# Rapid Crowd Evacuation for Passenger Ships using LPWAN

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***Abstract*—An emerging evacuation path planning technique that uses Low Power Wide Area Networks (LPWAN) to enable real-time danger prediction and user-oriented path planning can ensure the safe and timely navigation of evacuees in complex scenarios such as cruise ships. However, most existing LPWAN-based evacuation models assume pedestrians' walking speed remains constant and ignore crowd congestion in corridors before exits, which is not appropriate for rocking ships. To overcome these issues, this paper proposes a congestion-relived guiding framework with dedicated path planning for emergency evacuation on passenger ships. The basic idea is to averagely minimize the total evacuation time while meeting the deadline for ship capsizing under all circumstances by selecting uncrowded paths for each passenger individually. First, we use probability distributions rather than constant numbers to represent walking time (also called delay) along passageways. A worst-case delay bound with a high level of trustworthiness is also estimated for each passageway under the boundary condition of ship capsizing. Next, we predict the congestion of corridors by modeling the spatiotemporal movement of passengers, and then distribute evacuation loads evenly among corridors to alleviate the congestion. The total expected evacuation time of all corridors is finally minimized based on the delay probability distribution and estimated congestion, and the deadline for ship evacuation under all circumstances is met with the worst-case delay bound. Simulation results show that our approach significantly reduces the total escaping time of crowd evacuation by $45\%$ and $34\%$ while improving the navigation success ratio by more than $20\%$ and $80\%$ compared with the state-of-the-art emergency evacuation systems, namely the look-up table guiding scheme and the group-based guiding evacuation scheme, respectively.**

***Index Terms*—Passenger ship evacuation, Internet of things, User-centric guiding, rapid routing, Load balancing.**

## I. Introduction

MODERN passenger liners have the capability of carrying thousands of passengers and therefore if an accident involving such ships occurs its consequences will be disastrous. The safety of large passenger ships thus has gained increasing attention in recent years. Evacuation, a protective action in ship emergency circumstances, is very important in improving passenger and crew safety.

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Internet of Things (IoT), born with the ability to explore the dynamic environmental conditions and the movement of people, can be incorporated into an evacuation system to monitor and interact with the physical world [1], [2], [3], and [4]. When an emergency occurs, nodes collect the information on current hazard situation as well as the up-to-date distribution of people and send it to the path planning server which can provide guiding information to users equipped with smartphones or personal digital assistants (PDAs), so that they can escape from the hazardous area [5].

### A. Motivation

A diversity of specifically designed solutions for emergency evacuation with IoT has been proposed. On one hand, those works use wireless technologies such as IEEE 802.15.1 Bluetooth and IEEE 802.15.3 ZigBee low-rate wireless personal area networks (LR-WPANs) for sensor applications, which are not adapted to the ship evacuation scenario where it requires long-range transmission [6], [7], [8], [9], [10], [11], and [12]. LPWAN can provide long-range communication, while simultaneously it is inexpensive and highly energy efficient with a battery life of more than ten years [13], [14]. Therefore it is particularly suitable for the IoT application in emergency evacuation on large cruise ships, which only needs to transmit tiny amounts of data on environmental conditions (e.g., hazard information) to a path planning server in long range. In this paper, we supersede the widely employed short-range radio technologies by LPWAN. Fig. 1 shows the schematic representation of our proposed emergency evacuation scheme. In our scheme, a number of LPWAN nodes are deployed at exits, doors, and crossing points among corridors and/or doors of a passenger ship to monitor the real ship indoor environment. In addition, all passengers are equipped with smartphones that can communicate with nodes. The current location of each passenger is detected using the received strength of wireless signals on his/her smartphone, and the node ID with the strongest signal strength is used to determine the user's location in the blueprint database of node deployment. That is to say, we do not require accurate location information on each passenger in the proposed scheme. The smartphone periodically sends the determined position to the path planning server. When an emergency event is detected, the path planning server actively transmits a personalized evacuation path for each passenger to his/her smartphone and keeps updating it, according to the real-time collected information from users' smartphones and LPWAN nodes.

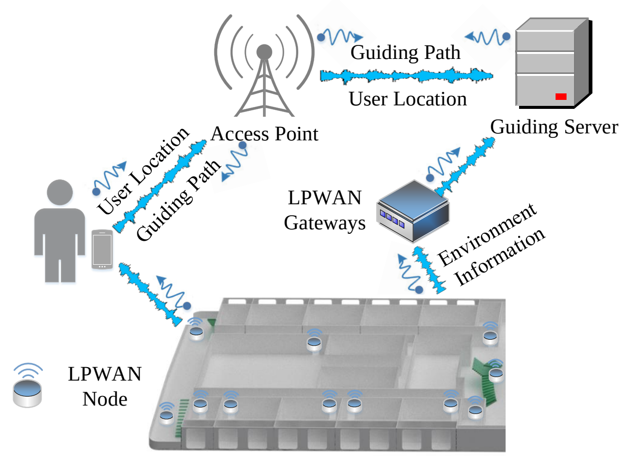



Fig. 1: Schematic representation of user-centric and congestion-relieved rapid emergency guiding scheme.

On the other hand, those works mostly address the emergency guiding in land-based buildings and do not sufficiently consider the unique characteristics of evacuation on passenger ships, such as the effect of changing inclination angles on passenger movement. Navigation solutions provided by those works deal with the situation where there is only a single constant numerical estimate of the delay/distance across individual passageways rather than a combination of probability distributions and upper bounds for delays of passageways. As a result, the planned escape paths are not necessarily optimal and even violate the deadline for ship evacuation, which is immensely perilous for passengers, due to the non-constant values of delay across individual passageways in an emergency on a passenger ship.

The prior work that is most related to ours assumed a model that characterizes each edge by a worst-case delay and a delay probability distribution. The performance objective considered in [15] is to identify safe paths that minimize the expected (i.e., average) delay. According to its provided solution, all passengers near a node, whose remaining deadlines are in the same interval, have to follow the same guiding direction of the next node. Considering the narrow corridors on passenger ships, escaping along the provided guiding direction is likely to cause a prolonged period required to evacuate passengers to the exit and even violate the specified deadline due to the possible waiting time resulting from congestion at certain passages or doors.

Before further introducing the motivation of this work, we present a formal definition as follows: the evacuation time of a path is defined as the sum of the moving time of corridors and the waiting delays of doors, exits, and crossing vertices.

Fig. 2 shows an illustrative example of the possible consequence of escaping along the guiding direction provided in [15] for 10 users, which helps to understand that it is indispensable to take into account the capacity of passageways/doors and the concurrent moving of different individuals in the design of passenger ship evacuation schemes. In the evacuation scenarios, the solid circles represent waypoints, and the green solid circle denotes the exit waypoint. The blue number alongside each edge between two waypoints indicates the expected delay that is computed using the delay probability distributions, and the red number denotes the worst-case delay which is the maximum delay that may be encountered in traveling the edge. In addition, the white number in each circle record the capacity of each waypoint. Based on the Hard-real-time routing algorithm in [15], the routing table at each waypoint is constructed, and all users, near the same waypoint and whose remaining deadlines are in the same interval, are guided to the same direction. According to temporal order, subgraphs (a)-(d) show the snapshots of evacuating 10 users in three intervals. We can see that there is no feasible route for the four users in red to take due to the needful waiting time caused by the congestion at $v_1$. We hope to utilize more idle and/or under-loaded paths such as the path $v_0 \rightarrow v_2 \rightarrow v_5$ as shown in Fig. 3 (the initial people distribution is the same as that at time $t_0$=0 in Fig. 2) evacuating the excessive users who will be delayed by the congestion and thus violate the specified deadline.

The above example reveals that it is unreliable to use the routing table provided by [15], and the congestion caused by the limited capacity of passageways/doors and the excessive number of people should be carefully taken into account in the design of evacuation for passenger ships. A safe and efficient evacuation approach should guide evacuees along the sub-optimal paths which are idle and/or underloaded so as to guarantee the eventual success of evacuation.

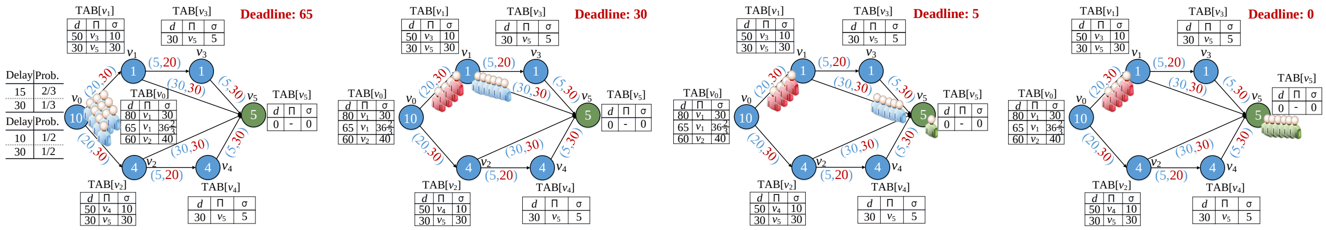
### B. *Contributions*

Inspired by the above analysis, in this work, a user-centric congestion-relieved rapid path planning scheme is designed for evacuation guiding on passenger ships based on LPWAN (see Fig. 1). By considering the expected and worst-case delay across each passageway, corridor capacities, and the spatiotemporal mobility of all passengers together, our scheme can generate dedicated paths to minimize the total expected evacuation time while respecting a specified deadline. We first assign the passenger evacuation order according to the current evacuation time to make the difference of evacuation loading among passageways as balanced as possible and then plan dedicated escape routes accordingly based on the evacuation order.

The main contributions and novelty of this study are concluded as follows:

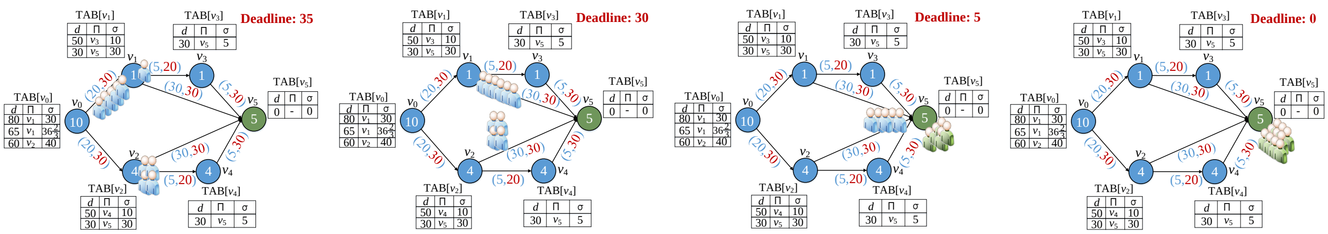
i) Currently, only LR-WPANs are of special concern in designing technology-assisted means to provide evacuees with navigation advice during emergencies. However, the ad-hoc deployment of LR-WPANs nodes in a large and complicated passenger ship will cause some nodes, especially near the gateway, to get more congested and thus resulting in packet losses and longer end-to-end delays in communicating environmental dynamics and navigation decisions. Our proposed scheme first uses the new wireless communication technology, i.e., LPWAN, to monitor the environmental condition on a passenger ship and transmit it to the path planning server.

ii) The evacuation condition on a damaged passenger ship is relatively complex, resulting in the movement of passengers




(a) $t$=0 (b) $t$=35 (c) $t$=60 (d) $t$=65

Fig. 2: Emergency evacuation for 10 users using the Hard-real-time routing algorithm in [15]. (a) indicates the distribution of people at time 0. The deadline is assumed to be 65. According to the constructed routing tables, all users escape from $v_0$ to $v_1$. Suppose that they encounter the worst-case delay of 30 across that edge. The up-to-date distribution of people at time 35 is shown in (b). There is no feasible path guaranteeing a delay bound smaller than 30 and thus it declares evacuation failure for the four users in red. (c) shows the distribution of people at time 60. A user in green is evacuated from the exit $v_5$. (d) indicates the distribution of people at time 65. Six users in green safely escape from the exit $v_5$.




(a) $t$=30 (b) $t$=35 (c) $t$=60 (d) $t$=61

Fig. 3: Multi-path routing for emergency evacuation of 10 users in the example graph of Fig 2. Both the specified deadline and the initial people distribution are the same as those of Fig. 2. (a) indicates the up-to-date distribution of people at time 30. Six users move along the edge from $v_0$ to $v_1$, and four others are navigated along the edge from $v_0$ to $v_2$. All users experience the worst-case delay of 30 across the two edges and then are guided to the exit as shown in (b). (c) shows the distribution of people at time 60. Six users safely escape from the exit. At the time 61, all users are navigated to leave the exit as shown in (d).

being affected seriously by the ship's dynamic inclination. Hence, compared with the existing work that aims to provide navigation paths in a deterministic environment, this paper incorporates the probabilistic information into our algorithm without compromising safety guarantees.

iii) Further, we relax the constraint on the number of guiding directions at every single waypoint to design a user-centric evacuation scheme where the passengers' spatiotemporal mobility, the possible corridor traversal time, and the corridor capacities are considered together for the first time to determine evacuation orders and dedicated paths for large-scale crowds to relieve the congestion of corridors and exits and minimize the total evacuation time while respecting the end-to-end deadline for ship evacuation.

iv) A prototype experiment is implemented to verify the feasibility of our scheme. In addition, extensive simulations are conducted and the results show the superiority of our framework with the comparison of the existing evacuation schemes with the guaranteed delay bound.

### C. Structure of the Article

The rest of this paper is organized as follows. Section II discusses existing works. Section III defines our user-centric path planning problem for passenger emergency guiding. Section IV presents our developed user-centric and congestion-relieved approach for dedicated path planning. Performance evaluations based on a real system and extensive simulations are shown in Sections V and VI. Finally, Section VII concludes the paper.

## II. Related Work

### A. Land-based evacuation based on IoT

Several land-based evacuation approaches with IoT have been proposed. From the perspective of dealing with crowd congestion, the current progress in support of emergency evacuation in buildings is classified into two categories: passive evacuation and proactive congestion-relived evacuation.

References [9], [16], [17], [18], [19], [20], [21] determined escape routes only according to the distance from each sensor to exits or hazards. [17] used potential fields in their algorithm to compute the navigation paths that maximize the minimum distance to hazardous areas, based on the global flooding generated at a destination sensor. In [18], [19], the temporally ordered routing algorithm with global flooding was developed for optimizing the length of safe paths. [19] also took the structures of 3D buildings into account. To reduce the communication expense, [20] introduced a skeleton graph, i.e., the sparse subset of the original graph, to approximate the optimal safe paths. [21] was able to plan navigation paths with much lower communication overhead by only exploiting local geographic information. Wang *et al*. presented a road map-based method, which relieved the reliance on accurate location information [16]. Under dynamic hazardous environments, these path planning solutions, depending on the recalculation of navigation routes, may lead to users' oscillations. Frequent oscillations inevitably result in users remaining in danger for a longer period of time and eventually missing the chance of survival due to the blocking of all escape routes. [9] proposed OPEN, a navigation approach that provides paths with the minimum probability of oscillations.

Without balancing the evacuation load in corridors and exits, the above-mentioned navigation schemes can guide evacuees to an over-congested route. Heavy congestion is likely to amplify users' panic and thus cause a higher threat to users' safety. [22] proposed a distributed load-balanced guiding protocol that dispersed people to multiple exits according to the load of each path to achieve mild congestion and assist people in escaping quickly. Considering the vulnerability of users nearby dangers to congestion, [10] constructed a hazard level map tracking the evolution of boundaries of hazardous areas, so that users close to an emergency can be branched into different routes to avoid heavy congestion. Those approaches, however, neglect to consider path and exit capacities and therefore they are not enough to solve the congestion problem due to the different capacities of corridors/exits. [23] took the evacuation capacities of exits into account. Each exit sensor is assigned a negative hazard potential value reversely proportional to its capability so that exits with higher evacuation capacities can attract more trapped users than exits with lower capacities. In [24], authors connected path capacity and moving speed. The artificial potential value of each sensor is determined by the moving speed of evacuees, distances to exits, as well as weighted exit capacities, and therefore the load of each road and exit can be balanced. [11] designed an analytical model in which corridor length and capacity, exit capacity, and concurrent movement and distribution of people are considered together to further reduce the total evacuation time. Because these methods are to find a guiding direction for every single sensor for evacuating people nearby, a group of people near a sensor have to follow the same direction. Thus, the evacuation load of corridors cannot be fully balanced. [25] relaxed the constraint on the number of direction assignments of every single sensor to design a user-centric guiding protocol, which provides a personalized guiding direction for each individual user and substantially reduces the total evacuation time. However, these methods neglected the high-level uncertainty of evacuation environments, they provided evacuation plans in a deterministic context which is not the case with researchers' considerations of uncertain real-world evacuation environments. [26] considered the uncertainty of population distributions in endangered areas, and expressed them as Type-2 fuzzy variables of an uncertain path-based one-destination network flow model. [27] took the uncertainty of travel time and risk into account and established a path-planning method based on multi-objective robust optimization to minimize the total cost function that combines the total evacuation time, the total risk, and the total congestion. [28] presented a stochastic dynamic traffic assignment model, which represents the time-varying characteristics of the traffic flow, for emergency evacuations with the consideration of background traffic. However, these approaches are not suitable for the problem we seek to solve due to not incorporating the "hard" end-to-end deadline that is a fundamental part of ship emergency evacuation.

### B. *Evacuation on passenger ships*

There is a significant research effort related to path optimization at sea aiming to aid ships in their navigation. Most of them focus on tackling the challenges associated with automatic collision avoidance concerning the maneuvering capabilities of ships as well as complying with maritime traffic rules [29], [30]. In addition, [31] constructed a space-air-sea-ground integrated monitoring network-based forecasting system for supporting the operational response of ships in distress. Compared with mature ship path planning, the work on passenger path planning on ships in case of emergencies is relatively limited.

The present studies on evacuation on passenger ships pay attention to simulating and modeling crowd behaviors under emergencies [32], [33], [34], and [35]. Our paper does not focus on human behavior modeling or the belief-desire-intention (BDI) framework for emergency scenarios. These methods are beyond the scope of this paper and are not discussed here. The prior work pertaining to ours is [36]. [36] took the limited ship survival time and the impact of ship motion on the movement speed of passengers into account. An adaptive emergency navigation strategy (ANT) based on rapid routing with guaranteed delay bounds algorithm was developed to determine hazard-free routes that typically experience the minimum delay while respecting the deadline by which passengers need to reach the embarkation points just beside the lifeboats or Marine Evacuation Systems (MES) under all circumstances. However, the related work finds optimal paths only using the typical-case and worst-case delay that characterize each passageway, while ignoring the waiting time due to congestion. In reality, if users evacuate along paths provided by ANT, it is likely to cause a prolonged typical period required to evacuate passengers to the exit and even violate the specified deadline considering the limited capacity of corridors/exits on ships. By far, a ship passenger evacuation solution is desired, which can provide safe and fast navigation service with IoT by taking multiple features (including the effect of ship motion on pedestrian motion, the limited ship survival time, the limited capacity of corridors/exits, and the up-to-date distribution and concurrent movement of passengers) into account.

## III. System Model and Problem Statement

We address the scenario in which trapped passengers are navigated toward an exit. In practice, the exit could be the specified muster station on a passenger ship. The goal is to ensure the passengers' safe and timely evacuation.

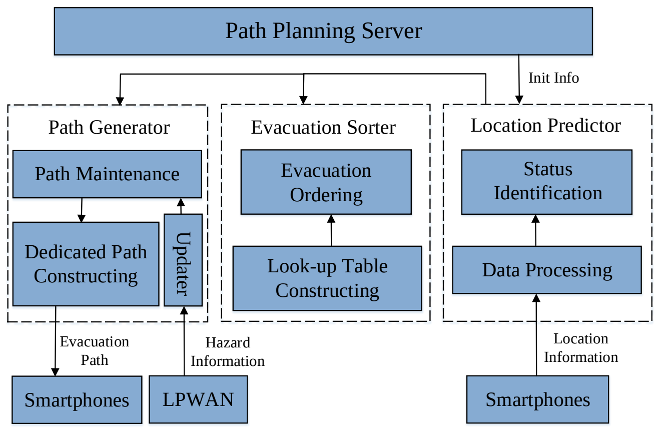



Fig. 4: Overview of our evacuation scheme.

In this section, we introduce the architecture overview of our proposed emergency guiding scheme, followed by the model and definitions. The third part describes the problem specification.

### A. System architecture

Fig. 4 shows the architecture of our evacuation scheme, which consists of three main modules: location predictor, evacuation sorter, and path generator. These modules are integrated into the path planning server, providing a dedicated route for each user. First, the location predictor receives the location information on each user and then set the corresponding nodes as user nodes. Second, the evacuation sorter assigns evacuation orders to individuals for dedicated path planning by considering multiple features (i.e., the up-to-date distribution and concurrent movement of passengers, the moving time probability distribution across each corridor, and the capacities of corridors) together. Finally, the personalized paths are determined and sent to users' smartphones. Escaping along these provided paths can achieve the shortest expected total evacuation time, while guaranteeing to get passengers to the exit by the estimated deadline for ship evacuation.

To achieve improved performance, it is needed to re-plan evacuation paths for passengers until they reach the exit when the emergency environment changes due to the dynamic nature of hazards (e.g., expansion, contraction, clearance, and movement of hazardous areas). In addition, we assume that all passengers follow the offered indicators on their smartphones during evacuation.

### B. Model and definition

We model the LPWAN deployed in the indoor space of a passenger ship with one exit as a directed graph $\mathcal{G}$=($\mathcal{V}$, $\mathcal{E}$) as shown in Fig. 5, where $\mathcal{V}$ represents the set of waypoints (i.e., LPWAN nodes) and $\mathcal{E}$ is the set of segments (i.e., the walk paths between waypoints). The waypoints in $\mathcal{V}$ are classified into three types: exit waypoints, door waypoints, and crossing waypoints, which indicate the waypoints located at exits, doors, or crossing points among corridors and/or doors.

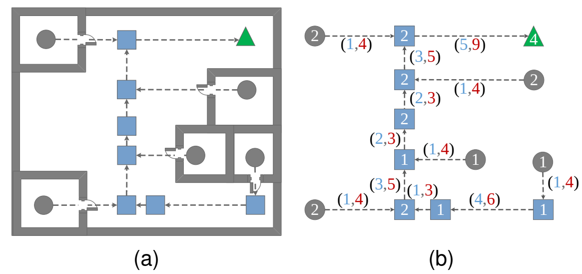



Fig. 5: Spatial modeling of indoor spaces. Squares, circles, and triangles represent crossing waypoints, door waypoints, and exit waypoints, respectively. (b) denotes $\mathcal{G}$ weighted by capacities and moving delay, where white numbers inside waypoints indicate their capacities, and blue numbers as well as red numbers alongside segments respectively represent the expected delays and worst-case delays across those segments.

Each waypoint $v_i$ is weighted by its capacity $c_i$ (i.e., the number of passengers allowed to enter the waypoints per second). If the number of passengers remaining at a waypoint is greater than or equal to its capacity when an evacuee reaches, then the evacuation time of the evacuee equals his/her total moving time plus the waiting delay caused by the congestion. In addition, if two or more corridors with different capacities intersect each other, separate crossing waypoints are added to the directed graph for each corridor capacity. For each segment $\overrightarrow{v_iv_j}$, a probabilistic moving time function $P_{\overrightarrow{v_iv_j}}$ is specified. In our proposed model, $P_{\overrightarrow{v_iv_j}}$ is assumed to be the discrete probability distribution of the finite set of actual delays across the segment $v_iv_j$. That is, $P_{\overrightarrow{v_iv_j}}(d)$ is defined as the probability that the delay in traversing $\overrightarrow{v_iv_j}$ is $d$. In this paper, we suppose that $P_{\overrightarrow{v_iv_j}}$ is known a prior for all segments $\overrightarrow{v_iv_j} \in \mathcal{E}$. In addition, each segment $\overrightarrow{v_iv_j}$ is labeled with the expected delay $d_{\mathrm{T}}(\overrightarrow{v_iv_j})$ and the worst-case delay $d_{\mathrm{W}}(\overrightarrow{v_iv_j})$. $d_{\mathrm{T}}(\overrightarrow{v_iv_j})$ is an estimate of the expectation of all possible delays on the segment, which is computed as follows:

$$d_{\mathrm{T}}(\overrightarrow{v_iv_j}) = \sum_{\left\{d | P_{\overrightarrow{v_iv_j}}(d)>0\right\}} d \times P_{\overrightarrow{v_iv_j}}(d). \tag{1}$$

While $d_{\mathrm{W}}(\overrightarrow{v_iv_j})$ is the deterministic upper bound on the delay that will be encountered upon traversing the segment $\overrightarrow{v_iv_j}$.

### C. Problem formulation

In this work, we study the problem of escaping with a low expected delay from the current location to an exit in the constructed graph, while guaranteeing to arrive at the exit within the deadline for ship evacuation by considering 1) the expected and worst-case moving time across each segment, 2) the capacity of each waypoint, 3) the spatiotemporal mobility of individuals.

We first introduce some notations for formulating the objective of our emergency evacuation scheme. $v_e$ denotes the exit waypoint and $\mathcal{V}_u$ is the set of the user waypoints. We assume that there are $N$ users and path $p_j$ is assigned user $u_j$, $1 \leq j \leq N$. Let $v_i^j$ denote the $i$-th waypoint on path $p_j$. $p_j$ is a waypoint sequence:

$$p_j \triangleq \left\langle v_u^j \equiv v_0^j, v_1^j, v_2^j, ..., v_k^j \equiv v_e \right\rangle.$$

where $v_u^j \in \mathcal{V}_u, \overrightarrow{v_{i-1}^j v_i^j} \in \mathcal{E}$ for $1 \leq i \leq k$, $v_0^j$ and $v_k^j$ respectively represent the waypoint location of user $u_j$ and the exit.

Let $w_{\mathrm{W}}^j(i)$ and $w_{\mathrm{T}}^j(i)$ be the worst-case and expected waiting time at waypoint $v_i^j$ respectively. The worst-case delay $d_{\mathrm{W}}(p_j)$ and expected delay $d_{\mathrm{T}}(p_j)$ of path $p_j$ are defined in the following manner:

$$d_{\mathrm{W}}(p_j) = w_{\mathrm{W}}^j(0) + \sum_{i=1}^{k}(d_{\mathrm{W}}(\overrightarrow{v_{i-1}^j v_i^j}) + w_{\mathrm{W}}^j(i)). \quad (2)$$

$$d_{\mathrm{T}}(p_j) = w_{\mathrm{T}}^j(0) + \sum_{i=1}^{k}(d_{\mathrm{T}}(\overrightarrow{v_{i-1}^j v_i^j}) + w_{\mathrm{T}}^j(i)). \quad (3)$$

Let $T_{\mathrm{W}}^{(1,j)}(i)$ and $T_{\mathrm{T}}^{(1,j)}(i)$ respectively be the worst-case and expected time to evacuate from $v_i^{j+1}$ for the last user of $u_1$, $u_2$,..., $u_j$. The worst-case waiting time $w_{\mathrm{W}}^{j+1}(i)$ and expected waiting time $w_{\mathrm{T}}^{j+1}(i)$ of user $u_{j+1}$ at waypoint $v_i^{j+1}$ can be calculated by:

$$w_{\mathrm{W}}^{j+1}(i) = \begin{cases} 0, \text{if} T_{\mathrm{W}}^{(1,j)}(i) < \sum_{l=0}^{i-1}(d_{\mathrm{W}}(\overrightarrow{v_l^{j+1} v_{l+1}^{j+1}}) + w_{\mathrm{W}}^{j+1}(l)) \\ T_{\mathrm{W}}^{(1,j)}(i) - \sum_{l=0}^{i-1}(d_{\mathrm{W}}(\overrightarrow{v_l^{j+1} v_{l+1}^{j+1}}) + w_{\mathrm{W}}^{j+1}(l)), \\ \text{otherwise} \end{cases} \quad (4)$$

$$w_{\mathrm{T}}^{j+1}(i) = \begin{cases} 0, \text{if} T_{\mathrm{T}}^{(1,j)}(i) < \sum_{l=0}^{i-1}(d_{\mathrm{T}}(\overrightarrow{v_l^{j+1} v_{l+1}^{j+1}}) + w_{\mathrm{T}}^{j+1}(l)) \\ T_{\mathrm{T}}^{(1,j)}(i) - \sum_{l=0}^{i-1}(d_{\mathrm{T}}(\overrightarrow{v_l^{j+1} v_{l+1}^{j+1}}) + w_{\mathrm{T}}^{j+1}(l)), \\ \text{otherwise} \end{cases} \quad (5)$$

That is, if the worst-case (or expected) arrival time at $v_i^{j+1}$ of user $u_{j+1}$ is smaller than $T_{\mathrm{W}}^{(1,j)}(i)$ (or $T_{\mathrm{T}}^{(1,j)}(i)$), user $u_{j+1}$ has to wait in the worst case (or the expected case) because some passengers are still jammed at $v_i^{j+1}$. Otherwise, there is no worst-case (or typical) waiting time at $v_i^{j+1}$ for user $u_{j+1}$ because there are no other passengers waiting at $v_i^{j+1}$. $T_{\mathrm{W}}^{(1,j)}(i)$ and $T_{\mathrm{T}}^{(1,j)}(i)$ can be calculated by:

$$T_{\mathrm{W}}^{(1,j)}(i) = \begin{cases} \sum_{l=0}^{i-1}(d_{\mathrm{W}}(\overrightarrow{v_l^j v_{l+1}^j}) + w_{\mathrm{W}}^j(l)), \text{if} v_i^j \notin p_{(1,j-1)} \\ \max(\sum_{l=0}^{i-1}(d_{\mathrm{W}}(\overrightarrow{v_l^j v_{l+1}^j}) + w_{\mathrm{W}}^j(l)), T_{\mathrm{W}}^{(1,j-1)}(i)), \\ \text{otherwise} \end{cases} \quad (6)$$

$$T_{\mathrm{T}}^{(1,j)}(i) = \begin{cases} \sum_{l=0}^{i-1}(d_{\mathrm{T}}(\overrightarrow{v_l^j v_{l+1}^j}) + w_{\mathrm{T}}^j(l)), \text{if} v_i^j \notin p_{(1,j-1)} \\ \max(\sum_{l=0}^{i-1}(d_{\mathrm{T}}(\overrightarrow{v_l^j v_{l+1}^j}) + w_{\mathrm{T}}^j(l)), T_{\mathrm{T}}^{(1,j-1)}(i)), \\ \text{otherwise} \end{cases} \quad (7)$$

We have the following base-case expressions $T_{\mathrm{W}}^1(i)$ and $T_{\mathrm{T}}^1(i)$:

$$T_{\mathrm{W}}^1(i) = \sum_{l=0}^{i-1} d_{\mathrm{W}}(\overrightarrow{v_l^1 v_{l+1}^1}). \quad (8)$$

$$T_{\mathrm{T}}^1(i) = \sum_{l=0}^{i-1} d_{\mathrm{T}}(\overrightarrow{v_l^1 v_{l+1}^1}). \quad (9)$$

Finally, the total worst-case and expected evacuation time of $u_1$, $u_2$, ..., and $u_j$ are respectively equal to:

$$d_{\mathrm{W}}(p_{(1,j)}) = \max(d_{\mathrm{W}}(p_1), d_{\mathrm{W}}(p_2), ..., d_{\mathrm{W}}(p_j)). \quad (10)$$

$$d_{\mathrm{T}}(p_{(1,j)}) = \max(d_{\mathrm{T}}(p_1), d_{\mathrm{T}}(p_2), ..., d_{\mathrm{T}}(p_j)). \quad (11)$$

The above estimation will be repeated until all evacuation time of $u_1$, $u_2$, ..., and $u_N$ are calculated. Our goal is to find a schedule minimizing the Total Evacuation Time (*TET*):

$$TET = \min((\max(d_{\mathrm{T}}(p_1), d_{\mathrm{T}}(p_2), ..., d_{\mathrm{T}}(p_N))), \quad (12)$$

subject to:

$$\max(d_{\mathrm{W}}(p_1), d_{\mathrm{W}}(p_2), ..., d_{\mathrm{W}}(p_N)) \leq DL. \quad (13)$$

where *DL* denotes the specified deadline for ship evacuation.

## IV. User-centric Congestion-relieved Rapid Evacuation Method

In this section, we solve the congestion-relieved rapid path planning problem for user-centric emergency evacuation based on the work [15]. The procedure of our method is presented in pseudo-code form in Algorithm 1. The steps to determine the personalized route for each user, which can achieve the short total expected evacuation time while simultaneously guaranteeing that the total worst-case evacuation time is no more than the specified deadline for ship evacuation, are as follows:

- Modeling the indoor environment of a passenger ship
- Mapping individual locations
- Calculating congestion-relieved evacuation orders for each passenger
- Planning personalized evacuation paths

In Section III-A and Section III-B, we have the description of how to model ship indoor environment and map individual positions to the blueprint database of LPWAN node deployment. Regarding the modeling of the multi-floor ship indoor space, we add segments for stairs between floors. In the following, we elaborate on the planning of congestion-relieved evacuation orders and personalized evacuation routes.

In Algorithm 1, $\mathcal{P}$ denotes the set of the planned paths for all users, $ET_{\mathrm{T}}^{v_i}$ and $ET_{\mathrm{W}}^{v_i}$ are the evacuation tables added to each waypoint $v_i$ respectively recording the expected and worst-case time required by all individuals to arrive at $v_i$. When an emergency event outside existing hazardous regions is detected, return to Line 1.

**Algorithm 1:** User-centric congestion-relived rapid evacuation.

**Input:** $\mathcal{G}$, $\mathcal{V}_u$
**Output:** $\mathcal{P}$
Construct evacuation graph;
**for** $i \leftarrow 1$ to $N$ **do**
  Map users $u_i$ to waypoints;
**end**
Call procedure Modified HRPG ($\mathcal{G}$=($\mathcal{V}$, $\mathcal{E}$), $\mathcal{V}_u$);
**for** $v_i \in \mathcal{V}$ **do**
  $ET_{\mathrm{T}}^{v_i}$={};
  $ET_{\mathrm{W}}^{v_i}$={};
**end**
**while** $N > 0$ **do**
  $d_{\mathrm{T}}(p_{min})$=min$\{d_{\mathrm{T}}(p) | d_{\mathrm{W}}(p) \leq D\}$;
  **for** $v_j \in p_{min}$ **do**
    $ET_{\mathrm{T}}^{v_j^{p_{min}}}\left[d_{\mathrm{T}}(v_0^{p_{min}} \rightarrow v_j^{p_{min}})\right]$++;
    $ET_{\mathrm{W}}^{v_j^{p_{min}}}\left[d_{\mathrm{W}}(v_0^{p_{min}} \rightarrow v_j^{p_{min}})\right]$++;
    $N$- -;
  **end**
**end**

### A. Ordering of evacuation for each individual

We design a congestion-relived scheme to determine the evacuation order based on the worst-case and typical evacuation time to the exit with the possible congestion caused by the escape of other users and the limited capacity of waypoints. The working flow of evacuation ordering for each individual is as follows.

1) Based on the algorithm in [15], the routes with specific expected delays while guaranteeing to respect the end-to-end deadline are determined for each user waypoint by only using the worst-case and expected delay across each segment. Note that we skip the comparison of the generated 3-tuples at user waypoints. That is, all tuples meeting the specified deadline are inserted for planning routes more efficiently. In addition, the 3-tuple in our scheme consists of $d$, $p$, and $d_{\mathrm{T}}(p)$ instead of $d$, $\pi$, and $\sigma$, with $d_{\mathrm{T}}(p)$ being the expected delay along the path $p$ within the guaranteed worst-case delay bound $d$. The modified HRPG algorithm is shown in Algorithm 2 in the Appendix, where $v_k$ represents the downlink neighbor of $v_j$. The set $\mathcal{N}_j^D$ of $v_j$'s downlink neighbors is defined as follows:

$$\mathcal{N}_j^D \triangleq \{v_k \in \mathcal{V} | \overrightarrow{v_j v_k} \in \mathcal{E}\}$$

All users are sorted as $u_1$, $u_2$, ..., and $u_N$ according to the planned escape routes $p_1$, $p_2$, ..., and $p_N$ with the shortest expected evacuation time $d_{\mathrm{T}}(p_1)$, $d_{\mathrm{T}}(p_2)$, ..., and $d_{\mathrm{T}}(p_N)$ while guaranteeing users' arrival by the deadline under all circumstances, where $d_{\mathrm{T}}(p_1) \leq d_{\mathrm{T}}(p_2) \leq ... \leq d_{\mathrm{T}}(p_N)$. If two or more users have the same shortest expected evacuation time, the user with a longer second shortest evacuation time is selected first, and so on. If their all safe paths (i.e., paths that guarantee the user will meet the deadline even under worst-case circumstances) to exits have the same expected evacuation time, one of them can be simply randomly selected first. User $u_1$ is evacuated first along $p_1$.

2) The remaining users are sorted as $u_2$, $u_3$,..., and $u_N$ by their paths $p_2$, $p_3$,..., and $p_N$ with the shortest expected evacuation time $d_{\mathrm{T}}(p_2)$, $d_{\mathrm{T}}(p_3)$,..., and $d_{\mathrm{T}}(p_N)$, while guaranteeing users' arrival by the deadline under all circumstances. But we take the possible congestion caused by $u_1$ in this ordering. $u_2$ is selected to evacuate along the route $p_2$ after $u_1$. Note that now the order of evacuation may differ from the previous sorting due to the possible jam resulting from the escape of $u_1$ along the path $p_1$.

3) Likewise, the remaining users are sorted as $u_3$, $u_4$,..., and $u_N$ by their paths $p_3$, $p_4$,..., and $p_N$ with the shortest expected evacuation time $d_{\mathrm{T}}(p_3)$, $d_{\mathrm{T}}(p_4)$,..., and $d_{\mathrm{T}}(p_N)$, while guaranteeing users' arrival by the deadline under all circumstances. In this sorting, the possible congestion due to both $u_1$ and $u_2$ are considered. If the number $n$ of users arriving at a waypoint $v_i$ at the time $t$ is less than or equal to the capacity $c_i$ of $v_i$, then all of them can concurrently pass $v_i$ at $t$ without any delay. Otherwise, $n - c_i$ users will be delayed and evacuated at $t$+1. Similarly, if $n - c_i$ is still larger than $c_i$, then $n - 2c_i$ users only can pass $v_i$ at $t$+2 and so on. The above process is repeated until all users are selected.

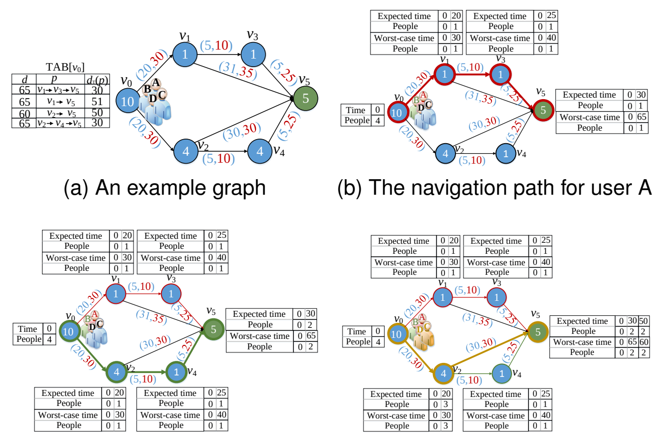
### B. User-centric congestion-relived rapid path planning

The path with a minimum expected delay while meeting the deadline is planned based on the determined evacuation order, the expected and worst-case delay of each segment, the capacity of each waypoint, and the spatiotemporal mobility of users as follows. Before further introducing our proposed path planning method, we present some related definitions: $v_{min}^j$ is the waypoint with the minimum capacity $c_{min}^j$ in path $p_j$ of user $u_j$.

1) Initially, the lookup tables constructed according to Algorithm 2 are added to each user waypoint. Based on the assigned evacuation order in Section IV-A, user $u_1$ is guided first. The expected and worst-case time required by $u_1$ to arrive at each waypoint $v_i^1$ along $p_1$ are recorded in $ET_{\mathrm{T}}^{v_i^1}$ and $ET_{\mathrm{W}}^{v_i^1}$ at all waypoints passed by $u_1$, respectively. In addition, the waypoint $v_{min}^1$ and its capacity $c_{min}^1$ in $p_1$ are also recorded.

2) Second, according to the determined evacuation order, the evacuation path $p_2$ with the minimum expected time $d_T(p_2)$ while meeting the deadline even under the worst case with the possible congestion caused by $u_1$ is provided to $u_2$. The expected and worst-case time it will take for $u_2$ to arrive at each waypoint along the path are respectively recorded in $ET_{\mathrm{T}}^{v_i^2}$ and $ET_{\mathrm{W}}^{v_i^2}$ at these waypoints. Note that if there are other users initially located at the same user waypoint as $u_1$, then $p_1 \equiv p_2 \equiv, ..., \equiv p_{c_m^1}$.

3) The aforementioned planning and recording process is repeated until the expected and worst-case time it will take for $u_N$ to arrive at each waypoint along $p_N$ are recorded in $ET_{\mathrm{T}}^{v_i^N}$ and $ET_{\mathrm{W}}^{v_i^N}$ at his/her passed waypoints respectively. By considering the spatiotemporal mobility of $u_1$, $u_2$,..., and $u_{N-1}$ and the all possible safe routes for $u_N$, the expected evacuation time $d_{\mathrm{T}}(p_N)$ can be minimized, while at the same time, the




(a) An example graph (b) The navigation path for user A

(c) The navigation path for user B (d) The navigation path for user C and D

Fig. 6: An illustrative example of the implementation of the proposed scheme.

worst-case evacuation time $d_{\mathrm{W}}(p_N)$ is less than or equal to the deadline.

### C. An example

Now we consider the path planning of the example graph of Fig. 6a by the algorithm of Section IV above.

- Initialization. As shown in Fig. 6b, our proposed modified lookup tables are constructed at user waypoint $v_0$. In addition, we specify the deadline for evacuation as 65 in this example.
- Planning of $p_1$. By using the ordering approach in Section IV-A, users $A$, $B$, $C$, and $D$ first are sorted as $u_1$, $u_2$, $u_3$, and $u_4$, respectively. Under the prerequisite of ensuring safety, user $A$ averagely requires at least 30 to escape to the nearest exit along path $v_0 \to v_1 \to v_3 \to v_5$ (see Fig. 6b).
- Planning of $p_2$. Considering the spatiotemporal motion of user $A$, the remaining users $B$, $C$, and $D$ are sorted as $u_2$, $u_3$, and $u_4$, respectively. User $B$ averagely requires at least 30 to escape to the nearest exit $v_5$ along path $v_0 \to v_2 \to v_4 \to v_5$ (see Fig. 6c).
- Planning of $p_3$. Considering the spatiotemporal motion of users $A$ and $B$, user $C$ averagely requires at least 50 to the exit $v_5$ along the path $v_0 \to v_2 \to v_5$ (see Fig. 6d).
- Planning of $p_4$. Considering the spatiotemporal motion of users $A$, $B$, and $C$, user $D$ averagely requires at least 50 to the exit $v_5$ along the same path as that of user $C$ (see Fig. 6d). Recall from the introduction of user-centric congestion-relived rapid path planning in Section IV-B that $p_3 \equiv p_4$ because $c_{min}^3 - 1 > 0$ (i.e., $c_1^3$-1 =3 $\geq$ 0).

Thus the total expected evacuation time obtained by our scheme to evacuate users $A$, $B$, $C$, and $D$ is 50.

### D. Reacting to behavior deviation

Some evacuees may not follow the provided instructions during the emergency evacuation due to panic, known as behavior deviation. Due to behavior deviation, the evacuation order and paths may no longer be optimal, and thus the recalculation of the evacuation order and paths has to be considered. A trivial but highly time/message costly and inefficient method is to entirely recalculate the new evacuation order and paths whenever the behavior deviation occurs. Instead, the behavior deviation only induces an impact on the evacuation order and paths for partial evacuees, and thus only a partial operation on the update of the evacuation order and paths is required. In this section, we detail the partial-update operation on the evacuation order and paths.

Recall that the process of assigning the evacuation order and paths to individuals in Sections IV-A and IV-B mainly includes the recursive comparison and sort of the expected evacuation time, which is conducted among the *i-th* user and other (*N-i*) users. After ordering the evacuation for all users, the expected time for the planned path $p_1, p_2, ..., p_N$ for the user $u_1, u_2, ..., u_N$ meets the following inequation:

$$d_{\mathrm{T}}(p_1) \leq d_{\mathrm{T}}(p_2) \leq ... \leq d_{\mathrm{T}}(p_N). \tag{14}$$

Accordingly, a partial evacuation order updating scheme is straightforward: when the evacuee $u_i$ deviates the navigation instruction, we only need to check his expected evacuation time from the current location to the nearest exit with the consideration of the possible congestion caused by evacuees ranked before him (i.e., $u_1, u_2, ..., u_{i-1}$), and then compare the expected evacuation time between the deviated evacuee $u_i$ and the evacuee $u_{i+1}$.

1) If $d_T(p_i) \leq d_T(p_{i+1})$, then the evacuation order remains and the update procedure terminates;

2) If $d_T(p_i) > d_T(p_{i+1})$, then exchange the evacuation orders of $u_i$ and $u_{i+1}$. After this, we need to compare $d_T(p_{i+1})$ and $d_T(p_{i+2})$. Likewise, if $d_T(p_{i+1}) \leq d_T(p_{i+2})$, then the update procedure terminates, otherwise exchange the evacuation order of $u_{i+1}$ and $u_{i+2}$. The above process is repeated until the procedure terminates.

## V. Performance Evaluation

We carry out extensive simulations to evaluate the performance of our approach. We compare this algorithm with the state-of-the-art navigation approaches, i.e., look-up table guiding method and group-based guiding method, from four perspectives, i.e., total evacuation time, evacuation success ratio, congestion distribution, and average escaping rate.

### A. Simulation setup

Fig. 7a shows the evacuation network within the simulated ship indoor environments, i.e., the second, third, and fourth floors of the "Yangtze Gold 7" passenger ship, where 346 waypoints are deployed with one exit waypoint. In addition, the network consists of 600 passageway segments and 5 staircase segments. The worst-case moving time $d_{\mathrm{W}}(\overrightarrow{v_iv_j})$ across a segment $\overrightarrow{v_iv_j}$ is estimated as follows:

$$d_{\mathrm{W}}(\overrightarrow{v_iv_j}) = \frac{l_{\overrightarrow{v_iv_j}}}{s_{\mathrm{W}}(\overrightarrow{v_iv_j})}. \tag{15}$$

where $s_{\rm W}(\overrightarrow{v_iv_j})$ is the worst-case speed, i.e., the walking speed when the ship inclination angle reaches 30°. In our simulations, we set the worst-case speed as 0.12 m/s. The probabilistic delay distribution across a segment $\overrightarrow{v_iv_j}$ is obtained by randomly selecting values from the interval $[d_{\rm H}(\overrightarrow{v_iv_j}), d_{\rm W}(\overrightarrow{v_iv_j})]$ as possible actual delays, which correspond to certain probabilities. $d_{\rm H}(\overrightarrow{v_iv_j})$ is estimated as follows:

$$d_{\rm H}(\overrightarrow{v_iv_j}) = \frac{l_{\overrightarrow{v_iv_j}}}{s_{\rm H}(\overrightarrow{v_iv_j})}. \tag{16}$$

where $s_{\rm H}(\overrightarrow{v_iv_j})$ is the walking speed when the ship inclination angle equals 0°. In our simulations, $s_{\rm H}(\overrightarrow{v_iv_j}) = 1.2$ m/s. The deadline for ship evacuation is estimated as follows:

$$DL = T_{\rm S} - T_{\rm A} - T_{\rm EL}. \tag{17}$$

where $T_{\rm S}$ denotes the total survival time until the ship will capsize, and $T_{\rm A}$ is the awareness time beginning upon initial notification of an emergency and ending when passengers accept the situation and start to move based on the provided navigation direction. $T_{\rm EL}$ denotes the sum of embarkation time and the launching time (i.e., the time required to provide for abandonment by the total number of persons on board). According to the guidelines approved by the Maritime Safety Committee (MSC), $T_S$ equals 60 minutes, $T_{\rm A}$ equals 10 minutes, and $T_{\rm EL}$ equals 20 minutes in our simulations. That is, $DL$ equals 30 minutes unless stated otherwise.

The number of inserted evacuees varies between 10 and 350. The number of hot-spot nodes is from 2 to 16. In each run of simulations, 50% evacuees are first randomly assigned to all waypoints and then the other 50% evacuees are randomly assigned to hot-spot nodes such that more passengers need to be guided at the hot-spot nodes than the other nodes. We perform the simulations written in Python on the Linux server equipped with Intel (R) Xeon (R) Silver 4210R CPU @ 2.40GHz and 125 GB memory. Each simulation is repeated 10 times and the average value is taken as the final result unless stated otherwise. We compare our scheme against the look-up table guiding method in [36] and the group-based guiding approach in [11]. The former guides evacuees to the neighbor that can achieve the minimum expected delay to the exit waypoint while ensuring the arrival within the specified deadline in the case of no congestion, while the latter provides groups of evacuees with the fastest paths based on the evacuation time estimated by their analytical model.

### B. Simulation results

Fig. 7 shows the possible evacuation paths by the three schemes mentioned in Section V-A for users in the simulated ship indoor environment. 100 user nodes and 20 hot spots are injected into the environment. We notice that it is different among the paths provided by the three approaches. We will further focus on four metrics for evacuation performance evaluation: total expected evacuation time, success ratio of evacuation, congestion distribution, and average escaping rate.

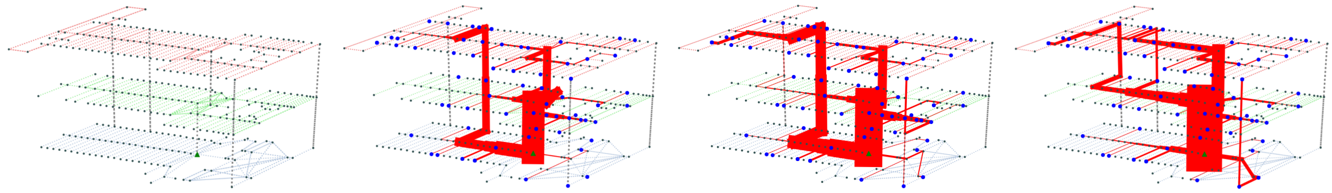
*1) Total evacuation time.* We evaluate the efficiency and safety of the evacuation service of our proposal in terms of the total expected and worst-case evacuation time of all injected users, respectively.

We inject 10, 40,...,310 users into the simulated indoor environment. The number of hot spots is set as 2. Fig. 8a shows the expected moving time of the three approaches under different numbers of users. This result demonstrates the superior evacuation efficiency using our method, especially in the scene with a high occupancy rate (more than 100 users). This is not much surprising as the look-up table method invariably requires that all users escape along optimal paths with minimum expected delays, which results in widespread congestion along the offered routes, while other less optimal (yet safe) will be idle throughout the evacuation. Therefore the performance of the look-up table method deteriorates when there are over 100 users. Moreover, we can see the performance of the group-based guiding approach is marginally better than that of the look-up table method. The main reason is group-based guiding scheme selects paths for users by jointly taking into account the capacity of nodes and parallel moving of users, which can efficiently alleviate possible congestion caused by other groups to minimize the total escaping time. Nevertheless, the performance of the group-based guiding approach remains unsatisfactory when many users exist near the same node, because a group of users near a node has to follow the same guiding direction to the same next landmark. That is, the evacuation load of passageways does not be fully balanced in this scheme, and thus the lowest total evacuation time for all users does not be achieved.

Fig. 8b shows the worst-case moving time. As the number of users continues to increase, the total worst-case time does not exceed the specified deadline for ship evacuation using our method. While it violates the deadline for the two other approaches in some cases. For example, when the number of users is more than 190 the deadline is violated using the look-up table method since it does not take the potential congestion into account. It is worth noticing that using the group-based method violates the deadline more than the look-up table approach because the group-based method does not consider the worst-case delay across each segment. In addition, the total expected and worst-case moving time of the three approaches seems to increase when there are growing users, which is caused by the inevitable waiting time considering the narrow corridors and the large number of users.

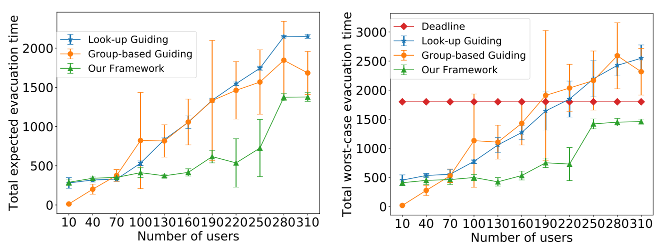
To test the robustness of our proposal against hot spots, we compare the total moving time with the different numbers of hot spots using the three evacuation schemes. We inject 250 users into the simulated ship indoor environment. The number of hot spots is from 2 to 32. From Fig. 9, we can observe that our method performs better than the other two approaches for all the numbers of hot spots.

*2) Success ratio of evacuation.* The purpose of this group of simulations is to compare our proposed method with two other schemes with respect to the evacuation success ratio. We consider four different cases: (i) 40 users being injected in the environment with 2 hot spots (named H2U40), (ii) 190 users being injected in the environment with 2 hot spots (named H2U190), (iii) 40 users being injected in the environment with 32 hot spots (named H32U40), (iv) 190 users being injected



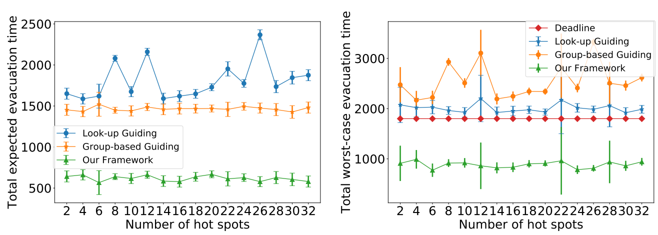
(a) The network of the second, third, and fourth floor of "Yangtze Gold 7" passenger ship with 346 nodes (b) Trace of users' egress paths using lookup table guiding scheme (c) Trace of users' egress paths using group-based guiding scheme (d) Trace of users' egress paths using our proposed guiding scheme

Fig. 7: Columns from left to right: (a) The original network with three floors and one exit (the green triangle). The segments on the first, second, and third floors are marked in blue, green, and red, respectively. Moreover, segments on the staircases are marked in black. (b) Trace of users' egress paths (highlighted in red) routed using the lookup guiding approach. (c) Trace of users' egress paths routed using the group-based guiding approach. (d) Trace of users' egress paths routed using our framework.




(a) Total expected evacuation time versus number of users (b) Total worst-case evacuation time versus number of users

Fig. 8: Total evacuation time versus number of users.




(a) Total expected evacuation time versus number of hot spots (b) Total worst-case evacuation time versus number of hot spots

Fig. 9: Total evacuation time versus number of hot spots.

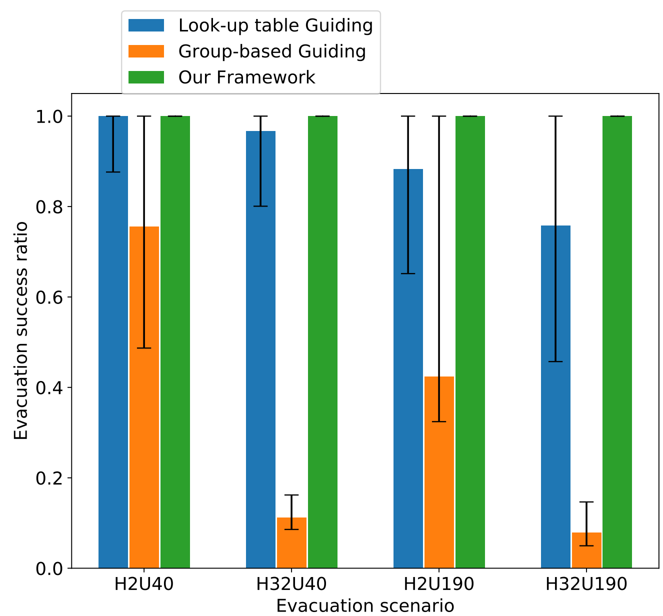
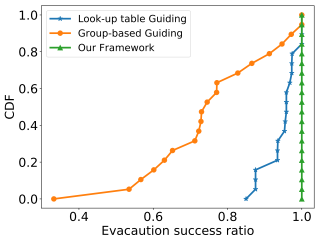


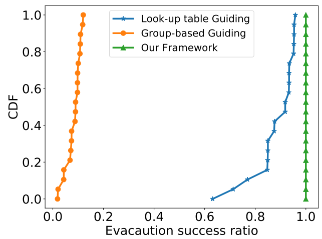

Fig. 10: Evacuation success ratio versus evacuation scenario.

in the environment with 32 hot spots (named H32U190). In our simulations, missing the deadline is considered the only factor which leads to evacuation failure. Therefore, we evaluate the evacuation success ratio using the possibility of arriving at the exit along the provided path before the specified deadline for ship sinking, which is expressed as 1-$\frac{d_{\mathrm{W}}(p)-DL}{d_{\mathrm{W}}(p)}$ in the case where $d_{\mathrm{W}}(p) \geq DL$. Otherwise, the possibility equals 1. Fig. 10 shows that our approach clearly outperforms the other two methods by always achieving a 100 percent evacuation success ratio in all scenarios. The look-up table guiding method and group-based guiding approach fail to ensure evacuation success in some scenarios, because they do not take the congestion of corridors and worst-case delay on each segment into account, respectively. As a result, the worst-case evacuation times of all the users using the two methods are likely to exceed the specified deadline. We can also see the performance of the look-up table guiding method is better than that of the group-based guiding method. The reason is explicit: all the routes are scheduled without considering the worst-case delay across each segment using the group-based guiding scheme, and thus the total worst-case evacuation time most likely exceeds the specified deadline, which yields the evacuation failure.

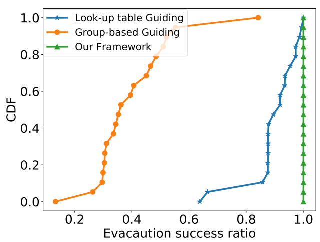
We further simulate the cumulative distribution function (CDF) of the evacuation success ratio of the three approaches under cases H2U40, H32U40, H2U190, and H32U190. Simulation results are the output of 20 runs of each approach under the different cases. It can be seen that 100 percent of users can be successfully directed to the exit using our method in the scenarios where 40 and 190 users have to be dispersed from the network with 2 and 32 hot spots, respectively. Our algorithm selects a path with the minimum expected evacuation time while guaranteeing to respect the specified deadline under all circumstances by jointly considering the capacity of the waypoints and the parallel moving of users. The cases in the four settings with our approach are better



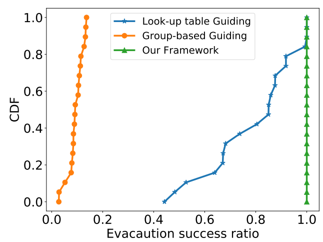

(a) CDF versus evacuation success ratio for 40 users and 2 hot spots




(b) CDF versus evacuation success ratio for 190 users and 2 hot spots




(c) CDF versus evacuation success ratio for 40 users and 32 hot spots




(d) CDF versus evacuation success ratio for 190 users and 32 hot spots

Fig. 11: CDF versus evacuation success ratio for different numbers of users and different numbers of hot spots.

than those with the look-up table guiding method and group-based guiding method. It is increasingly likely that there is no feasible route for a user to take with more users in the simulated environment. Therefore, the performance under the setting with 40 users is better than that under the setting with 190 users for the other two approaches.

*3) Congestion distribution.* We measured a segment's congestion by the number of scheduled paths the segment is involved in. The segments of routes are marked in red. The wider mark indicates heavier congestion of the segment, namely a more serious overuse by a specific evacuation approach mentioned in Section V-A. 100 users are generated in the simulated environment with 20 hot spots. As shown in Fig. 7, our proposed method has a better performance with respect to congestion distribution than the other two approaches, and it can discover a non-trivial path bypassing the over-congested parts. In comparison, the other two guiding approaches perform poorly.

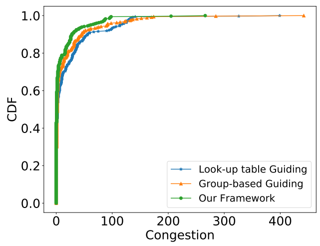
To show the superiority of our framework in terms of nodes' congestion, we also simulate the CDF of congestion of the waypoints based on the 300, 1000, 1700, and 2400 paths (30, 100, 170, and 240 users for 10 times tests), respectively. It is observed that our proposed method has a better performance in all cases. Take the scenario where 300 paths are generated for example, most waypoints in our method are involved in less than 100 paths. In contrast, about 10 percent of the waypoints are extremely over-involved in more than 150 paths in the Look-up table method and Group-based guiding method. That is to say, those waypoints have to burden more than half of the users, which on one hand prolongs the total evacuation time, and on the other hand, increases the threat to user safety since it is more likely that heavy congestion will cause a stampede of the directed users.

*4) Average escaping rate.* Fig. 13a shows the comparisons of the number of users not escaping every five seconds for 32 hot spots for 100 users. Using our scheme, more users can be evacuated if the evacuation becomes unavailable (due to ship sinking, falling ceilings, damaged passageways, or blocked exits) before all users escape. On the other hand, Fig. 13b shows the comparisons of average escaping rates in Fig. 13a. It is clear that our scheme can guide users as many as possible during the most congested period.

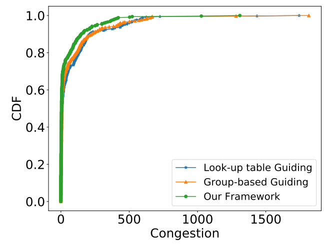
### C. Case study

The proposed rapid crowd evacuation strategy was applied to the Costa Concordia (call sign: IBHD, IMO number: 9320544, MMSI number: 247158500) disaster that occurred at 21:45 on 13 January 2012, due to the collision with the reef at 42°21′55″N, 10°55′18″E in the Tyrrhenian Sea, as shown in Fig. 14 (all times used in this paper are local). Despite the relatively long survival time from 21:45 to 24:00, during which the ship listed and ultimately capsized at 24:00, the incident still resulted in 33 lives of passengers and crew on board. The factors that contributed to the death of 33 people are complicated, with the inadequate evacuation process playing a major part. Next, we will apply our proposed evacuation strategy to this accident to evaluate the effectiveness of our approach.

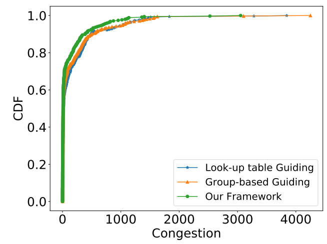
The simulated indoor environments are the first to eleventh floors, and we insert evacuees on the first, second, as well as sixth to eleventh floors of the ship. Fig. 15 shows the evacuation network of the first floor (the evacuation networks of the remaining floors are presented in Fig. 18 in the Appendix due to space limitations). The exit waypoints are located beside the lifeboats on the fourth floor. 4229 trapped individuals are uniformly distributed in the evacuation network. The survival time of the ship is set to be 90 minutes, specifically from 21:45 to 23:15 when the list of the Costa Concordia to starboard reached 45°. Once the angle exceeds 45°, passengers on board will no longer be able to move. Due to the evacuation being conducted in the night scenario, the awareness time is set to 10 minutes. Considering the embarkation and launching time of 20 minutes, the estimated deadline for ship evacuation is 60 minutes (i.e., 90-10-20). Based on [37], the worst-case speed across each corridor segment is estimated to be 0.06 m/s (i.e., $1.2 \times 0.05$), while for staircase segments, it is 0 m/s. The probabilistic speed distribution across a corridor segment is obtained by selecting values from the interval $[0.06, 1.2]$ as possible actual speeds with associated probabilities, while for staircase segments, it is obtained by choosing values from $[0, 1.0]$. 1.2 and 1.0 respectively represent the average walking speed across corridor segments and staircase segments when the ship inclination angle equals 0°. Through the case study, we evaluate the effectiveness of our approach in terms of total evacuation time. Fig. 16 shows the total expected and worst-case evacuation time against hot spots using our method. It is worth noticing that both the total expected and worst-case evacuation times are shorter than the deadline for ship evacuation in all cases. This implies that all evacuees can successfully evacuate using our scheme. Here we consider the



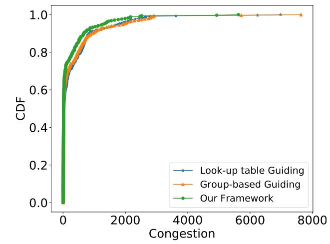

(a) CDF versus congestion for 300 paths




(b) CDF versus congestion for 1000 paths

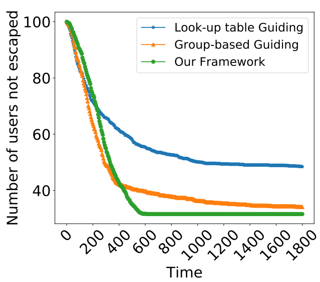



(c) CDF versus congestion for 1700 paths

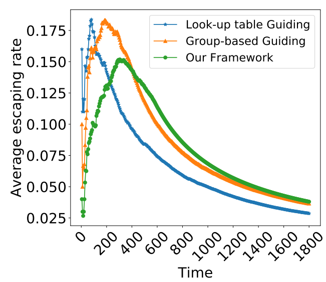



(d) CDF versus congestion for 2400 paths

Fig. 12: CDF versus congestion for different numbers of users in the network with 20 hot spots.



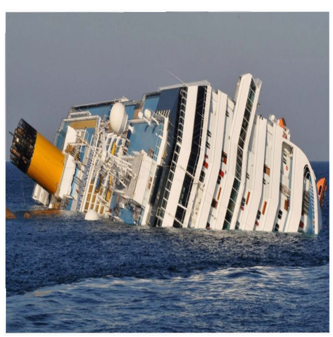

(a) Number of users not escaping every 5 seconds versus time for 32 hot spots and 100 users




(b) Average escaping rate every 5 seconds versus time for 32 hot spots and 100 users

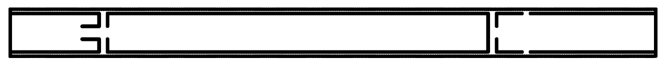
Fig. 13: Comparisons of the number of users not escaping and the average escaping rate every 5 seconds for 32 hot spots and 100 users.


(a)

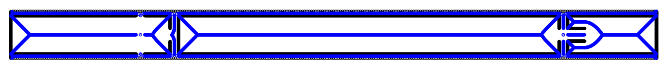


(b)

Fig. 14: Collision location of the Costa Concordia disaster.

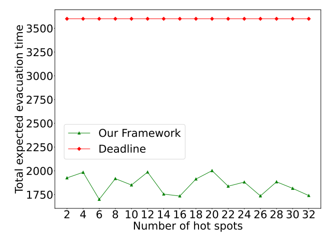


(a) The plan of the first floor



(b) The evacuation network of the first floor

Fig. 15: The evacuation network of the first floor of the Costa Concordia.




(a) Total expected evacuation time versus the number of hot spots


(b) Total worst-case evacuation time versus the number of hot spots

Fig. 16: Total evacuation time for all people on the Costa Concordia using our approach under scenarios with different hot spots.

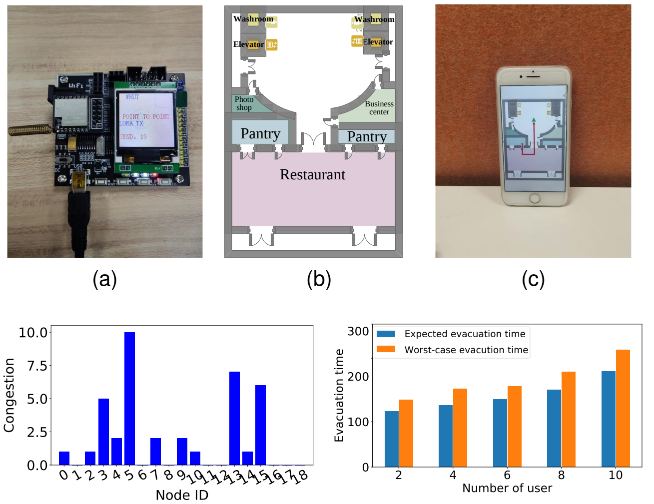
only factor causing the evacuation failure, is the excessing of the ship evacuation deadline. Therefore, by implementing our approach, it is possible to prevent the loss of lives that occurred in the Costa Concordia disaster, where 32 people died.

## VI. Prototype Implementation

As shown in Fig. 17a, we implement a prototype testbed using SX1276 chips, which can transmit the information on sensor status to a path planning server, The server adopts an event-driven framework written in Python to generate guidance information and send it back to internal users. Our test bed consists of 19 nodes deployed on the second floor of The "Yangtze Gold 7" passenger ship (see Fig. 17b).

In our experiment, we mainly focus on the total expected and worst-case evacuation time as well as nodes' congestion (i.e., the number of routes that a node is involved in). During the experiments, two nodes are set as the hot spots, and we randomly choose two to ten initial positions of users.

Fig. 17d depicts the congestion of each node in the scenario with 10 user nodes. We can see that the majority of nodes are involved in less than 3 paths, and there are only 4 nodes overcrowded, which are involved in more than 5 paths. These overcrowded nodes are located near the exit. Fig. 17e shows the expected and worst-case total evacuation time under different numbers of users. It can be seen that both of them increase gracefully from about 100 to 200, and 150 to 250 as the number of users increases from 2 to 10, respectively.




(a) (b) (c)

(d) The congestion of each node (e) Total expected and worst-case evacuation time

Fig. 17: System implementation of user-centric congestion-relieved emergency guiding.

## VII. Conclusion and Discussion

Evacuation guiding is essential for passengers when an emergency event occurs on a vessel. Thus over the last decade, substantial research has been conducted to investigate passenger evacuation behavior, optimizing and evaluating passenger evacuation performance. Most if not all of these works apply the land-based indoor evacuation approaches to provide passengers onboard vessels with advice regarding the evacuation procedure during emergencies. However, these methods neglect the specific challenges of ship evacuation, which differ from other evacuation scenarios. For example, the deadline for ship evacuation, the dynamics of travel time across each passageway caused by the unstable surface, the limited corridor capacity, and the massive crowd mobility all play critical roles in designing evacuation schemes for passenger ships to ensure passenger safety and survival. Existing ship evacuation strategies mainly focus on the paths with the shortest evacuation distance or evacuation time on static walking conditions, while in reality, the walking speed of passengers may vary in time due to the changing inclination angle of a damaged ship, and thus navigation paths provided by these methods are not necessarily optimal and even impassable during emergencies. Furthermore, those methods do not incorporate the hard end-to-end deadline that is a fundamental part of the ship evacuation problem.

Thus, this study for the first time simultaneously takes into account the unique challenges of ship evacuation such as the effect of dynamic ship indoor walking environments and the deadline for ship evacuation, as well as other factors that are also vital to the safe and efficient evacuation of passengers on ships such as the limit of the capacity for passageways and the concurrent movement of massive crowds. We propose a user-centric congestion-relieved rapid path planning scheme for ship evacuation guiding based on LPWAN that can automatically explore the dynamics of danger and the movement of passengers. Firstly, a loading-based scheme is designed to assign passenger evacuation orders according to the expected delay across each segment, the corridor capacities, and the spatio-temporal movement of evacuees to make the difference of evacuation loading among passageways as balanced as possible. Then based on the determined evacuation order, together with other factors influencing the ship evacuation (e.g., the worst-case delay as well as the probabilistic delay function specified on each segment, the up-to-date distribution of passengers, and the capacities of passageways), dedicated escape routes are generated to minimize the total expected evacuation time while respecting an end-to-end deadline for ship evacuation despite the changing ship inclination status. The implementation and experimental results demonstrate the advantages of our scheme.

However, the ship evacuation system community still has a degree of skepticism regarding the applicability of our proposed scheme. Its difficulty mainly lies in modeling the delays across individual passageways on passenger ships. That is, how to design a probabilistic model capable of capturing dynamics of traversal times across segments caused by the changing ship inclination angle is the primary challenge for the implementation of our proposed scheme. In this paper, we mainly focus on the design of an evacuation protocol, given a specific model of delay. Therefore the design and refinement of a delay model is an interesting issue to be studied in order to further enhance and implement our emergency evacuation scheme for passenger ships in the future.

In addition, hazardous areas may vary (e.g., emergence, disappearance, expansion, or shrinkage) over time during an evacuation. Accordingly, navigation paths provided by our scheme for evacuees should be adapted due to the dynamics of hazards, which may cause evacuees' oscillation. Frequent oscillation inevitably results in a decrease of the chances of survival for evacuees. Thus, how to sufficiently address the dynamics of danger to minimize the passive reentrant as much as possible is left to our future work.

Last but not least, in our scheme, navigation decisions are computed and forwarded by a central path planning server, to all end users as they pass through pre-determined waypoints that guide them towards safe exit points. The server is potentially damaged or disconnected in the event of ship damage, which will result in the failure of the entire emergency evacuation system. In future research we plan to design novel decentralized emergency evacuation systems for guiding passengers to safety, that pre-locate advisory data to passengers in intermediate waypoints, and also combine passenger attributes (e.g., their age, gender, and resistance to hazards).

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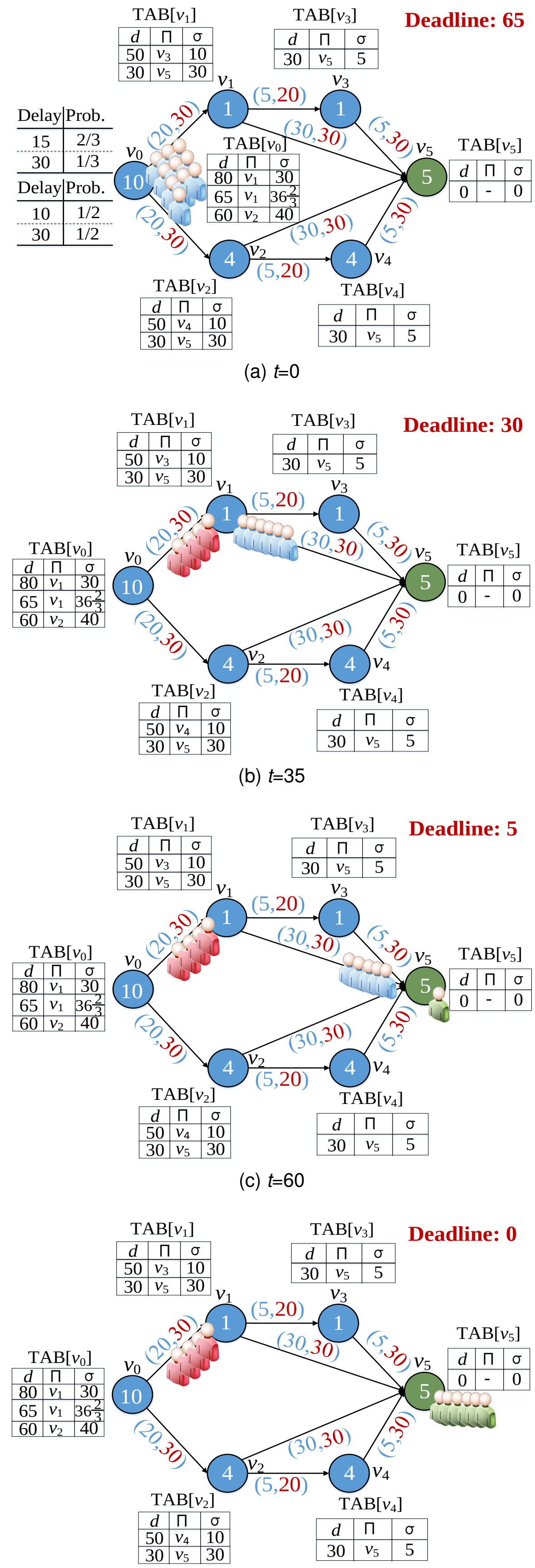
## Appendix I

This section explicitly presents Figures 2, 3, 6, and 18 for better understanding.

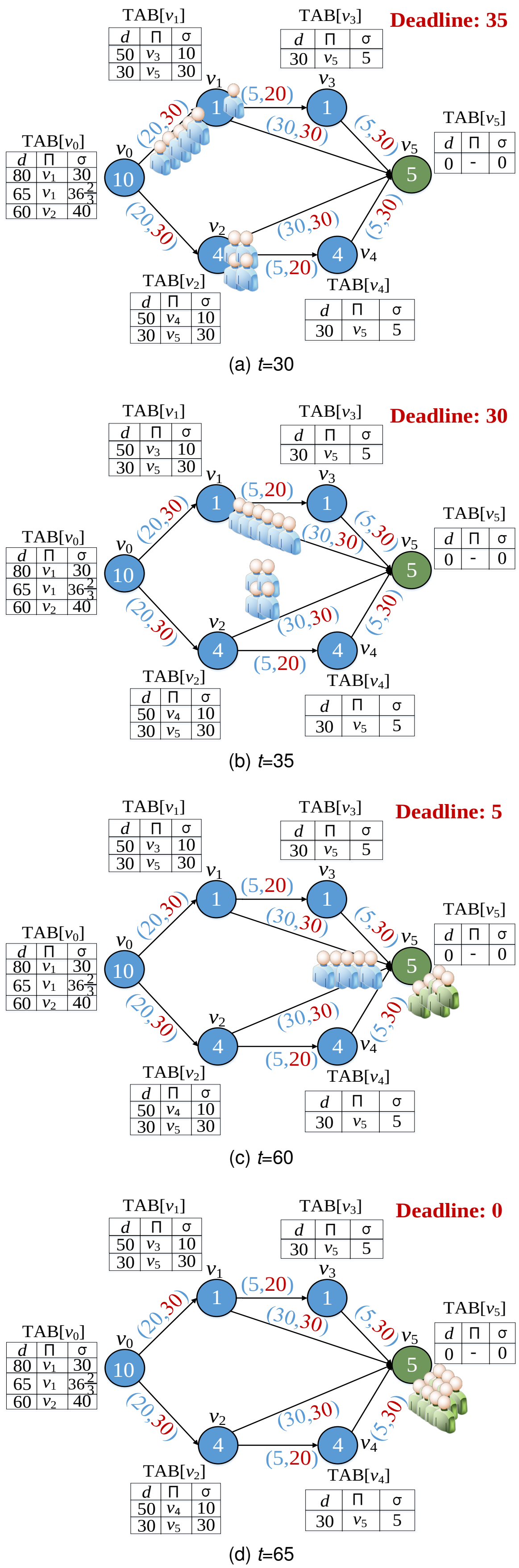
Fig. 2 shows the illustrative example of violating the specified source-to-destination deadline for multiple users using the approach in [15]. Fig. 2a indicates the example graph and the distribution of evacuees at the initial stage of the evacuation. All of the 10 people are located nearby the waypoint $v_0$. The deadline is assumed to be 65 units of time in this example. According to the advice provided by routing tables which are constructed based on the algorithm in reference [15], all the people are navigated to the waypoint $v_1$ along the segment $\overrightarrow{v_0v_1}$. Suppose that all of these people experience a delay of 30 time units across the segment $\overrightarrow{v_0v_1}$. Due to the waiting time caused by the limitation of the capacity of the vertex $v_1$ that only permits the passage of one person at a time, there are no feasible paths for the four people in red. That is, there is no segment to take from the waypoint $v_1$ for the four people, which will not violate the remaining deadline to the exit waypoint $v_5$, i.e., 29, and thus it will declare evacuation failure for them, as shown in Fig. 2b. Fig. 2c shows the distribution of the other six people at time 60. It is assumed that they encounter a delay of 30 across the segment $\overrightarrow{v_1v_5}$. we can see that the user in green is evacuated successfully from the exit waypoint $v_5$, and due to the capacity constraint of $v_5$, the other five people will escape from $v_5$ at the time 61, 62, 63, 64, and 65, respectively as shown in Fig. 2d. Therefore, the evacuation based on the algorithm in [15] is capable of guaranteeing the successful evacuation of six people as we illustrate above.

Fig. 3 shows the desired evacuation for the 10 users. Both The initial distribution of the 10 people and the specified source-to-destination deadline are the same as those of Fig. 2. The 10 people at the waypoint $v_0$ are divided into two groups: one, consisting of six people, escapes along the segment $\overrightarrow{v_0v_1}$, and the other, consisting of four people, escapes along the segment $\overrightarrow{v}_0 v_2$. Suppose that both of the two groups of people experience a delay of 30 across the segments $\overrightarrow{v_0v_1}$ and $\overrightarrow{v_0v_2}$, respectively. Fig. 3a indicates the distribution at time 30. We can see that the four users can simultaneously pass through the waypoint $v_2$ at a time, while the other six users have to pass through the waypoint $v_1$ one by one considering the capacity limit of 1 person per time unit at $v_1$. At the time 35, the remaining deadline is 30, and thus there is still a feasible outgoing segment $\overrightarrow{v_1v_5}$ to take from the waypoint $v_1$ for the last user in the group of six. Fig. 3b and Fig. 3c show the distribution of people at the time 35 and 60, respectively. It is assumed that both of the two groups experience a delay of 30 while crossing the segments $\overrightarrow{v_1v_5}$ and $\overrightarrow{v_2v_5}$, respectively. From Fig. 3c, it is observed that all the people in the group of four and one person in the group of six are successfully evacuated from the exit waypoint $v_5$ at the time 60. Fig. 3d shows that all people are successfully navigated at the time 65. Comparing the evacuation in Fig. 2 and Fig. 3, it is explicit that the consideration of the capacity of corridors and exits, as well as the exploitation of the idle paths, will benefit the overall evacuation of all evacuees.




(a) $t$=0 (b) $t$=35 (c) $t$=60 (d) $t$=65

Fig. 2: Emergency evacuation for 10 users using the Hard-real-time routing algorithm in [15].



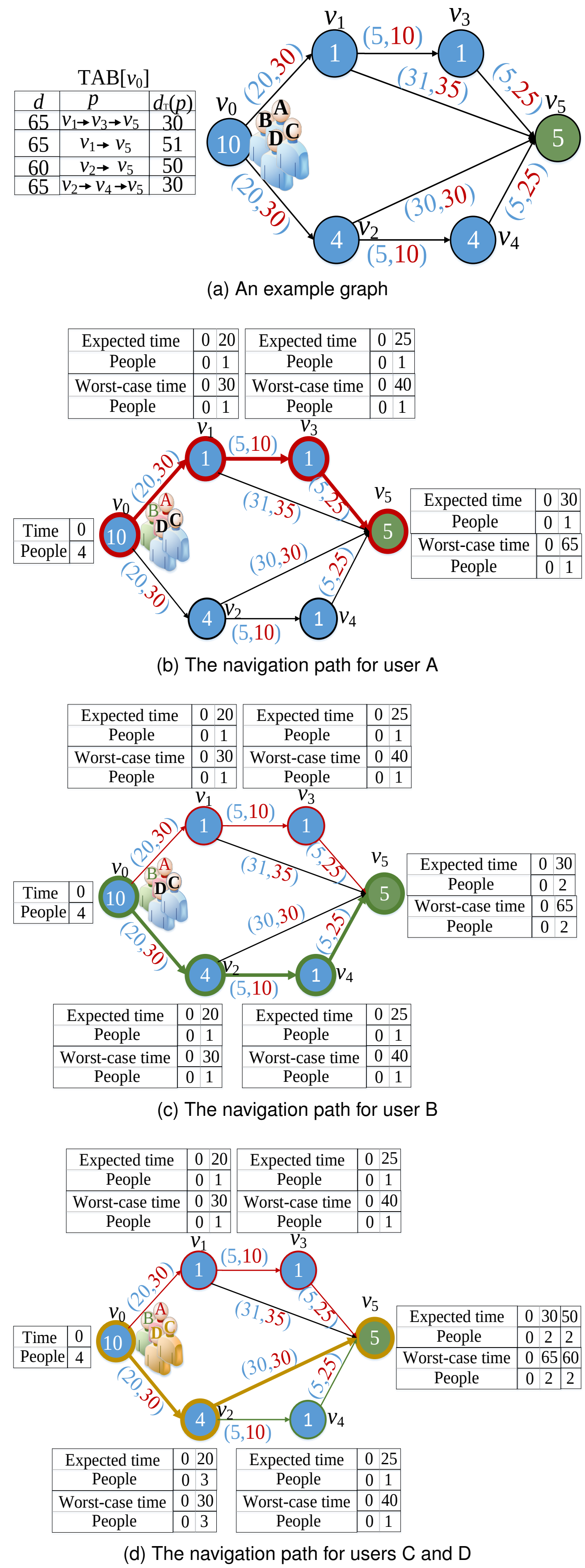

(a) $t$=30

(b) $t$=35

(c) $t$=60

(d) $t$=65

Fig. 3: Multi-path routing for emergency evacuation of 10 users in the example graph of Fig. 2.



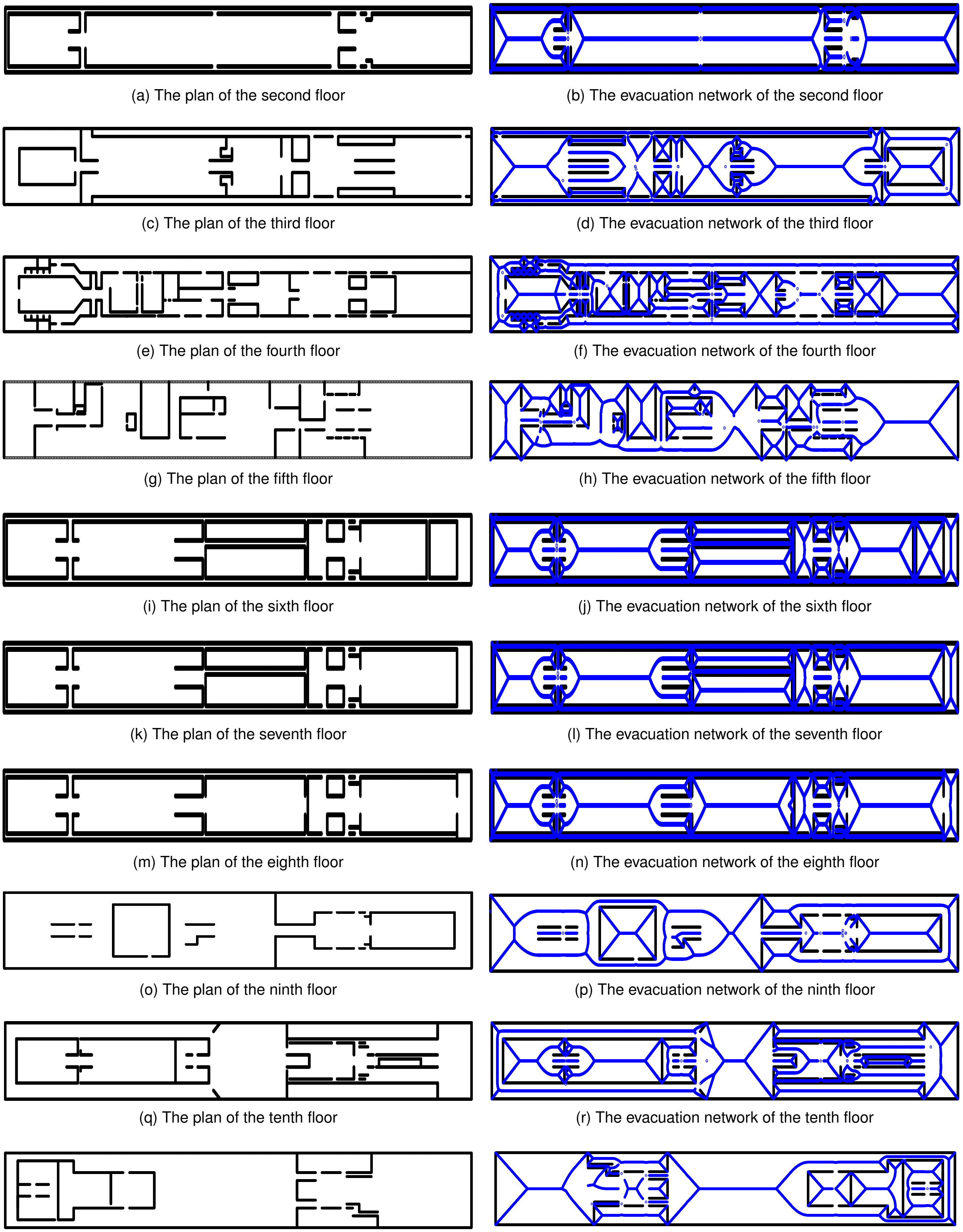

(a) An example graph

(b) The navigation path for user A

(c) The navigation path for user B

(d) The navigation path for users C and D

Fig. 6: An illustrative example of the implementation of the proposed scheme.



(a) The plan of the second floor
(b) The evacuation network of the second floor
(c) The plan of the third floor
(d) The evacuation network of the third floor
(e) The plan of the fourth floor
(f) The evacuation network of the fourth floor
(g) The plan of the fifth floor
(h) The evacuation network of the fifth floor
(i) The plan of the sixth floor
(j) The evacuation network of the sixth floor
(k) The plan of the seventh floor
(l) The evacuation network of the seventh floor
(m) The plan of the eighth floor
(n) The evacuation network of the eighth floor
(o) The plan of the ninth floor
(p) The evacuation network of the ninth floor
(q) The plan of the tenth floor
(r) The evacuation network of the tenth floor
(s) The plan of the eleventh floor
(t) The evacuation network of the eleventh floor

Fig. 18: The evacuation networks of the second to eleventh floors of the Costa Concordia.

Fig. 6 presents an illustrative example of the implementation of our scheme in Fig. 6a. There are four users at $v_0$, and the source-to-destination deadline is specified as 65. TAB $[v_0]$ denotes the lookup table at $v_0$ in the initialization phase. Fig. 6b, Fig. 6c, and Fig. 6d show the evacuation orders and the dedicated navigation paths for the four users using our scheme. The evacuation table is added to each waypoint along the planned path. The total expected evacuation time and worst-case evacuation time utilizing our scheme are respectively 50 and 65. Refer to Section IV-C for a detailed description of the procedure of our approach specifically for Fig. 6a.

## Appendix II

This section presents the algorithms 2 and 3 introduced in Section IV.

**Algorithm 2:** Modified HRPG algorithm.

**Input:** $\mathcal{G}$, $\mathcal{V}_u$
**Output:** TAB$[v_u]$, $v_u \in \mathcal{V}_u$

Call procedure Initialize ($\mathcal{G} = (\mathcal{V}, \mathcal{E})$);
**for** $i = 1 \leftarrow (|\mathcal{V}| - 1)$ **do**
  **for** $\overrightarrow{v_i v_j} \in \mathcal{E}$ **do**
    **if** TAB$[v_j] \neq [\,]$ **then**
      **for** $(d_j, v_k, d_{\mathrm{T}}(j)) \in$TAB$[v_j]$ **do**
        $d_i = d_{\mathrm{W}}(\overrightarrow{v_i v_j}) + d_j$;
        $d_{\mathrm{T}}(i) = d_{\mathrm{T}}(\overrightarrow{v_i v_j}) + d_{\mathrm{T}}(j)$;
        **if** $d_i \leq DL$ **then**
          Insert $(d_i, v_j, d_{\mathrm{T}}(i))$ into TAB$[v_i]$;
        **end**
      **end**
    **end**
  **end**
**end**
**for** $v_i \in \mathcal{V}$ **do**
  **if** $v_i \in \mathcal{V}_u$ **then**
    **for** $(d, v_j, d_{\mathrm{T}}(i)) \in$TAB$[v_i]$ **do**
      Substitute $p(v_i \rightarrow v_e)$ for $v_j$ ;
    **end**
  **else**
    Delete TAB$[v_i]$
  **end**
**end**

**Algorithm 3:** Initialize ($\mathcal{G} = (\mathcal{V}, \mathcal{E})$).

**Input:** $\mathcal{G}$
**Output:** TAB$[v_i]$, $v_i \in \mathcal{V}$

**for** $v_i \in \mathcal{V}$ **do**
  **if** $v_i \neq v_e$ **then**
    TAB$[v_i] = [\,]$;
  **else**
    TAB$[v_e] = [0, \mathrm{NIL}, 0]$;
  **end**
**end**

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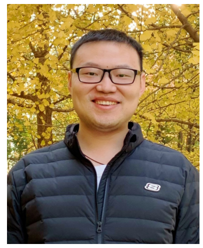

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