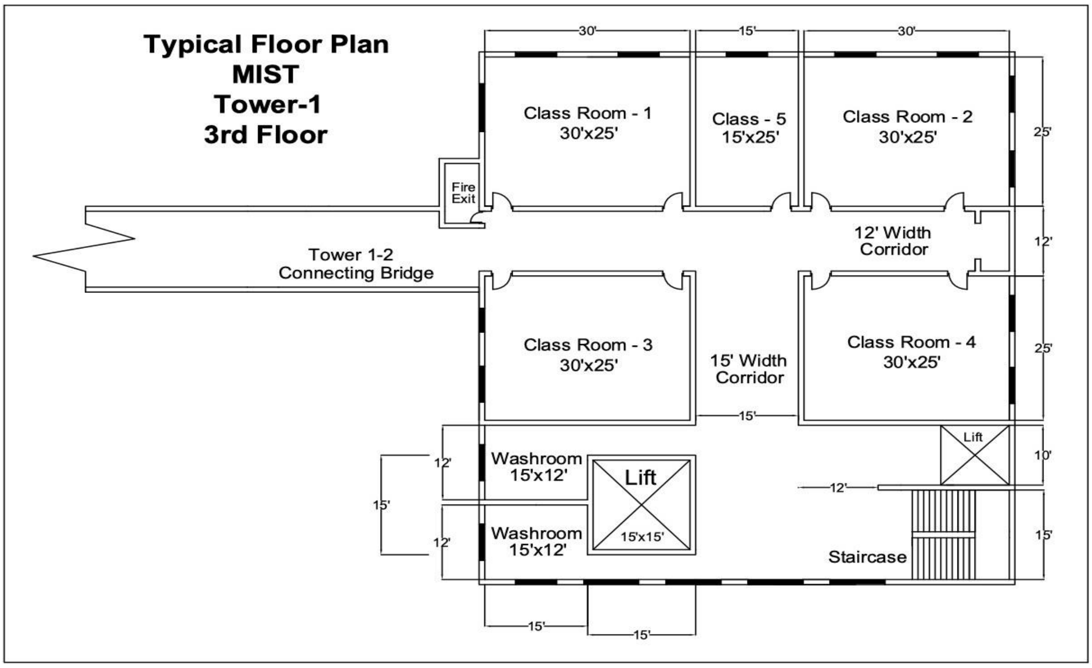

Figure 6: Floor plan of the MIST academic building

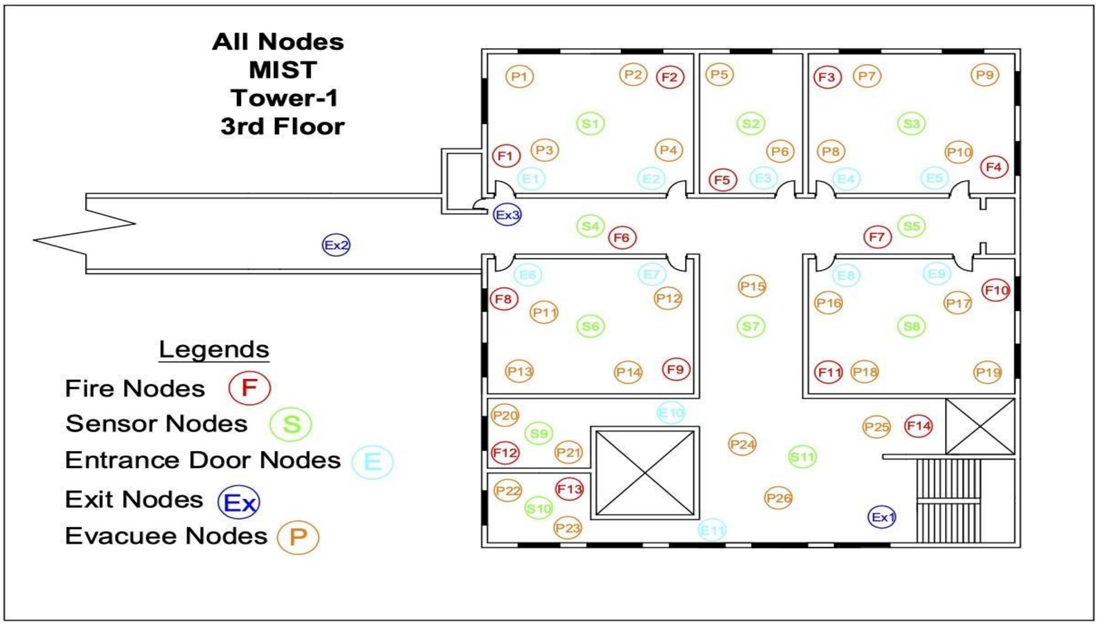

Figure 7: Combined nodes

As shown in Figure 6, the building can be modeled as a “graph”, or a series of connected nodes and weighted edges. Dijkstra’s Algorithm is a computational algorithm that is commonly used to find the shortest distance between two nodes in a graph (with weighted edges), making it the perfect computational tool to find the optimal escape path from one specified location to another. The main advantage of the algorithm is that it can plan the shortest path between any two locations (when modeled as a graph) with the smallest computational time. This is important as in a large building with many locations, nodes, and possible escape paths, there may be a very large number of possible combinations that the IoT system would need to compute if a “brute force” computation approach is used to find the shortest path, which may take far too long to compute in a real fire situation. The node-to-node distance is shown in Table 1 below.

3.4 Planning the Dynamic Fire Escape Path

3.4.1 Introduction and Overview

To demonstrate the application of IoT systems in a real firefighting scenario, this paper will make use of a web-based (http://dynamicfireescape.com:9999/SP_PROBLEM), simulation software "Dynamic Fire Fighting", a purpose-built to test out fire scenarios. The software will be used to simulate three fire scenarios, which will be visually represented as graphs by the software. Dijkstra's algorithm will then be applied by the software to illustrate how an IoT system may plan out an escape route.

3.4.2 Simulation Software

A web-based simulation software was created to demonstrate the application of Dijkstra's Algorithm as a proof of concept. This software takes a table of nodes and paths between the nodes as inputs (exactly in the format of Table 1 and outputs a table outlining the fastest path from one selected node to another. This software can be accessed at (http://dynamicfireescape.com:9999/SP_PROBLEM).

3.5 Executed Simulations for a Dynamic Fire Escape Path

Refer to Figure 7 Consider now a building with sensors, entrances, and exits in the locations as shown. Similarly, consider the evacuees and fires in the locations as shown in Table 2. The following is Table 2 of the scenarios that will be simulated for this demonstration.

Table 1: Node to node distance

Node to Node	Distance (ft)	Node to node	Distance (ft)
P1 – N1	20	P14 – N2	20
P2 – N1	39	P16 – N4	5
P3 – N1	5	P17 – N4	31
P4 – N1	31	P18 – N4	20
P1 – N2	39	P19 – N4	39
P2 – N2	20	P16 – N5	31
P3 – N2	31	P17 – N5	5
P4 – N2	5	P18 – N5	39
P5 – N3	20	P19 – N5	20
P6 – N3	5	P20 – N6	30
P7 – N4	20	P21 – N6	25
P8 – N4	5	P22 – N7	30
P9 – N4	39	P23 – N7	25
P10 – N4	31	E2 – N1	1
P7 – N5	39	E3 – N1	1
P8 – N5	31	N1 – N2	30
P9 – N5	20	N2 – N3	12
P10 – N5	5	N3 – N4	3
P11 – N1	5	N4 – N5	30
P12 – N1	31	N3 – N6	25
P13 – N1	20	N6 – N7	24
P14 – N1	39	E1 – N6	40
P11 – N2	31	E1 – N7	30
P12 – N2	5		
P13 – N2	39		

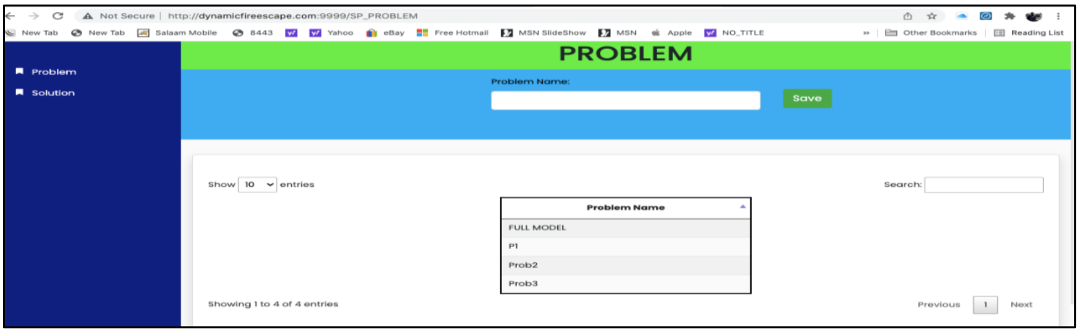

Figure 8: Simulation software interface

3.5.1 Scenario 1

Consider a case where, in the event of a fire breakout, there is an evacuee in the bottom left corner room, labeled Node P20 in Figure 7 As shown in Figure 10 below, it is not clear whether Evacuee P20 should take the exit Ex1 through the red path (Path A) or take exit Ex3 through the black path (Path B). There might be multiple paths in the real scenario under any hazardous situation. But we consider the shortest safety path, which will provide the most safety exist for the people. Our shortest path is based on the hazard location, not only the shortest by distance. Now, we can model this scenario exactly by using Table 1 and inputting the values into the software, and we have the following information from Figure 11.

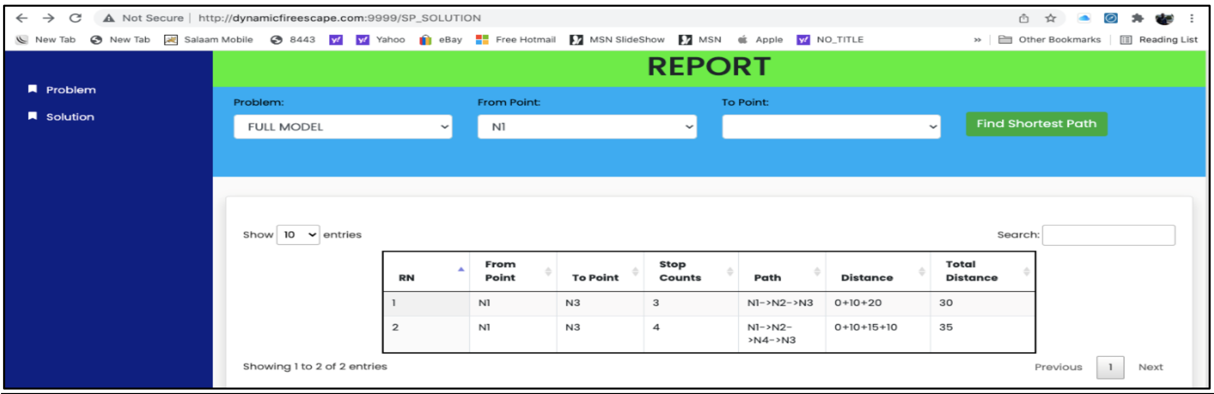

Figure 9: Simulation Software Interface

Table 2: Simulation dvancement

Scenario	Evacuee node	Possible target exits nodes	Fire node	Remarks, the rationale for the choice
1	P20	Ex3, Ex1	-	To illustrate a simple scenario without a fire node.
2	P1	Ex3, Ex2	F1	To illustrate a scenario where the fire is blocking the exit.
3	P19	Ex1, Ex3	F6, F11	To illustrate the most complex scenario where multiple fire nodes are blocking multiple entrances of the rooms, and it is not clear what is the shortest path the evacuee should take.

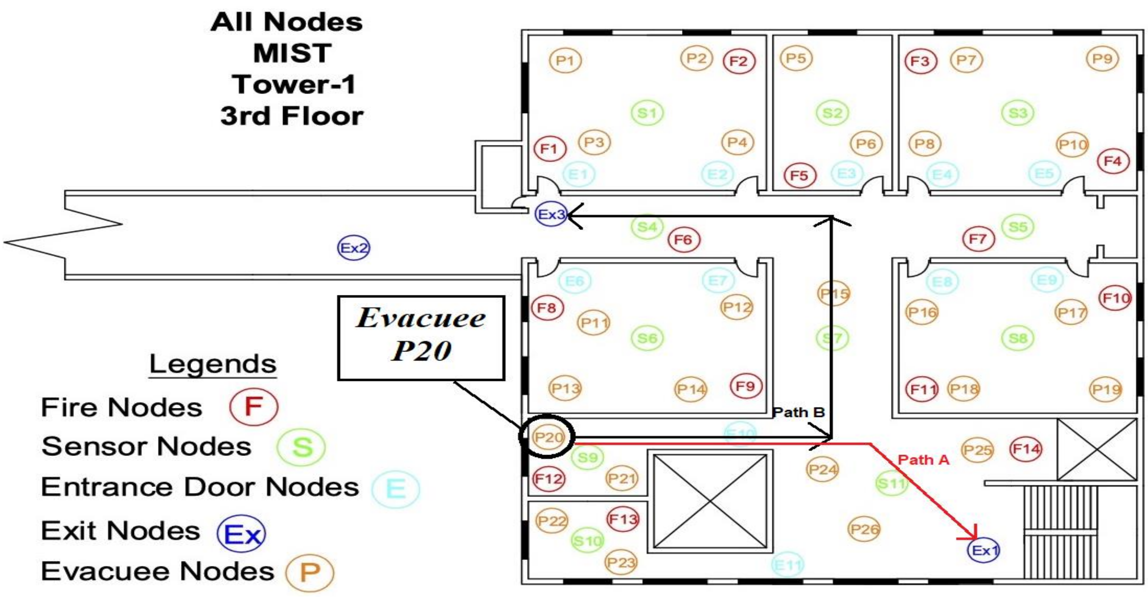

Figure 10: Possible escape paths of evacuee P20

As shown in Figure 12, the shortest path from P20 to Ex1 is 70 m. Thus, we can see that Path A to Ex1 in Figure 9 would be the shortest path available for the evacuee and will be recommended by the IOT system to the user.

In more complex and practical scenarios (such as Scenario 3), the system will always calculate the distances to ALL exits (not just Ex1 and Ex3). However, the other exits are not calculated in this example as it is observable by the eye that they are not as viable as Ex1 and Ex3, and the focus of this example is the result of the calculations. Indeed, all exits will be considered in the more complex Scenario 3.

3.5.2 Scenario 2

Next, consider the case of an evacuee represented by Node P1. As shown in Figure 13, under normal circumstances, his quickest exit route would be to take the green path (Path C) to exit Ex3. However, consider the scenario where that path is blocked by a fire, represented by node F1. Now, with the table row removed, we again run the algorithm with the 'from' node set to P1 and the target node set to Ex3. Now, as shown in Figure 15, the algorithm suggests that P1 goes to N2 first, (which is the further room door) then to N1 (outside the room), and finally to exit E3, thus avoiding the fire.

The algorithm now must re-calculate the quickest way out of the fire for the evacuee. In our model, N1 represents the room door that is being blocked by the fire node. So, to re-calibrate the software to incorporate the information of the fire node blocking the exit path, we remove the P1 - N1 node from the node-to-node table 1, and the value for the same is shown in Figure 14. As the data in Fifure 11 is identical to Table 1, only 10 out of 49 entries are shown to avoid cluttering this report with repetitive information. Now, in the "solution" section of the software, we set Ex3 and Ex1 to be our target nodes, as shown in Figure 10. The website now calculates the shortest paths to our target nodes using Dijkstra's Algorithm and displays each walk from node to node on each row.

Show 10 entries   Search:

Problem Name	From Point	To Point	Distance
FULL MODEL	P4	N1	31
FULL MODEL	P1	N2	39
FULL MODEL	P2	N2	20
FULL MODEL	P9	N5	20
FULL MODEL	P10	N5	5
FULL MODEL	P11	N1	5
FULL MODEL	P12	N1	31
FULL MODEL	P13	N1	20
FULL MODEL	P14	N1	39
FULL MODEL	P11	N2	31

Showing 1 to 10 of 49 entries   Previous 1 2 3

Figure 11: Possible escape paths of evacuee P20

RN	From Point	To Point	Stop Counts	Path	Distance	Total Distance
1	P20	E1	3	P20->N6->E1	0+30+40	70

Figure 12: Calculated exit path from P20 to Ex1

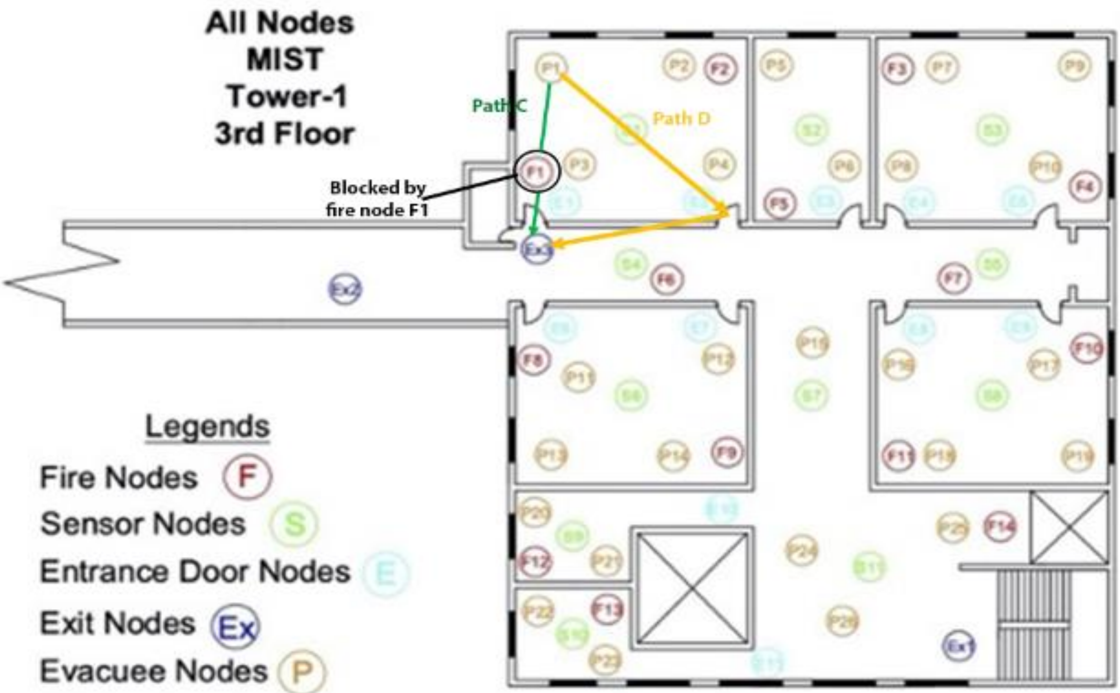

Figure 13: Quickest path to exit Ex3 avoiding.

FULL MODEL	P1	N1	20

Figure 14: Table row to be removed

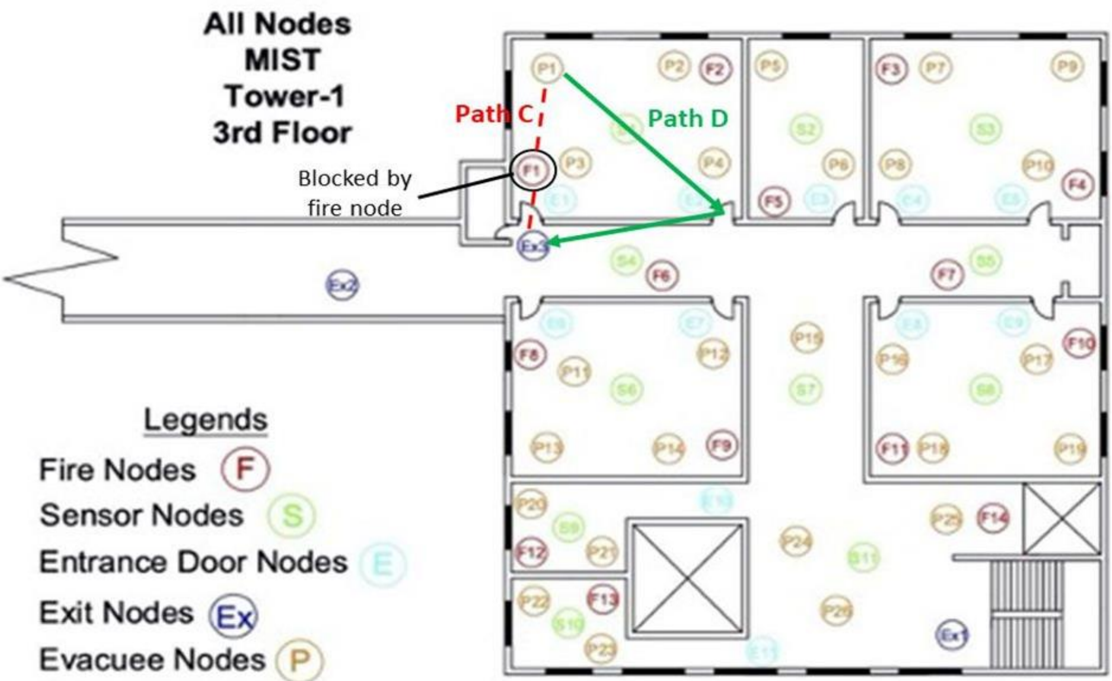

Figure 15: Evacuation path blocked by fire

3.5.3 Scenario 3

Finally, with such frameworks in place, consider the most complex (and likely realistic) fire scenario as shown in Figure 17, evacuee P19 trying to escape a fire, with fire nodes F6 and F11 actively blocking his path, and it is not clear how he should exit the building. This is the shortest path calculated by the software for all three exits combined. Charting this path on the Figure 7 diagram, we have Path F in purple, as shown in Figure 19.

Thus, through the application of Dijkstra's Algorithm in a complex fire scenario, we have successfully guided an evacuee through the shortest path to an exit while avoiding fires along the way. Now, in our software, we remove the node-to-node data connecting through F10 and F6 like in scenario 2. Setting each of the exits Ex1, Ex2, and Ex3 to be the target nodes, we get the following path in Figure 17 for Ex1.

3.6 System Flow Diagram

The system's proposed module is shown below in Figure 20 where signals from the fire alarm are sent to the database, which is then incorporated into the website, where the optimal route for escaping will be identified using the previous algorithm and the fire exit notification will be sent to all mobile users via Mobile Apps. Graphically, this is represented now by the yellow path (Path D) in Figure 13.

RN	From Point	To Point	Stop Counts	Path	Distance	Total Distance
1	P1	E3	4	P1->N2->N1->E3	0+39+30+1	70

Figure 16: Calculated path to be taken around fire node F1.

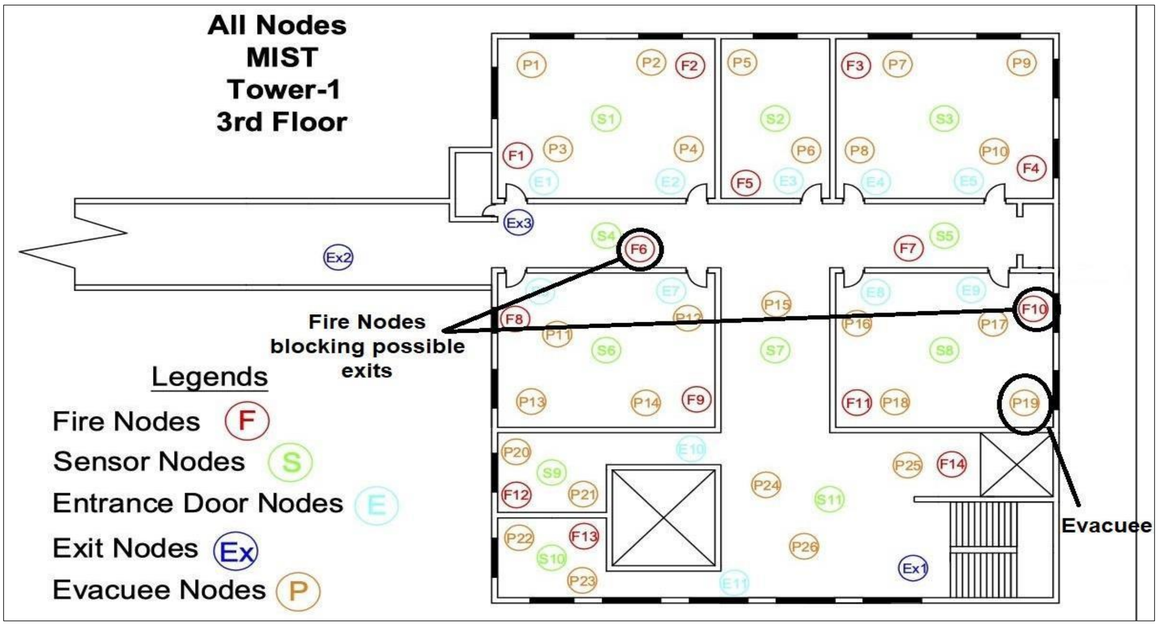

Figure 17: Complex fire scenario

RN	From Point	To Point	Stop Counts	Path	Distance	Total Distance
1	P19	E1	5	P19->N4->N3->N6->E1	0+39+3+25+40	107

Figure 18: Calculated path for evacuee P19 to take given a complex

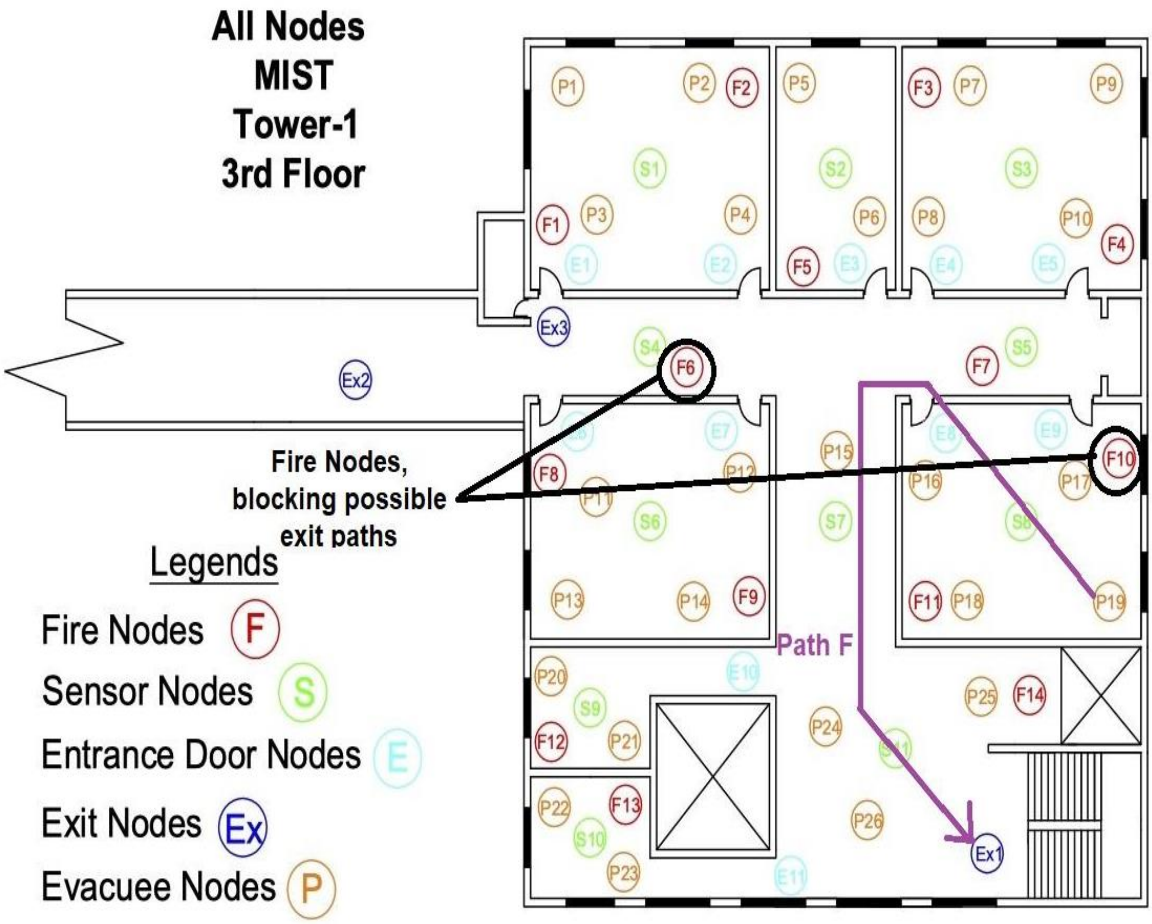

Figure 19: Exit path for evacuee P19

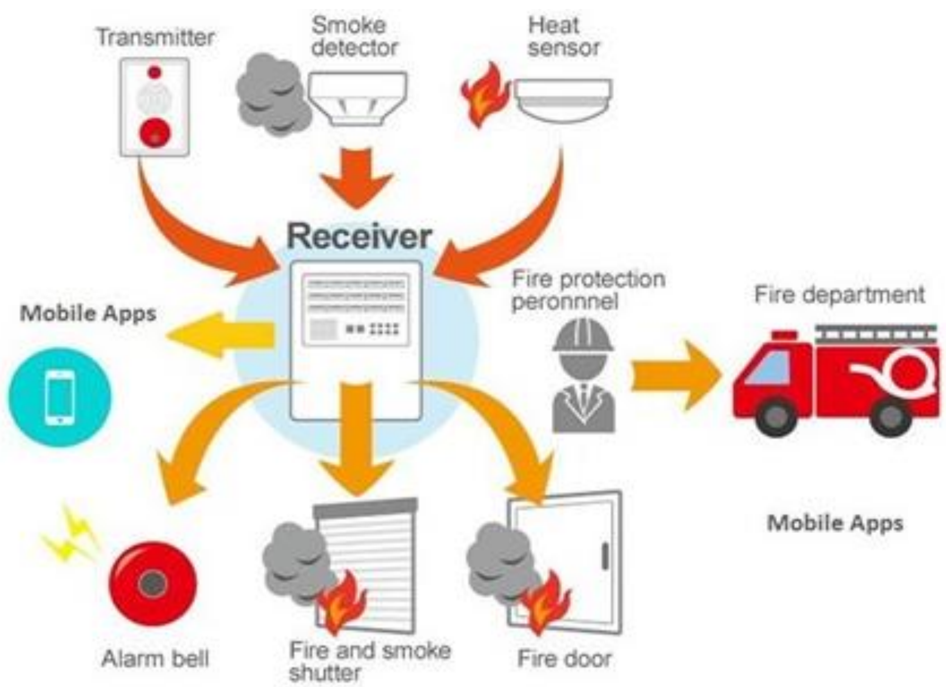

Figure 20: Components of Integrated Control System Module

5 CONCLUSIONS

The suggested IoT-based intelligent fire emergency response system can reduce casualties by recognizing the location of a disaster within a building to avoid directional confusion of emergency lights and improper evacuation assistance. By combining the intelligent and automated evacuation system with the central national disaster management agency, the intelligent emergency evacuation system can also aid firefighting by allowing for a speedy assessment of the exact location of the fire. It reduces casualties and evacuation time by directing evacuees to dispersed routes that avoid the location of the fire. Future research will focus on expanding the system's applicability to include not just building disasters, but also maritime boats and evacuation within buildings, disaster safety via web or mobile application services, and preventive activities for optimal disaster recovery.

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