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# Prediction based indoor fire escaping routing with wireless sensor network

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**Abstract** Fire hazard causes lots of economic loss and personal injuries every year. Many ways are proposed to help people escape quickly from dangerous region. As one key step for fire escaping, the fire escaping system detects fire and dynamically provides escaping route to help people escape from fire scene. With the advanced technique, Wireless Sensor Network (WSN), the fire escaping system is developed to be more promising for fire escaping than before. Most existing fire escaping systems ignore or simplify the dynamics of fire hazard. Thus people's safety is not guaranteed with fire spreading and growing. This paper designs a new fire spread model based on confidential data created by the powerful simulation system: Fire Dynamics Simulator (FDS). Based on the model, this paper predicts the Available Egress Duration (AED) of all locations in the building. Considering both the length and AED of each escaping route, this paper designs a faSt firE Escaping algorithm (SEE). To evaluate the performance of our approach, this paper conducts experiments on a real WSN platform with TelosB nodes. Experiment results confirm that the fire spread model in this paper can achieve high prediction accuracy. SEE outperforms the existing prediction based approaches by utilizing more AED, so that people can escape with higher probability.

**Keywords** Fire spread prediction · Fire spread model · Available egress duration · Least-required safe egress speed · Fire escaping system

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## 1 Introduction

Fire hazard puts health of millions at risk and results in billions of loss all around the world every year [1]. In many fire hazards, many injuries can be avoided if early warning and escaping route can be given [6, 15]. When fire hazard occurs in a building, especially the building with complex structure, it often causes unnecessary injury to escape from the building without guidance. People in the building are unable to find the feasible or better escaping route so as to waste the precious surviving time. Therefore, a fire escaping system that provides real time fire and routing information during fire escaping can help people escape as fast and safe as possible.

In recent years, many works have been devoted to the fire escaping system design [2, 3, 6, 9, 11, 13–17, 22–24]. Wireless Sensor Network (WSN) contributes much on monitoring fire hazard and guidance for the emergency response and evacuation because of its advantages on sensing, communication and deployment [2, 6, 11, 13–15]. WSN can collect fire data (temperature, heat radiation, smoke, gas density, etc.) and calculate escaping route to help more people escape from a building with less time consumption.

Part of the recent fire escaping systems try to provide emergency response and escaping route to help people escape based on real time monitoring fire hazard [3, 6, 9, 11, 13–16, 22, 23]. Chipara et al. design the WIISARD system to develop a reliable communication infrastructure for emergency response by taking advantage of mobile computing technology [6]. The system does not provide indoor guidance in case of emergency occurrence. Goodwin et al. propose a safety probability model of escaping route and design a learning algorithm in order to find the best escaping route [11]. Actually, the learning process costs much time so that the valuable escaping time is wasted. Li et al.

propose an efficient Emergency Rescue Navigation strategy (ERN) by treating WSN as navigation infrastructure to provide firemen rescue commands to eliminate key dangerous areas [16]. Seldom systems take prediction of fire hazard into consideration. Matthew et al. consider the importance of fire spread prediction and propose a fire spread model with fixed fire spread time between each pair of neighboring locations [2]. Lin Wang et al. design an oscillation-free navigation approach that minimizes the probability of oscillation [24]. In their approach, fire hazard is assumed to have a computable propagation speed. Almost all the existing fire escaping systems do not fully consider fire dynamics. Thus, the escaping routes of these systems may be unsafe for people to escape.

This paper explores the dynamics of fire hazard and designs a new fire spread model to predict the Available Egress Duration (AED) of each location in the building. AED indicates the safe time left for escaping after fire occurs. The fire spread model is constructed based on fire data created by the powerful simulation system: Fire Dynamics Simulator (FDS) [19]. Then this paper designs a faSt firE Escaping algorithm (SEE) to construct the escaping route tree. SEE calculates the Least-required Safe Egress Speed (LSES) of each escaping route so as to consider both the length and AED of these routes. It aims to find an escaping route which has the lowest LSES among all available escaping routes for each location in the building. We implement SEE and two benchmark algorithms on a real experiment platform with TelosB nodes. As it is rather difficult to conduct experiments in real fire hazard scenarios, the fire data in this paper is created by FDS. Experiment results confirm that the fire spread model can achieve high prediction accuracy. SEE outperforms the existing approaches by utilizing more AED, so as to help people escape with higher probability.

### Contributions

- We design a fire spread model based on confidential fire data generated by FDS. The model can be applied to wireless sensor node so as to predict fire spread time.
- We propose a fast fire escaping algorithm (SEE) based on WSN, which considers both length and AED of escaping route.
- We implement SEE and two benchmark algorithms on a real WSN platform with TelosB nodes. Experiment results confirm that SEE outperforms the existing approaches by utilizing more AED, so as to help people escape with higher probability.

**Road map** The remainder of this paper is organized as follows. Section 2 reviews the related works. Section 3 presents the models for our approach. Section 4 introduces the AED prediction algorithm and the fast fire escaping algorithm. System implementation and evaluation is the subject of Section 5. Section 6 concludes the whole paper, and discusses the future works.

## 2 Related work

In recent years, many fire escaping systems are designed based on WSN because of its advantages on sensing, communication and deployment [2–4, 6, 7, 9, 11–16, 22–27]. WSN is applied to collect fire data and calculate escaping route, helping people escape from fire scene with less time consumption.

Some recent fire escaping systems try to provide escaping routes to avoid fire region based on real time monitoring fire hazard [3, 6, 9, 11, 13–16, 22, 23]. Li et al. design the earliest fire escaping system [15]. In their approach, WSN is first employed to guide the movement of people in fire hazard. While they only consider the shortest escaping route, they do not consider people's safety in a fire region. The problem is addressed by Tseng et al. by introducing the concept of "hazardous region" [23]. The work of Tseng et al. is extended to 3D environments by Pan et al. in [20]. Li et al. propose an algorithm does not depend on location data [14], and in-situ interactions between users and sensors become ubiquitous. Filippoupolitis et al. introduce the idea "effective length" of an escaping route in their work [9], and build a building evacuation simulator [8]. Goodwin et al. propose a safety probability model of escaping route based learning algorithm in order to find the best escaping route [11]. Actually, the learning process costs much time so that the valuable escaping time is wasted. Li et al. propose an efficient Emergency Rescue Navigation strategy (ERN) by treating WSN as navigation infrastructure to provide firemen rescue commands to eliminate key dangerous areas [16].

Very few fire escaping systems consider fire hazard prediction to provide safer escaping routes. Berry et al. design the FireGrid, an integrated emergency response system [3]. FireGrid performs super real time simulation of fire hazard at the central server to aid the emergency response. But real time simulation requires a huge amount of computation resources. Besides, FireGrid requires large amount of network activities to collect fire hazard information and disseminate navigation information, because the system is implemented in a centralized way. Matthew et al. design a distributed fire escaping system which considers the importance of fire spread prediction [2]. But in their system, the proposed fire spread model is with predetermined fire spread time between each pair of neighboring locations. Lin Wang et al. design an oscillation-free navigation approach that minimizes the probability of oscillation and guarantees the success rate of emergency navigation [24]. In their approach, the danger region is assumed to have a computable propagation speed such that one can quantify the changing trend of danger. The dynamics of fire hazard is not fully considered.

In general, almost all the existing fire escaping systems do not fully consider fire dynamics. For a fire escaping system, the key challenge is how to find the shortest and safest escaping routes. Most existing fire escaping systems only consider the escaping route length. But due to fire hazard is dynamically changing, the AED of each location in the building is changing with time. The fire escaping systems which based on fire monitoring can not guarantee people's safety. The information of AED of each location in the building can be helpful during fire escaping.

This paper explores fire dynamics to design a fire escaping system. Firstly, a new fire spread model is designed based on the fire data generated by FDS. With the model, the AED of each location in the building is predicted in real time. Then this paper designs a fast fire escaping algorithm (SEE), which considers both the length and AED of escaping route. An escaping route which has the lowest LSES is selected for each location to help people escape from the building.

## 3 Problem formulation

This section first presents a new fire spread model and constructs an indoor corridor graph. The fire escaping problem is then formulated.

### 3.1 Fire spread model

The inherent hazard of fire spread is that fire causes temperature increasing so as to hurt surrounding people. Before giving our fire spread model, this block first introduces some key time moments: fire detected time and fire untenable time.

**Definition 1** (Fire Detected Time) It, denoted by $t_\alpha$, is the moment at which fire is detected by sensor node.

The fire detection condition is denoted as $\theta_\alpha$. At the fire detected time, the fire temperature is usually low so as not to hurt people seriously. In this paper, $\theta_\alpha$ is set to be 40 °C [18]. When temperature increases after that, the condition for fire escaping become untenable.

**Definition 2** (Fire Untenable Time) It, denoted by $t_\beta$, is the moment at which the tenable condition for fire escaping does not exist.

The fire untenable condition is denoted as $\theta_\beta$. At the fire untenable time, the fire temperature is much higher than that at the fire detected time. In this paper, $\theta_\beta$ is set to be 120 °C [5].

After fire is detected, people are alerted to escape and has certain time to pass some corridors and locations safely. Each corridor or location has its own safe time duration to allow people to pass through before fatal fire condition appears.

**Definition 3** (Available Egress Duration (AED)) It is the time period from time $t$ to the moment when the tenable condition disappears.

This paper designs a new fire spread model to predict the AED. The fire spread model in this paper describes the relation $f$ between fire spread time $t_s$ and two variables: fire hazard condition $\theta$ and fire spread distance $d$. The relation $f$ is presented with a function in Eq. 1.

$$t_s = f(\theta, d) = g_1(\theta) \times d^2 + g_2(\theta) \times d + g_3(\theta), \qquad (1)$$

where $t_s$ is the time duration of fire spreading from the fire source location $v_i$ to location $v_j$ and the temperature at $v_j$ reaches $\theta$. The fire spread distance $d$ is the shortest distance along the corridor between $v_i$ and $v_j$. $g_1(\theta)$, $g_2(\theta)$ and $g_3(\theta)$ are three coefficients related to $\theta$ and will be determined later. In this paper, $\theta$ can be $\theta_\alpha$ or $\theta_\beta$.

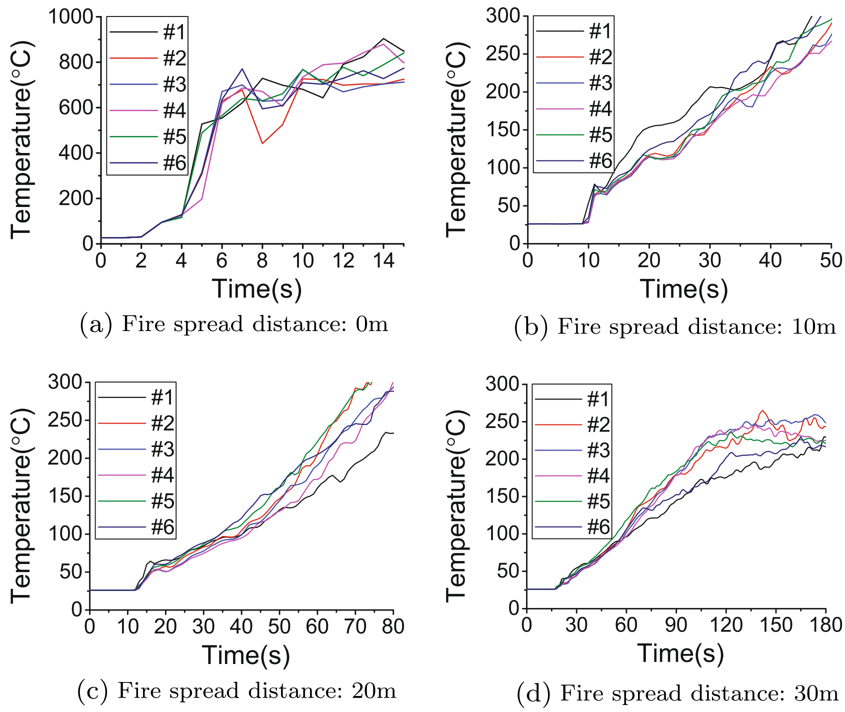
In most existing works, a location is said to be not passable once fire is detected, i.e. environmental temperature reaches $\theta_\alpha$ [2, 3, 6, 9, 13–16, 23]. It is too conservative since people may be unhurt or hurt less under the condition $\theta_\alpha$ since the temperature is usually 40 °C and tolerable for human body [11, 21]. At the early phase of fire hazard, the location is still passable. To utilize more AED, this paper considers a location is still safe until the fire untenable time so it has longer AED. When fire condition is $\theta_\alpha$, $t_\alpha$ can be calculated by:

$$t_\alpha = f(\theta_\alpha, d) = g_1(\theta_\alpha) \times d^2 + g_2(t_\alpha) \times d + g_3(\theta_\alpha). \qquad (2)$$

When fire condition is $\theta_\beta$, $t_\beta$ can be calculated by:

$$t_\beta = f(\theta_\beta, d) = g_1(\theta_\beta) \times d^2 + g_2(\theta_\beta) \times d + g_3(\theta_\beta). \qquad (3)$$

Each building has its own inner structure and material. The three coefficients, $g_1(\theta)$, $g_2(\theta)$ and $g_3(\theta)$, have different values accordingly. To determine their values, we introduce the powerful simulation tool FDS [19] developed by the National Institute for Standards and Technology. FDS




(a) Fire spread distance: 0m

(b) Fire spread distance: 10m

(c) Fire spread distance: 20m

(d) Fire spread distance: 30m

**Fig. 1** Temperature curve of 6 experiments at different fire spread distance

has been used to realistically model various fire dynamics phenomena and for fire reconstruction [5, 11]. Real fire detected time and real fire untenable time can be calculated by the result of FDS experiment. Figure 1 shows the temperature data of 6 FDS experiments, which illustrates the fire detected time and the fire untenable time are related to the fire spread distance. This paper uses the curve fitting tool in Matlab to determine $g_1(\theta)$, $g_2(\theta)$ and $g_3(\theta)$ by fitting the real fire detected time and real fire untenable time of FDS experiment.

In this paper, we consider the situation that there is only one kind of combustible material in the building. For example, we design a FDS experiment scene full of upholstery,

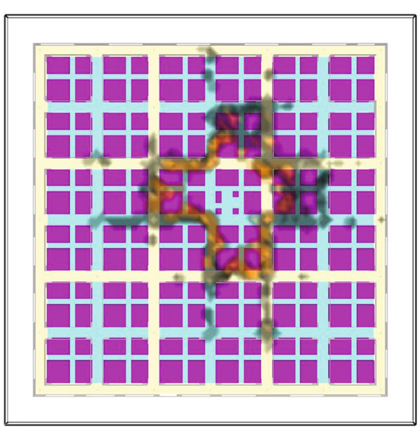


**Fig. 2** FDS experiment scene

as shown in Fig. 2. The corresponding fire spread model is shown in Fig. 3.

Based on the model, the fire detected time and the fire untenable time can be predicted. At time $t$, the fire detected time can be predicted by:

$$t_\alpha^* = t_\alpha - t, \tag{4}$$

and the fire untenable time can be predicted by:

$$t_\beta^* = t_\beta - t. \tag{5}$$

### 3.2 Indoor corridor graph

There are always corridors inside a building. In case of emergency, people can escape through these corridors. For building with complex inner structure, its inner corridors

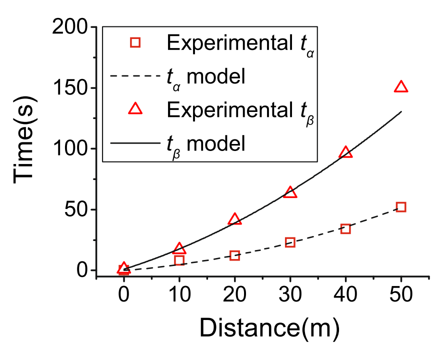



**Fig. 3** Fire spread model

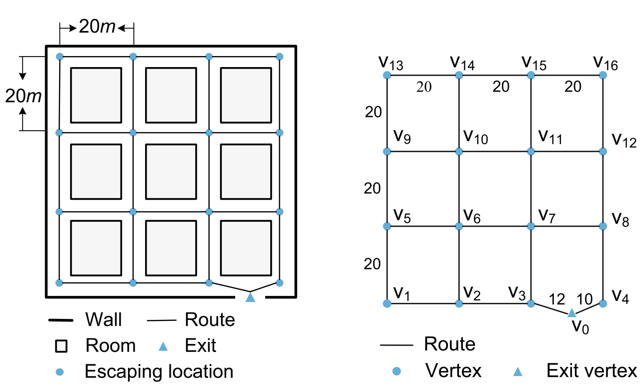
may be anfractuosity, such as supper mall. In such environment, it is quite hard and time consuming to find exit especially when fire hazard happens. Therefore, it is essential to build an indoor corridor graph so as to describe inner escaping route.

In this paper, the building inner corridors and exits are modelled as an undirected and weighted graph $G(V, E, W)$. In the graph, $V$ is the vertex set. Each vertex in the graph represents an escaping location. An escaping location can be a cross of two corridors, an exit etc. in the building. We assume that the escaping locations of a building are intentionally selected, so that all the corridors can be described by $G$. $E$ is the set of all corridors in the building. In $E$, each edge $e_{i,j}$ represents a corridor between two escaping locations. The weight $W(e_{i,j})$ of an edge $e_{i,j}$ is the distance between two vertices $v_i$ and $v_j$. For example, Fig. 4a shows the floor plan of a building. Each escaping location is marked as a dot in the plan. An exit is a special escaping location in the building, which is marked as a triangle in the plan. The corresponding indoor corridor graph is shown in Fig. 4b.

A WSN is deployed in the building to monitor fire hazard and calculate escaping route. This paper assumes that the WSN is dense enough to monitor each vertex and edge in $G$. We also assume that each sensor node can sense fire data of its surrounding environment with a specific range, and all the corridors in the building are covered.

### 3.3 Problem formulation

In fire hazard, there are several ways to avoid injury, such as run to exit, window or balcony. This paper only considers how to find an escaping route to exit. We assume there is one exit in the building, denoted by $v_0$, and the exit is always safe. We present the definition of escaping route first.




(a) Building floor plan (b) Indoor corridor graph

**Fig. 4** Building plan model

**Definition 4** (Escaping route) An escaping route starts from vertex $v_n$ to the exit $v_0$, denoted by $r(v_n) = \langle v_n, ..., v_i, ..., v_0 \rangle$, is a list of linked vertices from $v_n$ to $v_0$.

For example, in Fig. 4b, an escaping route starts from vertex $v_{13}$ is $v_{13} \rightarrow v_{14} \rightarrow v_{10} \rightarrow v_{11} \rightarrow v_7 \rightarrow v_3 \rightarrow v_0$, denoted as $r(v_{13}) = \langle v_{13}, v_{14}, v_{10}, v_{11}, v_7, v_3, v_0 \rangle$.

An escaping route $r(v_n)$ is characterized by two attributes: the route length $l(r(v_n))$ and the AED $t(r(v_n))$. $l(r(v_n))$ is the distance from $v_n$ to $v_0$ along the escaping route. For instance, the route length of the escaping route $r(v_{13})$ described above is $l(r(v_{13})) = 20 + 20 + 20 + 20 + 20 + 10 = 110$.

The AED of an escaping route at time $t$, denoted by $t(r(v_n))$, is the amount of time that the route remains safe. To take the AED of all vertices along $r(v_n)$ into consider, $t(r(v_n))$ is set as the minimal AED of all vertices on $r(v_n)$ except $v_n$. $t(r(v_n))$ can be calculated by:

$$t(r(v_n)) = \min_{v_i \in r(v_n), v_i \neq v_n} t(v_i) \tag{6}$$

This paper does not require any sensor node to store all the information of $G$. If the building is big enough, it is impossible to implement a fire escaping system in that way [14].

To take the length and AED of escaping route into account simultaneously, this paper introduces the least-required safe egress speed of an escaping route, which is defined as follow.

**Definition 5** (Least-required Safe Egress Speed (LSES)) For an escaping route $r(v_n)$, the least-required safe egress speed is the slowest escaping speed, at which people can reach the exit safely.

Since the AED and length of $r(v_n)$ can be calculated, the LSES of $r(v_n)$ can be computed by $\frac{l(r(v_n))}{t(r(v_n))}$. For any vertex $v_n$ in $G$, the selected escaping route $r^*(v_n)$ is the escaping route which has the lowest LSES among all possible escaping routes start from $v_n$. Let $R(v_n)$ denote the set of escaping routes start from $v_n$. The fire escaping problem is formulated as:

$$r^*(v_n) = \arg_{r(v_n) \in R(v_n)} \min \left\{ \frac{l(r(v_n))}{t(r(v_n))} \right\} \tag{7}$$

Most symbols used in this paper are summarized in Table 1.

## 4 Fast fire escaping algorithm

This section first introduces an AED prediction algorithm. Based on the AED prediction algorithm, we design a fast

**Table 1** Symbols and meaning

| Symbol | Description |
|---|---|
| $t_s$ | Fire spread time |
| $t_\alpha$ | Fire detected time |
| $t_\beta$ | Fire untenable time |
| $\theta$ | Fire hazard condition |
| $d$ | Fire spread distance |
| $G(V, E, W)$ | Indoor corridor graph |
| $d(v_i, v_j)$ | The distance between $v_i$ and $v_j$ |
| $t(v_n)$ | The AED of $v_n$ |
| $R(v_n)$ | The set of escaping routes starting from $v_n$ |
| $r(v_n)$ | The escaping route starting from $v_n$ |
| $l(r(v_n))$ | The length of $r(v_n)$ |
| $t(r(v_n))$ | The AED of $r(v_n)$ |

fire escaping algorithm (SEE) to construct an escaping route tree in $G$.

### 4.1 AED prediction

This block introduces the AED prediction algorithm. It predicts the AED of a location based on the fire spread model.

The early stage of fire hazard is separated into two phases: the fire spreading phase and the fire developing phase. For a location in the building, the fire spreading phase is the duration from fire occurrence to the fire detected time, i.e. $t \leq t_\alpha$. The fire developing phase is the duration from the fire detected time to the fire untenable time, i.e. $t > t_\alpha$. The length of the fire spreading phase and the developing phase can be measured by time $t_\alpha$ and $t_\beta - t_\alpha$ respectively.

Based on the fire spread model, this paper predicts the AED $t(v_n)$ of vertex $v_n$ in the fire spreading phase and the fire developing phase separately. The AED of $v_n$ at time $t$ can be calculated by the following equation:

$$t(v_n) = \begin{cases} t_\beta^* - t, & t \leq t_\alpha \\ t_\beta^* - t_\alpha^* - (t - t_\alpha), & t_\beta > t > t_\alpha \end{cases} \tag{8}$$

We next present AED prediction algorithm. At the beginning of fire hazard, if the sensor node at vertex $v_i$ detects fire, it broadcasts a message $Msg(v_i)$ to inform other sensor nodes of fire occurrence in the building. When a sensor node at vertex $v_n$ receives the message, it calculates the shortest fire spread distance between $v_n$ and $v_i$, denoted by $d$. Then it predicts $t_\alpha^*$ and $t_\beta^*$ for $v_n$. Every time when the sensor node senses fire data at $v_n$, it predicts the AED of $v_n$. During the fire spreading phase, the AED of $v_n$ is calculated by $t_\beta^* - t$. During the fire developing phase, the AED of $v_n$ is calculated by $t_\beta^* - t_\alpha^* - (t - t_\alpha)$. The AED prediction algorithm is summarized in Algorithm 1.

**Algorithm 1** AED prediction algorithm

**Input:**
Fire occurrence message, $Msg(v_i)$;
**Output:**
$t(v_n)$;
1: **if** fire occurs at $v_i$ **then**
2: Calculate the fire spread distance $d$ between $v_n$ and $v_i$;
3: Calculate $t_\alpha^*$ and $t_\beta^*$;
4: **end if**
5: **if** $t \leq t_\alpha$ **then**
6: $t(v_n) \leftarrow t_\beta^* - t$;
7: **else if** $t > t_\alpha$ **then**
8: $t(v_n) \leftarrow t_\beta^* - t_\alpha^* - (t - t_\alpha)$;
9: **end if**

### 4.2 Fast fire escaping algorithm

This part presents the design of a fast fire escaping algorithm (SEE) to help people escape. To guarantee people's safety while escaping, SEE takes real time prediction of AED and the length of each escaping route into account.

The objective of SEE is to find a fast and safe escaping route $r^*(v_n)$ for each vertex $v_n$ in $G$, which can be formulated as constructing a minimum spanning tree of $G$. The route selection metric of SEE is the LSES of escaping route. $r^*(v_n)$ is selected to help people escape if it has the lowest LSES among all the available escaping routes of $v_n$, which is presented in Eq. 7. In SEE, the sensor node at any $v_n$ calculates $r^*(v_n)$ and records the next safe vertex $v_{next}$ on $r^*(v_n)$, rather than to calculate and record all the vertices on $r^*(v_n)$. As for a vertex $v_n$, if there are several neighboring vertices $v_1, v_2, ..., v_i$ leading to the exit vertex, $v_{next}$ is selected by:

$$v_{next} = \arg_{v \in v_1, v_2, \ldots, v_i} \min \left\{ \frac{l^*(r^*(v)) + d(v_n, v)}{\min(t(v), t^*(r^*(v)))} \right\} \tag{9}$$

The basic idea of SEE is to construct an escaping route tree, and update it when better escaping route found. The input of SEE is a fire occurrence message and a route update message. The output of SEE is a vertex $v_{next}$, which is the next vertex on $r^*(v_n)$. At the beginning of SEE, a shortest escaping route tree is constructed. Once there's fire detected by sensor node at a vertex, the sensor node will compute its AED. The update of AED will incur route update. The route update message is denoted by $Msg(v_i, l_i, t_i)$. In the message, $v_i$ is a vertex feasible to reach the exit. $l_i$ is the route length from $v_i$ to the exit. $t_i$ is the AED of $r^*(v_i)$ of

$v_i$. Each vertex maintains a next vertex of an escaping route which has the lowest LSES to the exit. The length and AED of $r^*(v_n)$ are denoted by $l^*(v_n)$ and $t^*(v_n)$ separately. SEE is summarized in Algorithm 2.

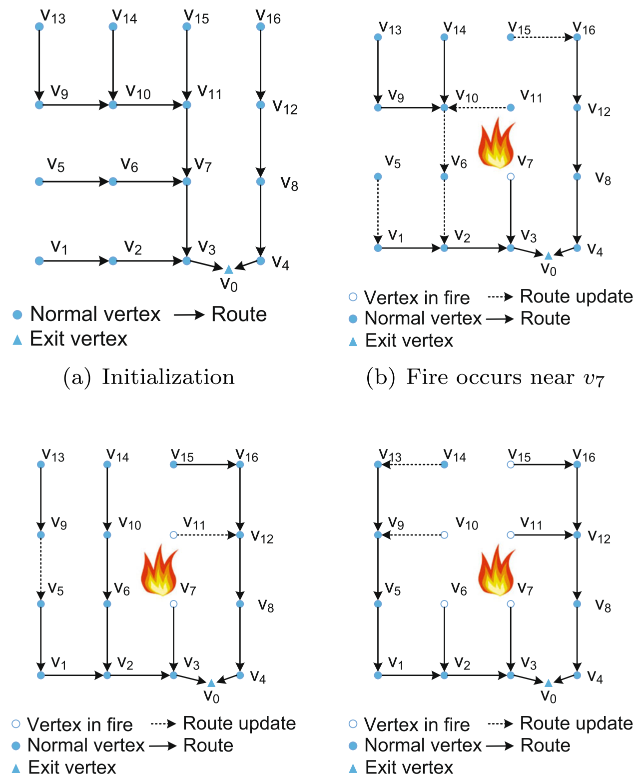
**Algorithm 2** Fast fire escaping algorithm

**Input:**
Fire occurrence message, $Msg(v_i)$;
Route update message, $Msg(v_i, l_i, t_i)$;
**Output:**
The next vertex on $r^*(v_n)$, $v_{next}$;
Predict $t(v_n)$ by Algorithm 1;
**if** Route update **then**
  $l_i \leftarrow l_i + d(v_n, v_i)$;
  **if** $v_i = v_{next}$ **or** $\frac{l_i}{t_i} < \frac{l^*(v_n)}{t^*(v_n)}$ **then**
    $v_{next} \leftarrow v_i, l^*(v_n) \leftarrow l_i, t^*(v_n) \leftarrow t_i$;
    Broadcast $Msg(v_n, l^*(v_n), \min(t^*(v_n), t(v_n)))$;
  **end if**
**else**
  Broadcast $Msg(v_n, l^*(v_n), \min(t^*(v_n), t(v_n)))$;
**end if**

There are two phases in the algorithm: the initialization phase and the fire escaping phase. We next introduce the algorithm in detail.

**1) Initialization** In this phase, SEE constructs a shortest escaping route tree of the indoor corridor graph $G$. At the beginning of this phase, the sensor node at the exit vertex broadcasts a route update message $Msg(v_0, 0, +\infty)$. The sensor nodes at its neighboring vertices will update their escaping route once they receive the message. Then these sensor nodes broadcast their route information to others. Upon the escaping routes of all vertices updated, the shortest escaping route tree is constructed. The routing tree is maintained until fire hazard occurs in the building. For example, Fig. 5a shows the result of the initialization phase of SEE.

**2) Fire escaping** In the fire escaping phase, the escaping route of each vertex is updated in real time. When fire hazard occurs in the building, the fire escaping phase begins. The sensor node at each vertex periodically detects fire and predicts the AED by Algorithm 1. The newest escaping route information of each vertex is broadcasted to their neighbors. When the sensor node at a vertex $v_n$ receives a route update message $Msg(v_i, l_i, t_i)$, there are two situations that the escaping route of $v_n$ should be updated: a) the message comes from the sensor at $v_{next}$; b) the new route has lower LSES. If the escaping route of a vertex is changed, the sensor node at the vertex broadcasts its new escaping route information. Figure 5b, c, d show the escaping route change with fire spreading.




(a) Initialization (b) Fire occurs near $v_7$

(c) Fire spreads to $v_{11}$ (d) Fire spreads to $v_6, v_{10}, v_{15}$

**Fig. 5** Escaping route changes with fire spread

## 5 Experiment and evaluation

This section presents the implementation of SEE and two benchmark algorithms on a real WSN platform with TelosB nodes. The accuracy of fire spread model is evaluated by comparing the predicted fire spread time to the real one. The performance of SEE is evaluated by comparing to the benchmark algorithms.

### 5.1 Setting

*5.1.1 Experiment setup*

This section constructs a real WSN platform with TelosB nodes, as shown in Fig. 6. The topological graph of the experiment platform is shown in Fig. 7. There are 17 sensor nodes, denoted by $v_0, v_1, \ldots, v_{16}$, and one sink node in the platform. The 17 sensor nodes run the escaping routing algorithm. $v_0$ represents the sensor node at the exit. The distance between $v_0$ and $v_3$ is 60 cm, and that between $v_0$ and $v_4$ is 50 cm. The distance between the rest neighboring nodes that connected by a route is 1 m. The sink node has two functions. The first function is that it broadcasts

**Fig. 6** Experiment platform

temperature data generated by FDS to simulate fire hazard in building. For the sensor node, receiving fire data message corresponds to fire spread detection in real fire hazard scenario. The sink node also collects escaping route, AED and fire information of all sensor nodes based on the Collection Tree Protocol [10].

SEE and two benchmark algorithms, PRE and GLOBAL, are implemented on the WSN platform. By PRE, the real fire detected time is used in fire escaping route calculation. As presented in Section 3.1, most existing fire escaping systems only consider the fire detected time, PRE can represent the upper bound of escaping time utilization of them. By GLOBAL, the real AED of locations, which can be read from the result of FDS experiment, is utilized to calculate their escaping route rather than the predicted one. The performance of SEE is compared to that of PRE and GLOBAL.

Because of the danger to set real fire, we adopt the data generated by FDS to simulate fire outbreak and spreading. This paper runs 12 FDS experiment cases with randomly chosen fire source locations. Each FDS experiment case runs for 600$s$, because the temperature of all escaping locations are higher than 120 °C at that time. In each FDS experiment, the temperature data is measured from all escaping locations in the building per second. This paper trains the fire spread model presented in Section 3.1 by the temperature data of 6 FDS experiment cases. Six fire escaping experiments are conducted based on the temperature data of the remainder 6 FDS experiment cases.

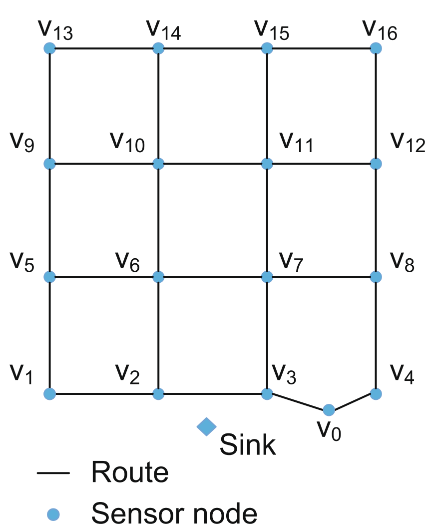



**Fig. 7** Topological graph of the experiment platform

In fire escaping experiment, temperature data generated by FDS experiment is broadcasted by the sink node per second in time sequence corresponds to the temperature data measurement. Considering package loss, the same temperature data is broadcasted for twice. If a sensor node still can not receive the temperature data, it uses the latest received one. A sensor node $v_i$, as presented in Fig. 7, only receives the temperature data of vertex $v_i$ in the indoor corridor graph of the FDS experiment scene, as shown in Fig. 4b. When receiving the temperature data, sensor node $v_i$ calculates its escaping route by the algorithms described above. To reduce the impact of route update message loss, each message is broadcasted for twice and all sensor nodes broadcast their escaping route information periodically as presented in Section 4.2. For two same route update messages, a sensor node only processes one of them and drops the other. Escaping route, AED and fire information of all sensor nodes are collected by the sink node per second based on the Collection Tree Protocol.

### *5.1.2 Metric*

The metrics to evaluate the fire spread model are prediction accuracy and mean prediction error. SEE is evaluated by Maximum Safe Egress Time (MSET). For each location in the building, its MSET is the amount of time that elapses between fire occurs in the building and the time when there is no feasible escaping route for the location. An escaping route is considered to be unfeasible when its LSES is higher than the max escaping speed accepted by common people. The max escaping speed of people in this paper is set as 5 m/s.

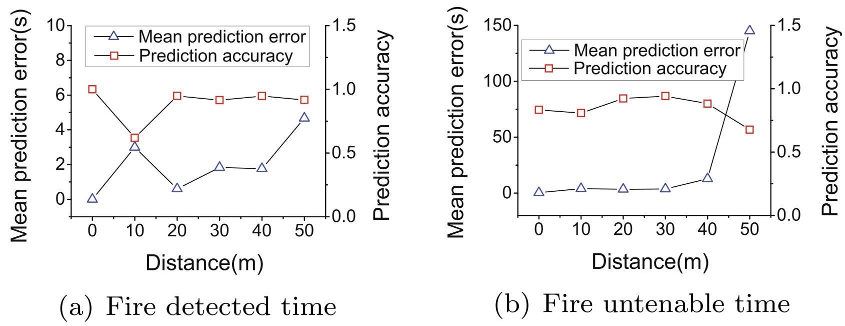



**Fig. 8** Prediction accuracy

Intuitively, if a fire escaping system can utilize more available escaping time of each location in the building, the system performs better. This paper compares the MSET of each locations achieved by SEE to that of PRE and GLOBAL. We do not present the evacuation rate and injury rate, because fire occurs randomly on geo-location and time.

### 5.2 Fire spread model accuracy

The prediction accuracy of the fire spread model is evaluated by comparing the predicted fire spread time to the real fire spread time calculated based on the data generated by FDS. Figure 8 shows the prediction accuracy of the fire spread model.

For the fire detected time prediction, as shown in Fig. 8a, the mean error at each fire spread distance ranges from 0 to 50 m is smaller than 5 s. The mean accuracy of the fire detected time prediction is 89.1 %. The prediction accuracy at 10 m is 62 %, which is because the real fire detected time of the location is very small.

For the fire untenable time prediction, Fig. 8b shows the results. When the fire spread distance ranges from 0 to 40 m, the fire untenable time prediction is with an accuracy of 88.8 % on average. When the fire spread distance is up to 50 m, the fire untenable time prediction accuracy reduces to 67.8 %. When the fire spread distance ranges from 0 to 50 m, our fire spread model can achieve high prediction accuracy of 86.8 % on average.

The line graphs of the predicted fire spread time and real fire spread time of 6 FDS experiment cases are shown in Fig. 9. For the predicted fire detected time, as Fig. 9a shows, it fits the real fire detected time well. Figure 9b shows the comparison between the predicted fire untenable time and the real fire untenable time of 6 cases, which demonstrates the predicted fire untenable time is at the lower bound of the real fire untenable time.

### 5.3 System performance

This paper conducts 6 fire escaping experiments with random fire source locations to evaluate the performance of SEE. The temperature data in these experiments are generated by FDS, as described in Section 5.1.

We present two bar graphs to show the MSET of 16 nodes of two cases with fire occurs near node $v_7$ and node $v_{11}$, as shown in Fig. 10. Node $v_3$ and $v_4$ are two nodes that with direct escaping route to the exit, the MSET for them are $+\infty$. This paper analyzes the experiment results based on the MSET of the rest nodes.

In the experiment depicted in Fig. 10a, the average MSET of PRE is 12.8 % of GLOBAL, while SEE can utilize 62.7 % of the MSET of GLOBAL on average. In the experiment depicted in Fig. 10b, the average MSET utilized by PRE is 11.9 % of the GLOBAL, SEE can utilize 53.5 % of the MSET of GLOBAL on average. As for the MSET usage rate to GLOBAL, SEE is 3.69 times more than PRE, which

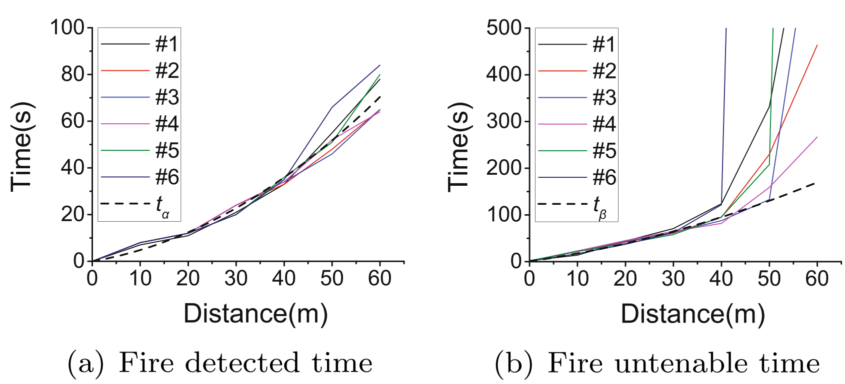
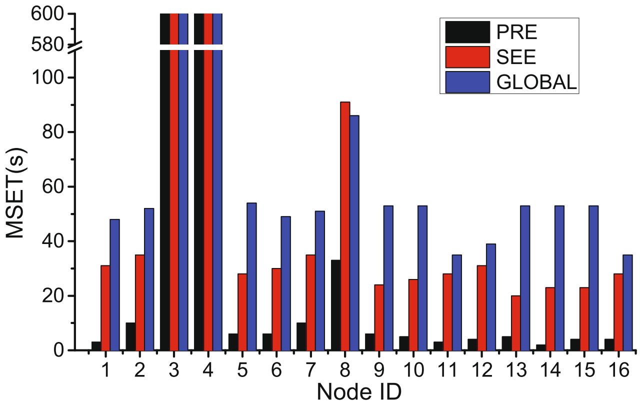
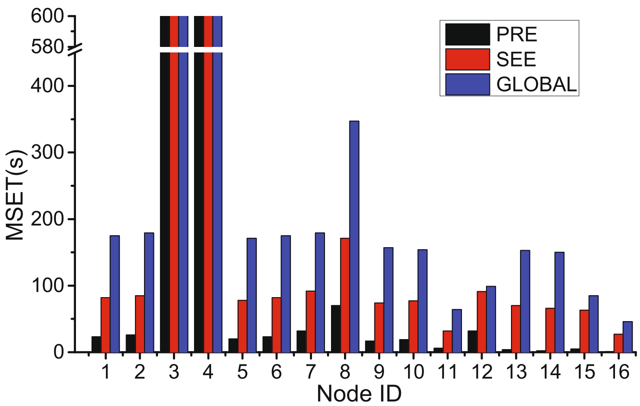



**Fig. 9** Predicted fire spread time compares to real fire spread time of 6 FDS experiments




(a) Fire occurs near $v_7$




(b) Fire occurs near $v_{11}$

**Fig. 10** Comparison among the MSET of SEE, PRE and GLOBAL

indicates SEE can utilize the AED ignored by most systems to help people escape.

Then we compare the MSET of SEE to the MSET of the GLOBAL algorithm in Fig. 10. Almost all the MSET of SEE is smaller than that of GLOBAL, while the MSET of node $v_8$ of SEE in Fig. 10a is bigger than that of GLOBAL. It is mainly because this paper aims at maximizing the prediction accuracy of all possible situations when determine these coefficients in the fire spread model. As the fire spread model in this paper can achieve high prediction accuracy of 86.8 % on average, the slight error of MSET is acceptable. Experiment results confirm that people's safety can be guaranteed.

## 6 Conclusion and future work

This paper designs a fire escaping approach based on real time fire prediction and implements it on a WSN platform. A new fire spread model is designed based on temperature data generated by FDS. The AED of each location in the building can be predicted based on the model. Considering the AED and the length of escaping route, a fast fire escaping algorithm, SEE, is proposed. SEE aims to help people escape by finding an escaping route which has the lowest LSES among all available escaping routes.

Experiments are conducted on a WSN platform based on the temperature data generated by FDS to evaluated the proposed approach. Experiment results show that the accuracy of fire detected time prediction and the fire untenable time prediction are 89.1 % and 86.8 % separately when the fire spread distance ranges from 0 to 50 m. When the fire spread distance is more than 50 m, the model can predict the worst fire spreading and developing situation in the experiments. As for fire escaping, SEE can utilize more than 3 times extra MSET than the existing works. Thus, people's safety can be guaranteed.

This paper marks an important contribution by exploring fire spread dynamics in fire escaping system designing. It, however, still has some limitations that are left for future work.

**1) Scalability** This paper considers fire escaping in single story building which has one exit. However, many buildings are multistory and have several exits in reality. The proposed method cannot be applied to such a building directly. To address the problem, more aspects should be considered in fire escaping system designing, such as how to choose exit and stairway, when to direct people to go upstairs, etc.

Packet loss, message overhead and latency are common problems in WSN, as the resources of sensor nodes are always limited. In this paper, in order to reduce the impact of package loss, each temperature data message and route update message are broadcasted for twice, which increases the message overhead. With growing number of sensor nodes, the message overhead increases and the latency problem appears. All these problems described above result in a delay when updating escaping route. In order to achieve real time fire escaping routing in a large building, more efficient algorithms should be designed.

**2) Fire spread model** Building fire can be influenced by the inner structure of the building as well as the materials, and many other conditions. Fire spreading speed and direction and fire developing are the main concerns. To predict fire spreading and developing can be challenging. As for the fire spread model in this paper, we have to determine these coefficients for every building. The fire spread distance in this paper is the shortest distance along corridor. There are other possible distances, such as the length of electric wire, to be considered.

**3) Navigation** How to efficiently direct people is also a challenging problem. LCD road signs or a hand-held PDA are commonly used. As for the LCD road signs, in fire hazard, on the one hand, people may not see the road signs with the building full of smoke. On the other hand, these road signs in the building may be burned out. As for directing people by a hand-held PDA, the connectivity of those devices must be guaranteed. Most existing fire escaping systems are designed in distributed manner. Thus, to guarantee the connectivity, a PDA has to communicate with a sensor node, such as a TelosB node. Protocols should be designed to support reliable and efficient communication.

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