Journal of
Software Engineering

ISSN 1819-4311

Academic
Journals Inc.

www.academicjournals.com

Journal of Software Engineering 9 (3): 641-649, 2015
ISSN 1819-4311 / DOI: 10.3923/jse.2015.641.649

Dynamics Model of Underground Mine Fire Spread in Complex Networks

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ABSTRACT

The system of underground mine fire is very complicated. The CA fire spread modeling method based on regular network cannot accurately describe the underground mine fire system. Based on the small world effect of the complex network theory, this study is to establish underground mine fire dynamic spread model. This model can describe the fire spread process caused by flame heat conduction, heat convection and heat radiation and the long distance fire spread caused by the fire spreading effect and the fire source effect the spread of fire. The present model can then be considered as the base of an operational tool for firefighting management as well as a training tool for firefighters.

Key words: Fire spread, dynamic model, small world network, SIS model

INTRODUCTION

Fire is one of the most severe threats to underground mines. It is crucial for fire emergency plan and hazard control to understand the mine fire spread mechanism. When a fire occurs in underground mine, the occupants may be injured or killed because of exposure to toxic gases, hot gases and high heat fluxes. Worse, an uncontrolled mine fire could ignite the available fuels (such as methane, coal dust, wood) on its propagation path which probably results in a severe mine disaster. The majority of deaths from mine fires and explosions are caused, by the inhalation of toxic gases, particularly, carbon monoxide but not by burning or blast effects (Zhou, 2010). Therefore, it is very important to build a fire spread model in the risk analysis.

Fire spread models are usually classified into two types: (1) Computer models and (2) Mathematical models. In mathematical models, the fire behavior is deduced from the resolution of the physical conservation laws explaining the flame and its environmental evolution process (Encinas *et al.*, 2007). Complex networks have demonstrated universal features such as small-world (Watts and Strogatz, 1998) and scale-free (Barabasi and Albert, 1999) effect which has been paid much attention in many fields, like social sciences, computer sciences, biological sciences and management (Strogatz, 2001; Mendes *et al.*, 2012; Wang *et al.*, 2013; Bullmore and Sporns, 2009; Lu and Guo, 2012; Du *et al.*, 2014). The spread of particular types of failures on networks has recently attracted more attention from many authors (Buzna *et al.*, 2006). However, up to date, there are a few studies about the spread dynamics of fire events. Long-range connections were recently modeled by a swn (Watts and Strogatz, 1998) with the main properties of the social network and possible connections between any two sites in the network through several steps.

Therefore, it is necessary to analyze the fire spread dynamics in complex networks by using the small world network (swn) model as an improved model proposed by Watts and Strogatz (1998). The proposed model can describe the fire spread process caused by flame heat conduction, heat convection and heat radiation and the long distance fire spread caused by the fire spreading effect and the fire source effect the spread of fire.

MATERIALS AND METHODS

WS small world network model: The concept of small world network and the model was first introduced by Watts and Strogatz (1998). The research shows that the most systems called 'WS small-world network', can be highly clustered, like regular lattices, yet have small characteristic path lengths, like random graphs. Firstly, WS model is used to study the regular network. The following random rewiring procedure is shown in Fig. 1. From the nearest coupled network of a ring lattice with n nodes and k edges per node, we rewire each edge at random with probability p, where by k is even, namely the node's degree. In WS small world network model, $p = 0$ corresponds to regular network and $p = 1$ corresponds to random network, by means of tuning the p numerical value between regularity ($p = 0$) and random ($p = 1$) to probe the intermediate region $0<p<1$. This model is suitable to many forms of social behaviors such as epidemics.

Beside the number k of nearest neighbors, φ long-range connections per node are randomly introduced throughout the whole network. A threshold value, p_c^{swn} is corresponding to the appearance of a cluster whose size behaves as a power law with p_c^{swn} (Zekri and Clerc, 2002). This threshold is extensively investigated for systems and its dependence on k and φ satisfies the following equation (Newman and Watts, 1999):

$$\varphi = \frac{(1-p_c^{swn})^{k/2}}{p_c^{swn}} \tag{1}$$

The exponent k/2 refers to the number of neighbors in the propagation direction. In the case of epidemics, this threshold corresponds to the smallest concentration of susceptible individuals leading to the disease outbreak (Newman and Watts, 1999). In the case of fires, it is the smallest density of the combustible and burning materials elements delimiting the spreading/nonspreading transition. The threshold p_c^{swn} is different from the value p_c^{rn}.

The present model can explain the short-range spreading from the burning the material to the nearest combustibles aswell as the long-range radiative/convective or firebrand impact.

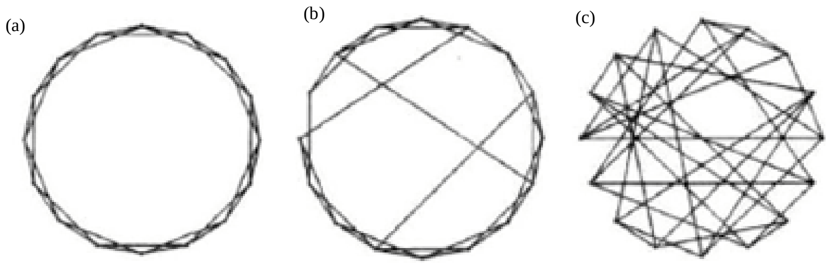

Fig. 1(a-c): Random rewiring procedure, (a) Regular Network ($p = 0$), (b) WS Network ($0<p<1$) and (c) Random Network ($p = 1$)

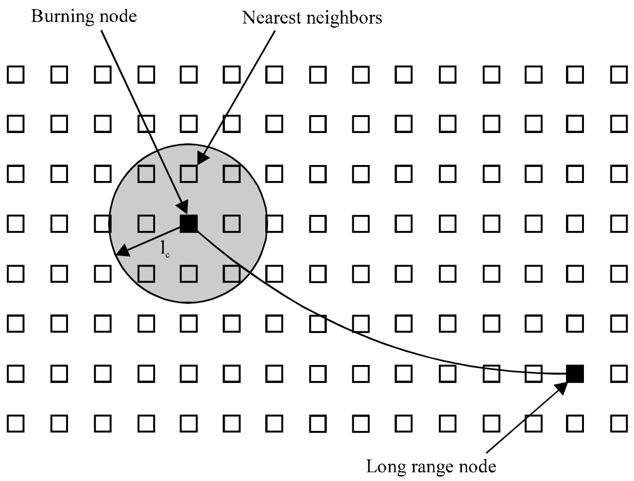

Fig. 2: Fire influencing zone

The concept of short-range connections k in the standard small world network is replaced by that of impact parameters defining the influence zone of a burning site as shown in Fig. 2. All active nodes in the influential zone are connected to the burning site by impacting parameters.

SIS model theory: In this study, a specific epidemiological model is introduced to fire spread model, called the Susceptible Infected Susceptible (SIS) model, over a network with n nodes (Javarone and Armano, 2012). The SIS model considers only susceptible and infected states. At a generic time t, the balance equations of the system are:

$$\begin{aligned} \frac{ds(t)}{dt} &= -\beta\langle k\rangle S(t)i(t)+\gamma i(t) \\ \frac{di(t)}{dt} &= -\gamma i(t)+\beta\langle k\rangle s(t)i(t) \end{aligned} \tag{2}$$

With s nodes in the susceptible state, I nodes in infected state, **β** contact rate and 1/γ average infectious period. The SIS model is used to imitate the fire spread model and the combustible and burning materials are susceptible and infective respectively. When the fire spreads to a combustible material, the fire can immediately spread from the burning material to the nearest neighbors or influential zone without the latent period. The combustible materials are homogeneously mixed; therefore all combustible materials are equally combustible and equally capable of spreading the fire. The burning materials could spread or burn out the fire. The burnt materials are treated as removals which are immune from catching fire again. Fire spread will lead to new burning materials due to contact between burning materials and combustibles.

Long-range connections correspond to the transport of fire from burning sites beyond the influential zone. In underground mine, fire spreads are far from the burning sites always via the weakest parts of the barriers. Long-range spotting may occur in the horizontal and vertical directions. The mechanisms of the fire spread in the horizontal direction include conduction, convection and radiation. Conduction, the heat in the burning sites is conducted through walls or ventilation shaft, causing an increasing temperature on the unexposed side and igniting combustible materials. Convection, hot gases or flames flow through openings to beyond burning sites and ignite combustible materials in it. Radiation, radiative heat flux from the fire compartment transfers across the corridor and ignites combustible materials in these compartments.

Model description: Based on the small world network theory and combining with the applicability analysis of SIS model in modeling of the fire spread this study established the curve formula of the flame spread of SIS model and the formula of the number of maximum effective fire and determined the parameters and the critical value. The specific contents are as follows:

Fire spread curve based on the SIS model: The fire spread curve was established in the following equation:

$$i(t) = [Ce^{-(\beta\langle k\rangle-\gamma)t} + (1-\lambda^{-1}\langle k\rangle^{-1})^{-1}]^{-1} \tag{3}$$

where, C is a constant.

When a fire falls in the most adjacent region, the probability combustible lit burning in the region is represented as $P_i(t)$, this parameter is closely linked to the humidity of flammable materials. The fire source causing the new fire is called the effective fire. The maximum effective fire number is shown as:

$$S_1(t) = \frac{1}{t_2}[\int_0^{t_2} S(t)p_i(t)dt]*S_2[1-\exp(-L/D_0)] \tag{4}$$

In this model, $S_1(t)$ represents the total number of the underground mine fire system. S_2 represents the total number of burning region. D_0 is the length value of the fire spread characteristic. This model involves two time parameters: The flame thermal degradation time t_1 and the combustion time of the fuel t_2. Thermal degradation process and combustion process are determined by the unit time length. After the ignition, it is assumed to n time step to form the complete combustion and then $t_i = n_i \times \delta t$.

Based on the kinetic theory of SW small world network, t_0 is defined a time of a fire igniting the nearest neighbor fire point. So, a separate fire area has a spread parameter R:

$$R = \frac{t_2}{t_0} \tag{5}$$

When $R \geq R_c$ (R_c is the critical value of the dynamic spread), the fire spread happens. When there is a fire, $R_c = 1$. When multiple ignition points exist, the value is usually less than 1.

In the model, there are two relevant length parameters. One is the distance from ignition point to the border of the fire affected areas from the border. In this study the parameter is defined as the effect length of the fire which is determined by l_x, l_y. The other is the fire spread length D_0. The fire spread situation presents two probabilistic behaviors based on the size of the fire system.

$$\begin{aligned} D_0 \geq L, \quad & S_1(t) = [\int_0^{t_2} S(t)p_i(t)dt)]*[S_2(t)\frac{L}{D_0}] \\ D_0 < L, \quad & S_1(t) = [\int_0^{t_2} S(t)p_i(t)dt]*S_2(t) \end{aligned} \tag{6}$$

RESULTS

Experiment results and analysis: The proposed trust computation model and load balancing algorithm were analyzed and simulated. The spreading evolution for 1000 time-steps was analysed, considering the 1% of infected nodes at $t = 1$ whose other parameters were set as follows:

$$N = 10^4,\ p = 0.1,\ \langle k\rangle = 6;\ \alpha = I(0) = 0.1;\ \beta = 0.02, 0.03, 0.04;\ \gamma = 0.1$$
$$L = 1\ \text{m},\ \delta_l = 0.33\ \text{m},\ t_c = 30\ \text{sec},\ t_{TD} = 100\ \text{sec},\ \delta_t = 1\ \text{sec}$$

Fire spread density curve: In the small-world network, the fire spread curve is shown in Fig. 3, where, $\beta = 0.02, 0.03, 0.04$. In Fig. 3, from the fire spread curve, it can be seen that there existed a critical value p, the fitting of the critical value p will be verified in the following section.

Speed curve of the fire spread: According to the definition of the WS small world network, fire spreading speed function is a relatively slow decline function curve. l_c is assumed as the distance of the arbitrary ignition to A boundary (in which l_c is determined by coordinates of l_x,l_y), the fire spread speed is defined as $\lambda = \delta l/\delta t = \alpha l_c^{\gamma}$, $\alpha_1 = 0.102$, $\gamma_1 = 1.51$; $\alpha_2 = 0.083$, $\gamma_2 = 1.51$. The different α, γ values are used to verify whether l_c can be randomly selected. In Fig. 4, $\lambda_1 = 0.102\ l_c^{1.51}$, $\lambda_2 = 0.083 l_c^{1.48}$ curves have the same power function attributes which illustrates the applicability of the model.

Performance of dynamic spread parameter: Based on the assumption of the model, if there is only one fire point, the critical value of dynamic spread $R_c = 1$. If the fire spread is under the condition of the linear, the dynamic spread parameter $R_c<1$. In a region, the most adjacent ignition point of an ignition point must be larger than 1. The multiple nearest ignition points phenomenon leads to increasing thermal degradation rate.

In Fig. 5, it can be clearly seen that regardless of how the influential parameters are valued, the dynamic spread critical value $R_c \approx 0.5$. Besides the values of R, t_2, all nodes of region have outstanding performance.

Critical value p of the percolation: The critical value p of the percolation of the regular network presents a distribution state of the law function and $p = 0.481_c^{-1}$ is got through the function

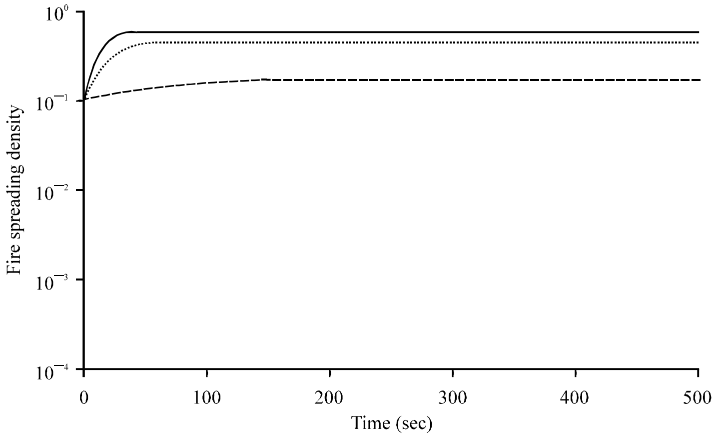

Fig. 3: Fire spreading curve

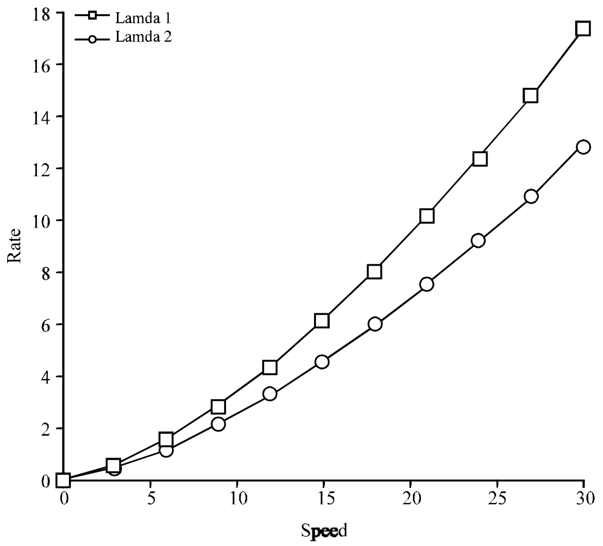

Fig. 4: Speed rate curve of the fire spread

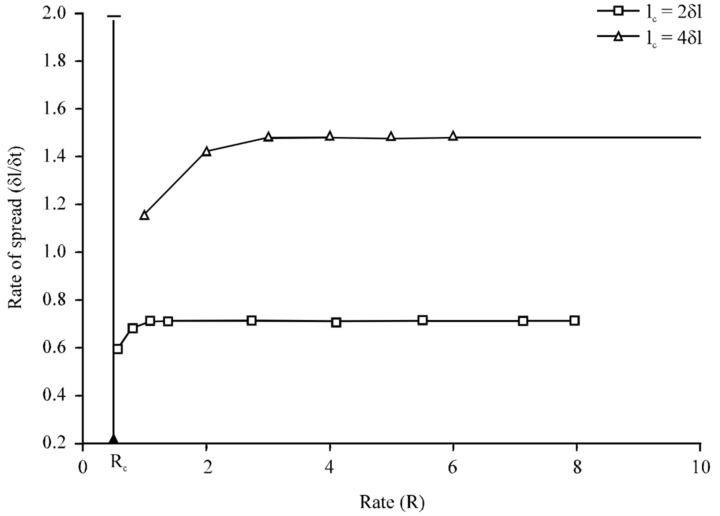

Fig. 5: Rate of the fire spread

fitting, as shown in Fig. 6. In the physics of view, it is proved that the thermal radiation and heat convection of the flame can modify the critical value of the fire dynamic spread/without spread.

Description of the effective fire source quantity: In Fig. 7, the fire source quantity changes with time continuously changing. The fire source quantity S_1 is determined by the characteristic distance D_0 and the change of the influence length of the fire l_y. The number of the fire source increases continuously with increasing spread distance and eventually the maximum value appears. This kind of behavior is very similar with the infectious disease model. In the absence of fire spreading conditions ($D_0 = 0$), S_1 curve increases to a maximum value with time linear and then begins to decline. When the fire begins to spread ($D_0 = 120\delta l$), S_1 curve has an exponential growth. The fire source number S_1 is proportional to the ignition point S_2. When $l_y = 3\delta l$, the fire spreading

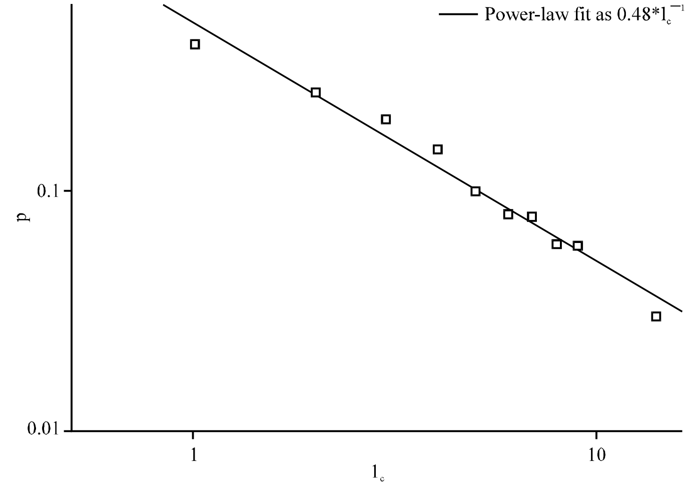

Fig. 6: Percolation critical value p of curve fitting

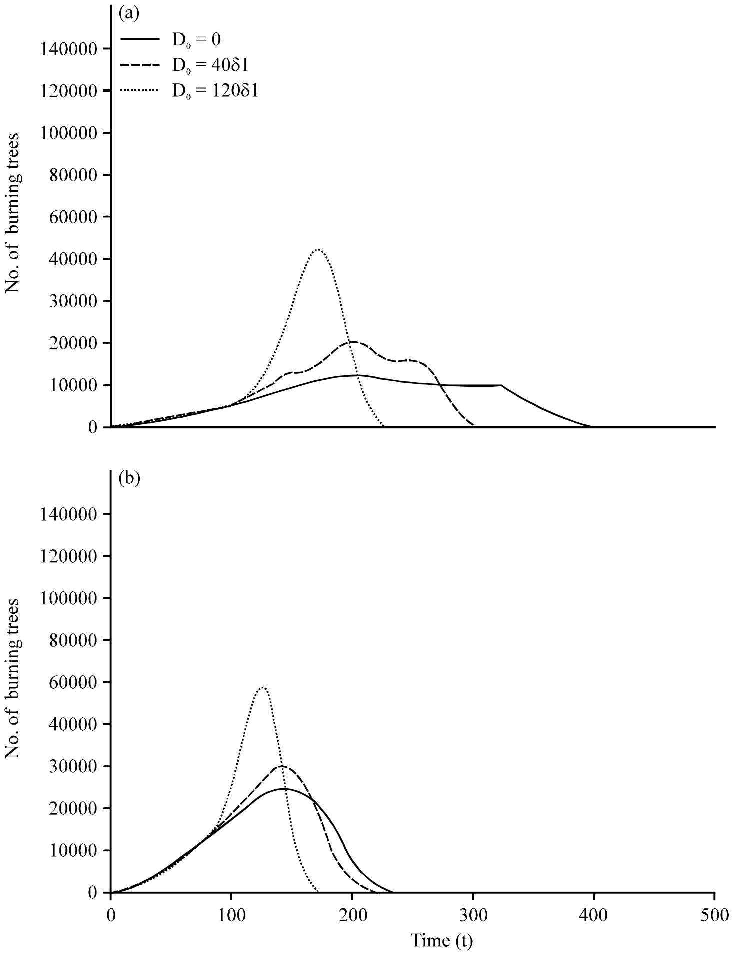

Fig. 7(a-b): Number of burning points with time evolution (a) ly = 3δl and (b) ly = 8δl becomes weak which absorbs heat to cause the second time fire. The number of ignition point plays an important role at this moment. However, when D_0 is small as shown in Fig. 7a, $D_0 = 40\delta l$, $t = 150\delta t$. The fire source falls down in burning area before which makes the ignition point quantity growth relatively slow and even have some downward trend. When the number of burning zones can cause the second time fire, the fire influence quickly is exerted. The greater the parameter value l_y of the influence becomes, the more easily the situation happens.

DISCUSSION

In the earlier studies, Markov process, percolation process and probabilistic network were used to model the fire spread. These models could successfully describe the fire spread process to certain degree (Cheng and Hadjisophocleous, 2011). Fire spread has been modeled for a long time by using regular network Barros and Mendes (1997), as well as cellular automata to include site weights (Pak and Hayakawa, 2011; Gu and Zheng, 2012; Vukasinovic and Rakocevic, 2012). However, such network did not take into account when the physical effects are over the neighbors of the burning site, how the individual fire node impacts other nodes, such as flame-induced radiative/convective effects. Some evidences have shown that models with local contacts only do not mimic real fire well. In this study ,the proposed fire spread model can make up the above deficiency. This model can describe the fire spread process caused by flame heat conduction, heat convection and heat radiation and the long distance fire spread caused by the fire spreading effect and the fire source effect the spread of fire.

CONCLUSION

In this study, the underground mine fire spread model is built based on the small world network. The proposed model can describe the fire spread process caused by flame heat conduction, heat convection and heat radiation and the long distance fire spread caused by the fire spreading effect and the fire source effect the spread of fire. First, two critical values are used to define the types of the fire spread. The first parameter is the length value l_c of the fire effect. Through function fitting, it is found that l_c and percolation critical value p_c^{rn} of regular network have site two order linear relationship $p_c^{rn} = 0.5l_c^{-1}$. Another parameter is the critical value R of dynamic spread. Then it is necessary to set up a model of a characteristic length value D_0 of fire spread and the number of fire source $S_1(t)$, to describe the fire spread of a long distance. Based on the experimental results, it can be determined when l_c and D_0 values increase gradually, the spread speed and area of the fire source will increase. The previous fire spreads by jumping way, especially when the value l_c is very small. Besides, it is found that the increasing number of the fire source will reduce the spread process of the fire on the whole. This dynamic spreading model can be used to study real fire problems in underground complex system.

ACKNOWLEDGMENT

This study is supported by The Special Funds for The Key Discipline Construction of Shaanxi Province of China (E08001).

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