IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 6, 2021, accepted June 17, 2021, date of publication June 21, 2021, date of current version June 29, 2021.

*Digital Object Identifier 10.1109/ACCESS.2021.3090997*

# Modeling Repeated Rumor Spreading in Coupled Social Networks

**QIYI HAN, KAIBO SHI, (Member, IEEE), MUSONG GU, LEI YOU, AND FANG MIAO**
School of Computer Science, Chengdu University, Chengdu 610106, China

Corresponding author: Qiyi Han (hanqiyi@cdu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61701048, and in part by the Science and Technology Bureau of Chengdu under Grant 2020-YF09-00005-SN.

**ABSTRACT** Social networks are becoming increasingly collaborative and interdependent for achieving a broader market and profits. However, the coupled social networks which caused by the collaboration and interdependence bring more significant security risks. Rumors will spread more effectively and more rampant in coupled social networks than in separate social networks. Rumors spread in a single social network have attracted considerable attention. In coupled networks, whereas, the research remains to be explored. In coupled networks, in view of the fact that the public will face more rumors, this paper proposes a SIHR rumor spreading model with the ''hesitation'' psychological state for studying the dynamic course of rumors. The mean-field equation is given for describing and analyzing the diffusion course. The various propagation performances of SIHR model are explained by theoretical and experimental analysis. At last, targeted security scheme is discussed.

**INDEX TERMS** Coupled networks, rumor spreading, social networks, psychological factor.

## I. INTRODUCTION

Social networks offer an online community where clients can share attractive backgrounds, activities, interests or connections. Nowadays, social network is very popular part and parcel of people's life. Unfortunately, malicious users have taken human weakness (e.g. laziness, indecision, credulity and carelessness) into account to design rumors. What is worse, human nature is not the only trigger of the rumors spreading to a wider range. Social networks with strong information dissemination ability also increase the risk of rumor spreading by small-world (SW) [1], scale-free (SF) [2] and high clustering [3].

Rumors are incredible or inaccurate information which is difficult to identify immediately but easy to spread on social networks. A well-planned rumor can be very attractive and persuasive. Once misled by rumors, the public would be in a very bad situation, e.g. panic, defamation, fraud, provocation, etc. Hence, it's important to investigate the mechanism for spreading rumors and to establish a security scheme.

Being similar with epidemics infecting organisms, Rumors infect people's minds [4]. based on the research of infectious disease transmission, Daley and Kendall [5] proposed the first SIR rumor propagation model. Then there are two research interests with proliferation modelling. First, numerous investigators focused on users' reactions to rumors. Yin [6] introduced psychology and sociology for analyzing the opinion interaction. Dang [7] investigated the psychological motivation of the rumor diffusion. Zhao [8] introduced a forgetting and a memory mechanism to spread gossip process. Wang [9] introduced discernible mechanism and confrontation mechanism to quantify the level of people's cognitive abilities and the competition between the rumor and truth.

At the same time, the other researches focused on the topology of social network and characterize rumor spreading under various networks. Zanette [10] investigate rumors spread in small world networks by complex network theory and prove that there is a critical threshold for rumor propagation. Moreno [11] has established a rumor propagation model in scale-free networks and concluded that unity influences the rumor dynamics. Over the last few years, studies based on complex networks have made an important progress for the emerging of coupled networks, which can be seen as interconnection networks or networks with various interconnection types [12]. In the coupled network, rumors can be spread between multilayers, and users will face more propagation.

The associate editor coordinating the review of this manuscript and approving it for publication was Sedat Akleylek.

Therefore, it becomes more complex and difficult to exploration and study the inner rumor spreading mechanism with the impact of interdependence and the coupled structure which is absent in a single network.

To the best of our knowledge, few works focus on the rumor dynamics of coupled network, not to mention that both the structure of the coupled network and the psychology. Therefore, this paper mainly focuses on the issues of the dynamics of rumor spreading in coupled network and the psychology. The main contributions of the paper are reflected as follows

1) In view of the structure of the coupled network and the hesitation psychological state, both the security environment and repeated rumor spreading mechanisms are further concerned to construct the SIHR (Spreader, Ignorant, Hesitant and stifleR) rumor spreading model.
2) To analyze the influence on the SIHR model parameters of the rumor propagation, theoretical and numerical analysis is introduced in this paper.
3) Based on the results of theoretical and numerical analysis, the targeted security schemes are presented to restrict the rumor spreading.

The rest of the article is arranged below. The second part introduces security analysis and cross propagation in coupled networks. Section III gives the SIHR model with mathematical analysis, and section IV studies the numerical results. Lastly, we end in the Section V.

## II. SECURITY ANALYSIS OF COUPLED NETWORK

Embracing the new information era, the system has become closely associated and mutually dependent. Therefore, the network system is evolving more hierarchically and sterically, and the corresponding concept is to transit from ‘‘network’’ to ‘‘cyberspace.’’ Therefore, interdependence and cooperation help introduce coupled networks and start attracting researches [13]–[16].

A coupled network is also considered as multi-layer, multi-level, multi-slice, multi-dimensional, interdependent, interconnected network, and network of network (NoN) [17]. Coupled networks can be used for simulating other complex systems, like transportation [18], infrastructure [19] and smart grid [20]. Social networks often combine with other systems to form coupled networks, like social media [21], [22], social-based P2P [23], [24] and social services [22], [25].

Security problems will arise when these networks interconnect as some security issues in their own system will be magnified in coupled networks. Coupled networks contain multiple types of interconnections, which lead to greater threats than single-layer networks. A very critical threat in coupled networks is the spread of rumors because rumors can spread layer by layer. In the merged social network, rumors follow the relevant dynamic process [13]. Rumors from one layer may spread to another, or even merge with the former, forming a vicious circle. Fig. 1 exhibited that the two nodes indicate two accounts in two social applications, confronting the double-layer spread of rumors. However, there are no effective security measures between the two networks for avoiding RRS through cross-layer links. On basis of the design of user experience, partner social Apps are born with trust and dependence, without any reinforcement [21], [25], [26] which means rumors can shuttle back and forth through various social applications. Therefore, once an account is infected, the corresponding interconnected accounts are also captured. As a result, one successful spreading turns out to be multiple infections. What is worse, the multiplication will lead to a chain effect and disseminate in various social networks. Therefore, rumors are easy to spread in various social apps, resulting in the first-order phase transition in percolation theory, more terrible than the second-order phase change of single-layer network [27], [28].

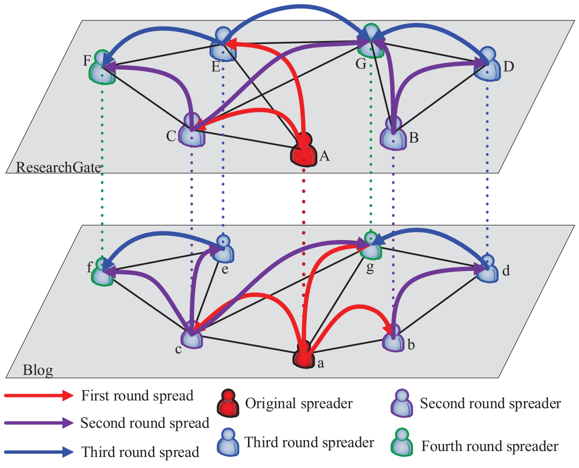


**FIGURE 1.** Rumor spread in coupled networks.

As shown in Fig. 1, there are two types of edges existed in the coupled network: inner edge (indicated by a solid line) and cross edge (dotted line). For example, the internal edge represents the friendship on ResearchGate, while the cross edge represents the transition probability from ResearchGate to Blog. [13]. After the original spreader initialed the first round spread both in ResearchGate network and Blog network, the ResearchGate account E and Blog account g dismissed the rumor. However the C, c and b became spreaders and started to spread the rumor. In the second round spread, note that the user b also forwarded the rumor in his ResearchGate account B. Once accepted a rumor in a social network account, the user would forward the rumor in the other social network. Similar cases followed, eventually everyone became spreader. Note that E resisted the spreading in second round but infected in the third round from e. Moreover, resistance means more spreadings. The fourth round spreaders G and g even received a total of 7 repeated spreadings.

## III. SIHR MODEL

In a coupled social network, rumors can spread at any layer and can be repeated at any time without conflict. Resistance to once attack does not guarantee safety. This is also in line with the actual situation. "Rumors come true after thousand times repeat." People would sway and were probably infected a rumor, when increasing friends convinced them to believe that rumor. Receiving a message, Ignorant (I) user, who never got this information before, must have 3 kinds of standpoints i.e. negative, hesitant and positive. In the classical SIR model [4], [5], people who hold positive views are Spreaders (S), while those who hold negative views are stifleRs (R). However, there is little research on hesitant (H) people.

In this paper, the hesitant state is creatively joined in the classical SIR model [5]. The hesitant indicates some hesitant users who have received the rumor but have no intention to spread the rumor until receiving the rumor more times. On the other side, the spreaders may turn to the hesitant for losing interest or getting dubious.

Assuming that the total population of the social application account is $N$, the nodes are divided into four states: Ignorants, representing those who have never heard of rumors. Spreaders, which represent those who have received the rumor and prefer to post on social networks. Hesitants, which represent those who received the rumor and prefer to hold on until receive more information. Stiflers represent people who know rumors but stop spreading them to get to the truth.

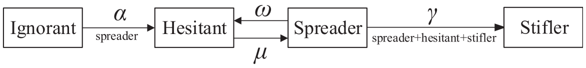


**FIGURE 2.** **SIHR rumor propagation state machine.**

Suppose that RRS is through direct contact, then the rumor propagation course of the SIHR model is illustrated in Fig. 2. There are four states: Ignorant, Spreader, Hesitant and stifleR. The spreading rules of the SIHR model are below.

- When an ignorant person contacts the spreader, the ignorant person will become hesitant at the speed of $\alpha$.
- A hesitant will convince the rumor and then turn into the spreader at the speed of $\mu$.
- A spreader will come to vacillating or lose concentration and then become hesitant at the speed of $\omega$.
- Resulting from stiflering mechanism [4], the spreader will learn the truth and wake up to a stifler at the speed of $\gamma$ after having received more information from others.

Therefore, the classical SIR rumor spreading model [5] is just a specific case of our model which runs in a single-layer network with the $\mu = 1, \omega = 0$. Next, the theoretical analysis is carried out to examine the dynamic process of the model separately in homogeneous and heterogeneous networks.

### A. HOMOGENEOUS NETWORKS

As the propagation rules mentioned above, the average field equation of SIHR model of homogeneous networks has expressions below.

$$\frac{dI(t)}{dt} = -\alpha\bar{k}I(t)S(t). \tag{1}$$

$$\begin{aligned}\frac{dS(t)}{dt} &= \mu H(t) - \omega S(t)\\ &\quad - \gamma\bar{k}S(t)(R(t)+H(t)+S(t)).\end{aligned} \tag{2}$$

$$\frac{dH(t)}{dt} = \alpha\bar{k}I(t)S(t) + \omega S(t) - \mu H(t). \tag{3}$$

$$\frac{dR(t)}{dt} = (\gamma)\bar{k}S(t)(R(t)+H(t)+S(t)). \tag{4}$$

where $I(t), S(t), H(t), R(t)$ represent the proportions of the four states at time t separately, and $\bar{k}$ indicates the mean degree of network. The normalization condition is satisfied as follows.

$$I(t) + S(t) + H(t) + R(t) = 1. \tag{5}$$

Assuming only a spreader (randomly selected) existing in the network at the initial moment, and the remaining nodes are all ignorants, the initial condition is below.

$$S(0) = \frac{1}{N}, \quad I(0) = \frac{N-1}{N}, \; H(0) = R(0) = 0. \tag{6}$$

Applying standard integral method, as time $t \to \infty$, it can be inferred that $S(\infty) = 0, H(\infty) = 0$. the final size of $R$ which is regarded as the steady state and can represents the influence of rumor, here $R = \lim_{t\to\infty} R(t) = R(\infty)$.

From Equation (1) and Equation (4), it can be obtained that

$$\begin{aligned}\frac{dR(t)}{dI(t)} &= \frac{\gamma\bar{k}S(t)(S(t)+H(t)+R(t))}{-\alpha\bar{k}I(t)S(t)}\\ &= \frac{\gamma\bar{k}(1-I(t))S(t)}{-\alpha\bar{k}I(t)S(t)}\\ &= \frac{\gamma I(t)) - \gamma}{\alpha I(t)}.\end{aligned} \tag{7}$$

Therefore

$$dR(t) = \frac{\gamma}{\alpha}dI(t) - \frac{\gamma}{\alpha I(t)}dI(t). \tag{8}$$

Since $R(0) = 0, I(0) = \frac{N-1}{N} \approx 1, I(\infty) = 1 - R(\infty) = 1 - R$ it is obtained through integral on both sides of Equation (8)

$$R = 1 - e^{-\varepsilon R}. \tag{9}$$

here $\varepsilon = \frac{\alpha+\gamma}{\gamma}$.

Assuming $y = x - 1 + e^{-\varepsilon x}$, derivatives are $y' = 1 - \varepsilon e^{-\varepsilon x}$ and $y'' = \varepsilon^2 e^{-\varepsilon x} > 0$. Then $y$ represents a convex function. For getting a nontrivial solution of $R$, it must satisfy that $\varepsilon > 1$. Exactly $\varepsilon = 1 + \alpha/\gamma > 1$, the $R$ always has a nontrivial solution. Therefore, the SIHR model has no spreading threshold and always breaks out under any conditions.

### B. HETEROGENEOUS NETWORKS

Heterogeneous networks emerge scale-free and uncorrelated features [2,4]. Since $P(k')$ denotes the degree distribution and $\langle k\rangle$ denotes the mean degree, the degree-degree correlations is $P(k'/k) = k'P(k')/\langle k\rangle = q(k')$ [4], representing the conditional probability of nodes of degree $k$ connecting to nodes of degree $k'$

Therefore, the mean-field equation of SIHR model in heterogeneous network are below

$$\frac{dI_k(t)}{dt} = -\alpha k I_k(t) \sum_{k'} S_{k'}(t) P(k'/k). \tag{10}$$

$$\begin{aligned}\frac{dS_k(t)}{dt} &= \mu H_k(t) - \omega S_k(t) \\ &\quad - \gamma k S_k(t) \sum_{k'} [S_{k'}(t) + R_{k'}(t) + H_{k'}(t)] P(k'/k).\end{aligned} \tag{11}$$

$$\frac{dH_k(t)}{dt} = \alpha k I_k(t) \sum_{k'} S_{k'}(t) P(k'/k) + \omega S_k(t) - \mu H_k(t). \tag{12}$$

$$\frac{dR_k(t)}{dt} = \gamma k S_k(t)) \sum_{k'} [S_{k'}(t) + R_{k'}(t) + H_{k'}(t)] P(k'/k). \tag{13}$$

where $S_k(t)$, $I_k(t)$, $H_k(t)$ and $R_k(t)$ represent the densities of the four states with degree $k$ at time $t$, separately.

Notice that $S(t) = \sum_k S_k(t)P(k)$. Similarly, $I(t) = \sum_k I_k(t)P(k)$, $H(t) = \sum_k H_k(t)P(k)$, $R(t) = \sum_k R_k(t)P(k)$. Like homogeneous networks, the normalization condition is $S_k(t) + I_k(t) + H_k(t) + R_k(t) = 1$. The initial condition is $I_k(0) = I(0) \approx 1$.

Integrated Equation (10), that is

$$I_k(t) = e^{-\alpha k \phi(t)}. \tag{14}$$

in which the auxiliary function is

$$\phi(t) = \int_0^t \sum_k q(k) S_k(t') dt' = \int_0^t \langle\langle S_k(t') \rangle\rangle dt'. \tag{15}$$

in which abbreviation $\langle\langle g(k) \rangle\rangle = \sum_k g(k) q(k)$ is used to make formulas short.

$\phi_\infty$ should be work out before final size of $R$, where $\phi_\infty = \lim_{t\to\infty} \phi(t) = \phi(\infty)$. Multiply Equation (11) with $q(k)$, sum on $k$ and integrate the formulas with $t$. Then

$$\begin{aligned}\frac{d\phi(t)}{dt} &= \mu \int_0^t \sum_k q(k) H_k(\tau) d\tau - \omega \int_0^t \sum_k q(k) S_k(\tau) d\tau \\ &\quad - \gamma \int_0^t \sum_k q(k) S_k(\tau) [1 - \sum_k e^{-\alpha k' \phi(\tau)} q(k')] d\tau \\ &= \mu \psi(t) - \omega \phi(t) \\ &\quad - \gamma \int_0^t \langle\langle k S_k(\tau) \rangle\rangle [1 - \left\langle\left\langle e^{-\alpha k \phi(\tau)} \right\rangle\right\rangle] d\tau.\end{aligned} \tag{16}$$

here $\psi(t) = \int_0^t \sum_k q(k) H_k(\tau) d\tau = \int_0^t \langle\langle H_k(\tau) \rangle\rangle d\tau$.

Similarly

$$\begin{aligned}\frac{d\psi(t)}{dt} &= \alpha \int_0^t \sum_k k q(k) e^{-\alpha k \phi(\tau)} \langle\langle S_k(\tau) \rangle\rangle \, d\tau \\ &\quad + \omega \int_0^t \sum_k q(k) S_k(\tau) d\tau - \mu \int_0^t \sum_k q(k) H_k(\tau) d\tau \\ &= 1 - \left\langle\left\langle e^{-\alpha k \phi(t)} \right\rangle\right\rangle + \omega \phi(t) - \mu \psi(t).\end{aligned} \tag{17}$$

For $t \to \infty$, there is $d\phi/dt = 0$and$d\psi/dt = 0$, From Equation (16) and Equation (17), there is

$$\begin{aligned}0 &= \mu \psi(\infty) - \omega \phi(\infty) \\ &\quad - \gamma \int_0^\infty \langle\langle k S_k(\tau) \rangle\rangle [1 - \left\langle\left\langle e^{-\alpha k \phi(\tau)} \right\rangle\right\rangle] d\tau.\end{aligned} \tag{18}$$

$$0 = 1 - \left\langle\left\langle e^{-\alpha k \phi(\infty)} \right\rangle\right\rangle + \omega \phi(\infty) - \mu \psi(\infty). \tag{19}$$

Unite Equation (18) and Equation (19), there is the equation for $\phi_\infty$

$$\begin{aligned}0 = 1 &- \left\langle\left\langle e^{-\alpha k \phi(\infty)} \right\rangle\right\rangle \\ &- \gamma \int_0^\infty \langle\langle k S_k(\tau) \rangle\rangle [1 - \left\langle\left\langle e^{-\alpha k \phi(\tau)} \right\rangle\right\rangle] d\tau.\end{aligned} \tag{20}$$

Integrated Equation (11) and Equation (12) to zero order in $\gamma$ respectively, there is

$$S_k(t) = \mu \int_0^t H_k(\tau) d\tau - \omega \int_0^t S_k(\tau) d\tau + O(\gamma). \tag{21}$$

$$\begin{aligned}H_k(t) &= 1 - e^{-\alpha k \phi(t)} + \omega \int_0^t S_k(\tau) d\tau - \\ &\quad - \mu \int_0^t H_k(\tau) d\tau + O(\gamma).\end{aligned} \tag{22}$$

Unite Equation (21) and Equation (22), there is

$$S_k(t) = 1 - e^{-\alpha k \phi(t)} - H_k(t) + O(\gamma). \tag{23}$$

Solving Equation (22), there is

$$\begin{aligned}H_k(t) &= 1 - e^{-\alpha k \phi(t)} - \mu \int_0^t e^{\mu(\tau - t)} \Big\{ [1 - e^{-\alpha k \phi(t)}] \\ &\quad + \omega \int_0^\tau S_k(u) du \Big\} d\tau + \omega \int_0^t S_k(u) du + O(\gamma).\end{aligned} \tag{24}$$

Equation (24) is substituted into Equation (23), equation of $S_k(t)$ is

$$\begin{aligned}S_k(t) &= \mu e^{rt} \int_0^t e^{-(2r+\omega)\tau} \Big[ \int_0^\tau e^{(r+\omega)u} (1 \\ &\quad - e^{-\alpha k \phi(u)})' du \Big] d\tau + O(\gamma).\end{aligned} \tag{25}$$

here $r = \frac{-\omega \pm \sqrt{\omega^2 + 4\mu\omega}}{2}$.

When the propagation rate approaches the threshold, $\phi(t)$ and $\phi_\infty$ are very small. A finite function $f(t)$ can be introduced to obtain $\phi(t) = \phi_\infty f(t)$. Taylor expand Equation (25) in $\phi_\infty$, there is

$$S_k(t) \approx \mu\alpha k\phi_\infty e^{rt}\int_0^t \left[e^{-(2r+\omega)\tau}\int_0^\tau e^{(r+\omega)u}f'(u)du\right]d\tau + O(\phi_\infty^2) + O(\gamma). \quad (26)$$

Equation (20) is substituted into Equation (26) and taylor expand in $\phi_\infty$, there is

$$0 = \phi_\infty\left[\alpha\langle\langle k\rangle\rangle - \phi_\infty(\alpha)^2\left\langle\left\langle k^2\right\rangle\right\rangle\left(\frac{1}{2} + \gamma C\langle\langle k\rangle\rangle\right)\right] + O(\gamma^2) + O({\phi_\infty}^3). \quad (27)$$

here $C = \mu\int_0^\infty\{f(\sigma)e^{r\sigma}\int_0^\sigma[e^{-(2r+\omega)\tau}\int_0^\tau e^{(r+\omega)u}f'(u)du]\, d\tau\}d\sigma$ is a finite positive definite integral. Obviously, $\phi_\infty = 0$ is a trivial solution of Equation (26), while the non-trivial solution is

$$\phi_\infty = \frac{\alpha\langle\langle k\rangle\rangle}{\alpha^2\left\langle\left\langle k^2\right\rangle\right\rangle(\frac{1}{2} + \gamma C\langle\langle k\rangle\rangle)}. \quad (28)$$

Observed $\langle\langle k\rangle\rangle = \left\langle k^2\right\rangle/\langle k\rangle$, $\left\langle\left\langle k^2\right\rangle\right\rangle = \left\langle k^3\right\rangle/\langle k\rangle$ and $\phi_\infty < 1$, it subjected to

$$\alpha \geq \frac{\left\langle k^2\right\rangle}{\left\langle k^3\right\rangle(\frac{1}{2} + \gamma C\frac{\langle k^2\rangle}{\langle k\rangle})}. \quad (29)$$

Finally, the steady state of $R$ is

$$\begin{aligned} R &= \sum_k P(k)R_k(\infty) \\ &= \sum_k P(k)[1 - I_k(\infty) - H_k(\infty) - S_k(\infty)] \\ &= \sum_k P(k)(1 - e^{-\alpha k\phi_\infty}). \end{aligned} \quad (30)$$

It can be employed for measuring the influence range of rumor propagation. Equation (30) explains that the value of $R$ is depended on the degree distribution $P(k)$. By Taylor expansion in $\phi_\infty$, the exponential part of $R$ is obtained

$$R \approx \alpha\phi_\infty\sum_k P(k)k = \langle k\rangle\alpha\phi_\infty. \quad (31)$$

In comparison to the rumor diffusion in single-layer networks [4], [8]–[11], in the coupled social network the average degree of rumor propagation has at least doubled. What's more, there is always a critical threshold $\lambda_c = \delta/\bar{k}$ for rumor spreading in single-layer networks [4], [8]–[11]. However, the threshold of SIHR model is close to 0 along with the increasing of network size. Therefore, within the doubled average degree and without the threshold, the rumor in the coupled social network spreads more easily and smoothly.

## IV. SIMULATIONS AND DISCUSSION

Following the theoretical analysis, this section gives the numerical results of SIHR model to illustrate not only the final steady-state characteristics but also transient performance of dynamic process. Propagation dynamics also lies on the structure of the network. Since an SW-SW coupled network only presents small world property [1] and an SF-SF coupled network only presents scale free property [2], this article simulates the propagation dynamics in a coupled network interconnected by SW networks (homogeneous networks) and SF networks (heterogeneous networks) to study the influence of both small world property and scale free property. The details of SW network, SF network and coupled network are shown in Table 1. The final result is an average of 100 random initial spreader simulations.

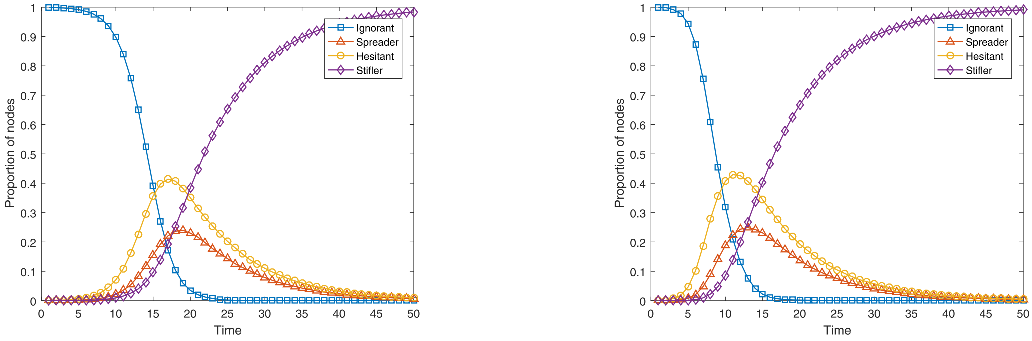
**TABLE 1.** **Network attributes.**

| Attributes | Network type | | |
|---|---|---|---|
| | Small-world | Scale-free | Coupled |
| Nodes number | $10^5$ | $10^5$ | $10^5$ |
| Rewiring probability | 30% | N/A | N/A |
| Initial nodes | N/A | 5 | N/A |
| Mean degree | 8 | 8 | 16 |
| Mean path length | 4.41 | 3.42 | 2.98 |
| Cluster coefficient | 0.23 | 0.03 | 0.09 |

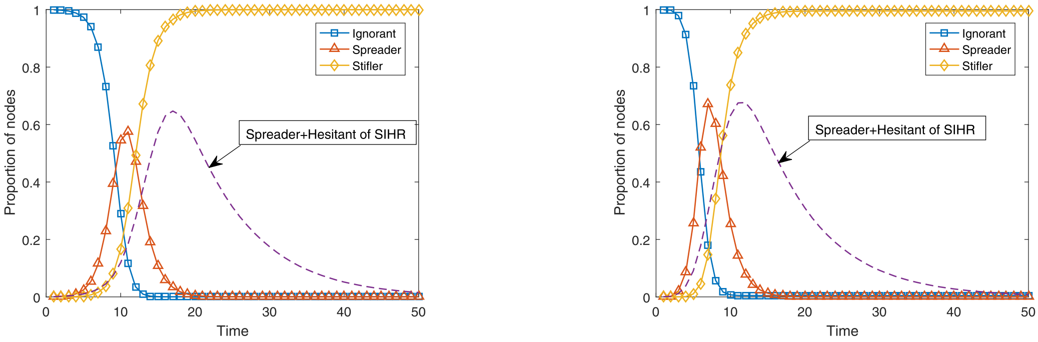
### A. COMPARISON SIHR MODEL WITH SIR MODEL

Fig. 3 compared the SIHR model with SIR model [5] in two cases: SW network, SF network, and separately exhibited the SIHR model in coupled network since the SIR model is built on the single-layer network itself. It is worth noting that there is a general trend: As time goes on, the rumor experiences the incubation period, the outbreak period, the decline period and finally dies out. For example, in SIHR model the ignorants progressively turn into the hesitant and spreaders. After rising to the peak, the hesitant and spreaders shrink and turn into stiflers. Specifically, the hesitant and spreaders in SF network (Fig. 3(b)) realize faster velocity and greater peak value than those in SW network (Fig. 3(a)). Since high-order nodes called Hub nodes [2] exist in SF networks, these Hub nodes significantly accelerate and enhance the rumor spreading. This phenomenon is more obvious in coupled networks (Fig. 3(e)). This is because the coupled network not only integrates the Hub node of scale-free network, but also confronted with bilayer spreaders as mentioned in section II.

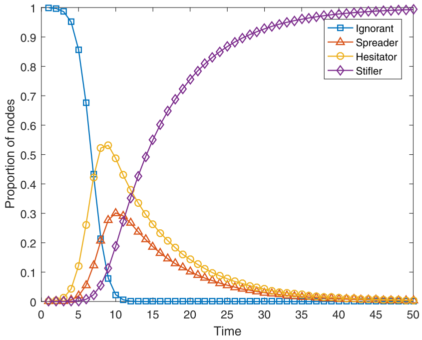
Comparing with SIR model, because of the existence of the hesitant, the rumor in the SIHR model breaks out later and lasts longer as shown in Fig. 3(c) and Fig. 3(d). The acceleration and enhancement effect of the Hub nodes remains observed. Moreover, in SW network, the peak value of SIHR model is greater than that of SIR model in Fig. 3(c), that is because the existence of the hesitant help the rumor spread farther and further. In SF network, this part of the role is



(a) SIHR in WS network (b) SIHR in SF network



(c) SIR in WS network (d) SIR in SF network



(e) SIHR in coupled network

**FIGURE 3.** **The evolution of rumor dynamics.**

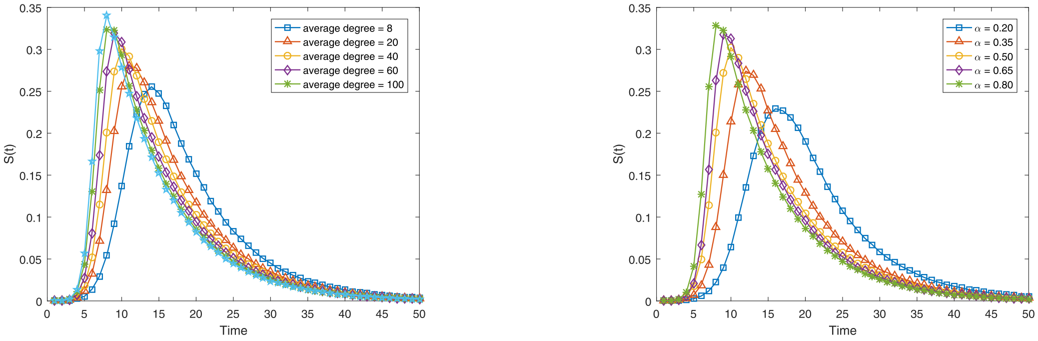
played by the Hub nodes. Therefore, in Fig. 3(d) the two peak values are about the same.

## *B. SIMULATIONS IN COUPLED NETWORKS*

The three scenarios above are not enough to investigate the performance of the SIHR model. Therefore, more simulations are carried out in the coupled networks to illustrate the dynamic process. Here the proportion of spreaders ($S_k(t)$) is employed for observing the rumor dynamics. Referred to [4]–[13], unless otherwise specified, the coefficients are set as $\alpha = 0.5$, $\gamma = 0.45$, $\mu = 0.4$, $\omega = 0.4$.

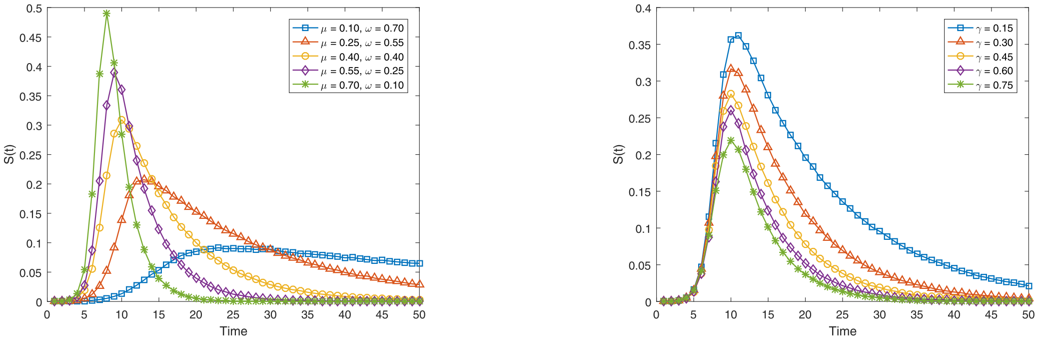
Firstly in Fig. 4a, the performances of $S_k(t)$ with varying average degrees are compared. The increasing of average degree is conducive to accelerate the propagation of rumor as well as increase the peak value of spreaders. In detail, along with the gradually increasing of average degree, the speed and peak value of spreaders are not linearly increasing. The increasing below 40 is more obvious than that over 60. The weakening of edge effect explains that the lower the average level of rumor control, the better. The security scheme is realized by decomposing the interconnection of coupled networks into several individual networks.

Secondly, performances of $S_k(t)$ with various $\alpha$ are compared when other coefficients are fixed. As shown in Fig. 4b, the performance of various $\alpha$ is similar with the performance of average degrees in Fig. 4a. Furthermore, the effect of $\alpha$ is more significant. In reality, $\alpha$ describes the infectious power of rumors. The more fascinating the rumor is, the more people



(a) The impact of *average degree*

(b) The impact of $\alpha$



(c) The impact of $\mu$ and $\omega$

(d) The impact of $\gamma$

**FIGURE 4.** **Various parameters of rumor dynamics.**

indulge with. The fabrication of rumor cannot be controlled. However, the security scheme can be achieved by educating and promoting security advertisements to reduce the deception of rumors.

Thirdly, the performances of $S_k(t)$ with various $\mu$ and $\omega$ are compared when other coefficients are fixed. Fig. 4c exhibited that as $\mu$ rises and $\omega$ reciprocally drops, the speed and peak value of spreaders are increasing significantly. On the other side, it is noted that there is a tailing phenomenon with low $\mu$ and high $\omega$. Fortunately, the $S_k(t)$ is very low and negligible. In reality, the pair of coefficients $\mu$ and $\omega$ depicts the balance between the hesitant and spreaders. When a hesitant person receives repeated rumors, the balance will be transferred to $\mu$. Whereas, if spreaders no longer receive rumors and then loses interest, $\omega$ will dominate. With the increase of $\omega$ and the decrease of $\mu$, more spreaders may become hesitant. This means that the spread scope of rumors is limited, so fewer groups are talking about these rumors. The security scheme can be realized through surveillance of nodes in the monitoring centers and disconnecting the interconnection link of the coupled network.

Finally in Fig. 4d, performances of $S_k(t)$ with various $\gamma$ are compared when other coefficients are fixed. The increasing of $\gamma$ only affects the peak value of spreaders, while the speed is escaped. In fact, $\gamma$ describes the stiflering mechanism [4], and more people may recover from the rumor and become stifler. This security strategy can be realized through publicity and education of fraud cases, establishment of trust mechanism, strengthening monitoring and improving the ability of anti rumor.

### C. DISCUSSION ON SECURITY SCHEME

From the simulations above, it is noted that

(1) The factors ranked from strong to weak that affect the spread of rumors are $\mu$ and $\omega$, $\gamma$, $\alpha$, average degree. Considering the security response to rumor spreading, instead of relying on malicious users for making mistakes and passively expecting people to resist rumors, it is better to carry out public education and active security policy.

(2) In coupled social networks, the spreading speed and peak value of rumors are enhanced by the interconnection links and crossing propagations. Therefore, more checks and thresholds should be inserted between different social applications rather than inherent trust or unconditional sharing.

## V. CONCLUSION

In a coupled social network, rumors can spread layer by layer and iterate to more repeated propagation. For ensuring safety, rumor spreading needs rapid identification, positioning and control. Considering that users will face repeated infection, we propose a SIHR model for investigating RRS in coupled social networks. Appropriate security measures should be formulated to intervene and limit the spread of rumors in different scenarios. From the simulations, it is found that the factors $\mu$ and $\omega$, $\gamma$, $\alpha$, average degree, which are ranked from strong to weak, impact the rumor spreading. Therefore, carefully handling the interconnection links and restricting rumors' influence power are the most efficient way to control the rumor. In addition to rumor propagation, our model can also be applied to other propagation processes in coupled networks, like information dissemination, malware spreading and virus propagation.

RRS in coupled networks is still a young investigation field. The details and principles behind the rumors are yet to be disclosed. The dynamic process can be further explored and analyzed. Secondly, more attention should be paid to the early stage of rumor spreading because the harm has not been fully revealed. It can nip these threats in the bud by providing wise judgment and wise choice through Big Data and artificial intelligence technology.

## REFERENCES

[1] D. J. Watts and S. H. Strogatz, "Collective dynamics of 'small-world' networks," *Nature*, vol. 393, no. 6684, pp. 440–442, 1998.

[2] A.-L. Barabási and R. Albert, "Emergence of scaling in random networks," *Science*, vol. 286, no. 5439, pp. 509–512, Oct. 1999.

[3] M. Kas, L. Carley, and K. Carley, "Monitoring social centrality for peer-to-peer network protection," *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 155–161, Dec. 2013.

[4] M. Nekovee, Y. Moreno, G. Bianconi, and M. Marsili, "Theory of rumour spreading in complex social networks," *Phys. A, Stat. Mech. Appl.*, vol. 374, no. 1, pp. 457–470, Jan. 2007.

[5] D. J. Daley and D. G. Kendall, "Epidemics and rumours," *Nature*, vol. 204, no. 4963, 1964, Art. no. 1118.

[6] X. Yin, H. Wang, P. Yin, and H. Zhu, "Agent-based opinion formation modeling in social network: A perspective of social psychology," *Phys. A, Stat. Mech. Appl.*, vol. 532, Oct. 2019, Art. no. 121786.

[7] A. Dang, M. Smit, A. Moh'd, R. Minghim, and E. Milios, "Toward understanding how users respond to rumours in social media," in *Proc. IEEE/ACM Int. Conf. Adv. Social Netw. Anal. Mining (ASONAM)*, Aug. 2016, pp. 777–784.

[8] L. Zhao, X. Qiu, X. Wang, and J. Wang, "Rumor spreading model considering forgetting and remembering mechanisms in inhomogeneous networks," *Phys. A, Stat. Mech. Appl.*, vol. 392, no. 4, pp. 987–994, Feb. 2013.

[9] Y. Wang, F. Qing, J.-P. Chai, and Y.-P. Ni, "Spreading dynamics of a 2SIH2R, rumor spreading model in the homogeneous network," *Complexity*, vol. 2021, pp. 1–9, Feb. 2021.

[10] D. H. Zanette, "Dynamics of rumor propagation on small-world networks," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 65, no. 4, Mar. 2002, Art. no. 041908.

[11] Y. Moreno, M. Nekovee, and A. F. Pacheco, "Dynamics of rumor spreading in complex networks," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 69, no. 6, Jun. 2004, Art. no. 066130.

[12] Nandini, P. Kumar, and R. Tejender, "Review paper on spreading process in multilayer network," *Int. J. Innov. Res. Comput. Commun. Eng.*, vol. 4, no. 5, pp. 9363–9368, 2016.

[13] M. De Domenico, C. Granell, M. A. Porter, and A. Arenas, "The physics of spreading processes in multilayer networks," *Nature Phys.*, vol. 12, no. 10, pp. 901–906, Oct. 2016.

[14] N. Jia, G. Sun, C.-C. Chen, and S. Bin, "Research on robustness of coupling networks based on multi-subnet composite complex network model," in *Proc. IEEE 2nd Eurasia Conf. Biomed. Eng., Healthcare Sustainability (ECBIOS)*, May 2020, pp. 56–59.

[15] L.-S. Lv, K. Zhang, T. Zhang, and M.-Y. Ma, "Nodes and layers PageRank centrality for multilayer networks," *Chin. Phys. B*, vol. 28, no. 2, Feb. 2019, Art. no. 020501.

[16] L. Ming, L. Lü, Y. Deng, M. B. Hu, H. Wang, M. Medo, and H. E. Stanley, "Historydependent percolation on multiplex networks," *Nat. Sci. Rev.*, vol. 7, no. 8, pp. 1296–1305, 2020.

[17] J. Gao, D. Li, and S. Havlin, "From a single network to a network of networks," *Nat. Sci. Rev.*, vol. 1, no. 3, pp. 346–356, Sep. 2014.

[18] Y. Zhang, Y. Li, M. Li, and J. Ma, "Method to enhance traffic capacity for multilayer networks," *Int. J. Modern Phys. B*, vol. 34, no. 13, May 2020, Art. no. 2050140.

[19] L. Hu, H. Wen, B. Wu, F. Pan, R.-F. Liao, H. Song, J. Tang, and X. Wang, "Cooperative jamming for physical layer security enhancement in Internet of Things," *IEEE Internet Things J.*, vol. 5, no. 1, pp. 219–228, Feb. 2018.

[20] S. V. Buldyrev, R. Parshani, G. Paul, H. E. Stanley, and S. Havlin, "Catastrophic cascade of failures in interdependent networks," *Nature*, vol. 464, no. 7291, pp. 1025–1028, Apr. 2010.

[21] M. Mirbabaie, S. Stieglitz, and F. Brinker, "Dynamics of convergence behaviour in social media crisis communication—A complexity perspective," *Inf. Technol. People*, to be published.

[22] W. X. Zhao, S. Li, Y. He, E. Y. Chang, J.-R. Wen, and X. Li, "Connecting social media to E-commerce: Cold-start product recommendation using microblogging information," *IEEE Trans. Knowl. Data Eng.*, vol. 28, no. 5, pp. 1147–1159, May 2016.

[23] H. Wang, F. Wang, J. Liu, C. Lin, K. Xu, and C. Wang, "Accelerating peer-to-peer file sharing with social relations," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 9, pp. 66–74, Sep. 2013.

[24] Y. Hu, D. Wang, H. Zhong, and F. Wu, "SocialTrust: Enabling long-term social cooperation in peer-to-peer services," *Peer Peer Netw. Appl.*, vol. 7, no. 4, pp. 525–538, Dec. 2014.

[25] M. Luca, R. Francesco, V. Antonino, and V. Pietro, "Social business hybrids' diversification: Effects on socioeconomic combined performance," in *Proc. Academy Manage. Annu. Meeting*. 2020, Art. no. 17113.

[26] M. Fire, R. Goldschmidt, and Y. Elovici, "Online social networks: Threats and solutions," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 2019–2036, 4th Quart., 2014.

[27] R. Parshani, S. V. Buldyrev, and S. Havlin, "Interdependent networks: Reducing the coupling strength leads to a change from a first to second order percolation transition," *Phys. Rev. Lett.*, vol. 105, no. 4, Jul. 2010.

[28] W. Yu, P. Jiao, W. Wang, Y. Yu, X. Chen, and L. Pan, "A novel evolutionary clustering via the first-order varying information for dynamic networks," *Phys. A, Stat. Mech. Appl.*, vol. 520, pp. 507–520, Apr. 2019.

**QIYI HAN** received the B.S. and Ph.D. degrees from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2009 and 2016, respectively. He is currently a Lecturer with the School of Information Science and Engineering, Chengdu University, Chengdu. His research interests include distributed networks and complex theory, with emphasis on security and protection tactics.

**KAIBO SHI** (Member, IEEE) received Ph.D. degree from the School of Automation Engineering, University of Electronic Science and Technology of China. From September 2014 to September 2015, he was a Visiting Scholar with the Department of Applied Mathematics, University of Waterloo, Waterloo, ON, Canada. He was a Research Assistant with the Department of Computer and Information Science, Faculty of Science and Technology, University of Macau, Taipa, from May 2016 to June 2016 and from January 2017 to October 2017. He was also a Visiting Scholar with the Department of Electrical Engineering, Yeungnam University, Gyeongsan, South Korea, from December 2019 to January 2020. He is currently a Professor with the School of Information Sciences and Engineering, Chengdu University. He is the author or coauthor of more than 60 research articles. His current research interests include stability theorem, robust control, sampled-data control systems, networked control systems, Lurie chaotic systems, stochastic systems, and neural networks. He is a very active reviewer for many international journals.

**MUSONG GU** received the Ph.D. degree in traffic information engineering and control from Southwest Jiaotong University, China, in 2014. He is currently an Associate Professor with Chengdu University, China. His research interests include wireless sensor networks and convolutional neural networks.

**LEI YOU** received the B.E. and M.S. degrees in computer science from Sichuan University, China, in 2000 and 2006, respectively, and the Ph.D. degree in nuclear technology and applications from the Chengdu University of Technology, China, in 2012. He is currently a Professor with the School of Computer Science, Chengdu University, China. His research interests include computer science and technology.

**FANG MIAO** received the Ph.D. degree in radioactive geology from the Chengdu College of Geology, in 1990. Then, he joined the Department of Computer Engineering, Chengdu College of Geology, and was promoted as a Professor, in 1995. He is currently a Professor with the School of Information Science and Engineering, Chengdu University, China. His research interests include data architecture and information security.

• • •