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ORIGINAL ARTICLE

A social immunity based approach to suppress rumors in online social networks

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Abstract
Online social networks (OSNs) connect people around the globe under one virtual society. It helps people gather, commutate and share their common interests. But many times, OSNs are also exploited and eventually become a major platform for rumor or false information propagation. Controlling such rumors in OSNs has been the most challenging research interest in recent days. Since OSNs are a platform of collective behavior, we focus on a collective rumor containment approach to control or eradicate rumors. In this paper, an anti-rumor information spreading approach is proposed to contain rumors collectively by following a bio-inspired immunization method called social immunity. First, A competitive information propagation model called competitive cascade (CC) model that spreads rumor and true information simultaneously is defined. This model continuously updates the trustworthiness of individuals in the network on every communication among the participants of OSNs. Then, the initial spreaders of anti-rumors are identified with the help of the intensity of the rumor in the network as well as the individual's trustworthiness. Finally, a collective rumor containment approach is applied by considering the cost of rumor containment and a rumor intensity threshold. The proposed approach is compared with recent and well-known rumor control approaches and the results show that the proposed approach is effective in eradicating rumors.

Keywords Rumor control · Online social networks · Cyber security · Social immunity · Collective rumor containment · Truth spreading · Anti-rumor spreading

1 Introduction

Online social networks (OSNs) are finding its way to be part and parcel of everyone's virtual world for the dissemination of a plethora of opinions, news, and innovative marketing for businesses [1, 2]. In this era of social networking, an increased amount of novel information is spreading with different viewpoints on an unprecedented scale [3]. OSNs are typically considered to be a double-edged sword in terms of information diffusion. In one-hand it provides an open way to communicate among people; but on the other-hand, OSNs play as a platform for rumor dissemination [4]. Such rumor propagation in OSNs causes panic and chaos during emergency events, causing a negative effect. The transmission rate of these rumors is faster in online networks compared to offline networks [5, 6]. Once the rumor reaches millions of people, it causes irreparable damage to society. Consequently, studying the rumor diffusion and restraining the rumor in OSNs is of critical research interest in recent times.

Rumor is defined in the social psychology field as a piece of information whose source cannot be verified as true or false at the time of circulation [7]. In OSN terms, a rumor is a story or claim that is unverified or deliberately not true and the same is propagated among participants in the network. There are various rumor identification approaches for efficiently detect rumors in OSNs [8–11]. OSNs can be protected from the identified rumors at any of these levels: (1) *Preventing rumor* educating the individuals to share only legitimate content and avoid unverified contents. (2) *Initial restrain* identifying rumor in the network and remove the information early. (3) *Blocking rumor* blocking rumor spreaders to stop spreading the rumors, (4) *Suppressing rumor* spreading true information and educate people about the rumor to suppress the rumor spread in the network. Out of these, suppressing rumor and blocking rumor are rumor

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containment approaches studied along with information diffusion in OSNs.

Typically, government organizations or official bodies circulate/spread true information to suppress the rumor. When a government organization or any official body tries to spread true information against a rumor, then these two information try to compete with each other to establish itself in the OSN application. Kostka et al. study the competing nature of two rumors as a gaming problem and prove that the first rumor has no precedence to spread wider compared to the second rumor [12]. It implies the second information can reach a maximum number of people even though it starts the propagation later in the network. This competitive nature needs to be studied to successfully propagate the true information as a reactive measure. This paper introduces a cascading model called the Competitive Cascade model to study the rumor and protector diffusion nature.

Generally, the anti-rumor propagation methods follow the below approach: an information propagation model to study the rumor and true information propagation define the social networking environment. Then a set of individuals as initial spreaders are identified for the anti-rumor spread to effectively act against the rumors. Finally, the anti-rumor spreading approach will be deployed that propagates true information until the rumor breaks or the end condition meets. Utilizing this methodology, various truth spreading mechanisms proposed to combat rumors from social networks [13–16]. All these approaches study the anti-rumor spreading as an activity of individuals propagating truth against the rumor. But rumor containment can be a group activity where a set of individuals initiate a group information propagation that reaches the maximum number of individuals at the earliest. This helps in controlling the rumor faster than other approaches. To achieve this purpose, this paper proposes a rumor combating approach that follows the immunization method of social insects called "Social immunity".

Most of the rumor spreading models are derived based on the inspiration of natural epidemic models [17, 18] due to the similarity of spreading processes. In the same way, rumor control can also be studied with the help of social insect's immunization because rumor control and social insect's immunization are possessing the same behavior. To quote a few: (1) rumor and insect's epidemic spread through one-to-one contact. (2) Blocking of infected individuals can control rumor in social networks and epidemic spread in social insects. (3) Reducing susceptibility of individuals can also be through transferring immunity in insects and propagating true information to social networks. (4) Collective decision-making approach is followed in social insects for fever immunization [19] as well as participants in social networks for information propagation [20, 21]. So, this paper is attempting to study the rumor containment by the inspiration from the immunization technique of social insects.

Social immunity is a colony immunization approach followed by social insects such as honeybees, ants and so on. Parasite infection in the colonies is spreading faster through the contact between insects. In order to reduce susceptibility, insects spread immunity agents among the colony members as a sequential approach. This continues effort of insects remove the parasites from the colony or killed. This is a collaborative behavior among the colony members. This collective approach reduces the susceptibility of the social insects in the colony.

The objective of this paper is to suppress the rumor by spreading the true information against rumor as a group activity. Rumor spreads in OSNs as a cooperative approach: a spreader should convince the receiver to believe and spread to the receiver's neighbors. This approach should be continued to achieve rumors to reach the maximum number of people. Rumor combating also should be a cooperative approach to suppress the rumor. In this paper, a novel rumor containment approach is proposed by the inspiration from a bio-inspired, social immunity-based approach. This method enhances the rumor combat as a collective approach and makes true information to reach a maximum number of people faster than the rumor. First, this approach utilizes opinion dynamics and severity of rumor to identify the influential initial spreaders. These initial spreaders enable the group information propagation within as well as across the communities. Opinion dynamics is used to study the influence of individuals on the neighbor through their opinion or belief. This belief factor plays a significant role in information propagation. The proposed approach introduces an extended HK model based on the HK model [22] for the opinion updates. From the best of our knowledge, this is the first approach that applies opinion dynamics in rumor containment issues. Then a collective rumor containment approach is proposed with the help of the initial spreaders identified in the first step. This rumor containing approach considers the cost of spreading the true information and a threshold of rumor depth in the network. The novelty of this paper lies in three aspects: (1) proposing a new information propagation model called competitive cascade model which continuously updates the belief of individuals, (2) using opinion dynamics and severity of rumor in identifying the influential seed spreaders, (3) a novel collective rumor containment approach with the least cost and proportional to the threshold of rumor severity.

The contribution of this paper is as follows.

1. Proposes an information propagation model called Competitive Cascade (CC) model that mimics the real-world rumor as well as true information spreading nature among communities in OSNs.

2. The intensity of rumors and the trustworthiness of participants in the network are utilized to identify the influential spreaders from a. participants who enable the herding process within the community and b. participants who can enable information to spread across the communities. These influential spreaders are utilized to propagate the anti-rumor.
3. A cooperative rumor containment approach is proposed to spread true information against the rumor by examining the rumor depth and rumor containment cost. This enables the collective rumor combating with the help of anti-rumor. This collective approach is inspired by the social immunity nature of insects.
4. Validates the proposed approach with six datasets, four real-world and two synthesized datasets, and prove the effectiveness of the proposed approach. The proposed approach is compared with recent and well-known rumor combating approaches.

The rest of this paper is organized as follows: Sect. 2 elaborates the related works on rumor containment and social immunity. Then in Sect. 3, this paper discusses social immunity approaches followed by various social insects. Section 4 explains the proposed competitive cascading model and formulate the problem. In Sect. 5, the paper extensively elaborates the proposed approach on combating the rumor spread. Experimental evaluation and results discourse in Sect. 6. Section 7 elaborates the significance of the proposed approach in controlling the rumors in light of key findings from the study. This paper concludes in Sect. 8 with possible future enhancements.

2 Related works

Online social networks are termed to be collective rumor mills [23]. From the time OSNs emerged, rumor containment is of prime concern among researchers because it spreads faster than normal information in OSNs [6, 24]. Suppressing rumor through anti-rumor and blocking rumors through influential individuals have been important rumor containing approaches. Containing rumor by spreading true information is more advantageous due to the benefit of making people know the true information as a contagious effect.

There are various true information spreading approaches proposed by exploring various QoS (Quality of Service) factors like cost of educating individuals, quality of education, the budget, time, etc., Rumor restriction using a greedy algorithm is proposed in Li et al. [25]. The influential spreaders to propagate true information are identified from both affected as well as not affected set of spreaders. The same problem is addressed by selecting a specific number of individuals to spread true information in [13, 26, 27]. A community-level anti-rumor spreading approach is proposed in [13]. Authors identify connecting nodes between communities and utilize those nodes as seed nodes for truth spreading. This approach uses only cost as QoS but failed to find influencers from within the community and did not study the time taken to control rumors. A rumor containment method proposed in [26] is a truth spreading mechanism that considers the budget and time constraints. They proposed two cascading models based on well-known models like Independent cascade and Linear threshold model. In [27], the independent cascade model is adapted to contain the rumors. Independent cascade and linear threshold are preliminary models that study the rumor propagations. But most of the rumor containment approaches studied on advanced epidemic spreading models like SIR, SIS, etc. Also, these approaches did not study constraints related to rumor like the severity of rumors, the percentage of people affected.

A rumor control training for higher degree individuals to propagate anti-rumor is proposed in Kotnis [15]. This training scheme evaluates the cost constraint along with the rumor outbreak condition while finding the number of individuals as well as the quality of training. But the influencer finding in this method is through the simple metric: the degree of individuals, i.e., a higher number of connections. In the real world, the number of connections does not define the influence of participants in the network. This approach does not deal with the believability of individuals on neighbors in spreading the anti-rumor.

Based on time taken to believe rumors, Tripathy et al. proposed two models to combat the rumor through anti-rumor propagation, namely the Delayed Start model and Beccan model [28]. These models are termed as an anti-rumor model to study the reactive situation of true information spreading with a time lag in responding to the rumor. In this model, authorities and their agents only can spread anti-rumors. This method couples the rumor identification with rumor control but failed to discuss the rumor finding mechanisms. Both models proposed in this work are not considering the intensity of rumors or the influence of anti-rumor spreaders which are the most important factors in anti-rumor propagation. Similarly, Huo et al. analyzed the interplay between rumor and scientific knowledge during an emergency [29]. The authors derived a 4D model by equally considering the spreading of rumor and scientific knowledge. They argue that the official body has more responsibility in acting wisely during the emergency and this act plays a major role in controlling the rumor. In both approaches, only the official body has the authority to propagate the true information. But there are other influential spreaders who can succeed in spreading anti-rumors through competing information propagation [30].

In social networks, rumors, and anti-rumors spread by competing with each other. A Competitive Linear Threshold model (CLT) [31] is proposed to study competitive influence propagation. In the CLT model, positive and negative weights are assigned to a node for the propagation of opposite attitude information. The authors aimed to block the influence of information by using other competitive information. In a similar way, Liu et al. also considered the competitive nature of two opposite information and proposed a model called D–C (Diffusion and Containment Influence) model [30]. The authors proposed a greedy algorithm to contain the diffusion influence information with the help of containment influence information. In both approaches, the Linear threshold model is extended to study the competing nature of positive and negative influences. Also, influential positive individuals are identified through probabilistic weights. These competing methods did not provide greater results in containing rumors which require more improvement in terms of models used and finding proper influential spreaders [32].

Rumor blocking is another approach to contain rumors in online social networks [14, 33]. Hu et al. proposed a rumor blocking approach through wise individuals [14]. The authors claim the individuals are wise to understand the rumor and avoid it when the official information is passed to them. But wise individuals cannot control the rumors once it spread across the network. The influence of individuals plays a vital role in combatting the rumor. Kimura et al. proposed to block the important links instead of blocking a node [33]. In the real-world, blocking the links may not be optimal as the users can still propagate the rumors from other links since OSNs are scale-free networks.

Komi has introduced a new rumor dynamics model, SEIR [34] by the inspiration of the SIR epidemic model [35]. Komi proposed to educate ignorant people and study their behavior. This work claims that educated ignorant individuals have the ability to reduce the rumor. Forgetting mechanism is used as a major deciding factor in the spreading process in the researches like [24, 36]. SIHR [37] introduced one more state called Hibernator in the SIR epidemic model by considering the forgetting and remembering mechanism of spreaders. There are other such methods that extend the classical epidemic models to study the rumor spreading [17, 18, 38]. Recently, a new Rumor Containing (RC) model is proposed with budget constraints [39]. This defines an epidemic model called uncertain-rumor-truth-uncertain (URTU) which is similar to the SIR model. RC model defines suppressing the rumor by spreading true as an optimization problem. This model evaluates the forgetting rate, rumor duration for containing the rumor. But the main QoS such as cost, the severity of rumors are not considered in these methods. These approaches are modeled based on different kinds of propagating natures of spreaders. However, in real-life, opinions of the individuals on the neighbors play a vital role in information propagation [40, 41]. But these methods are not considering the actual opinion of individuals during rumor propagation.

The common drawbacks seen in the works discussed so far are (1) the important QoS to contain rumors are cost, budget is omitted in many of the approaches. (2) In most of the works, the strength of rumor in the network is not examined while propagating anti-rumors, (3) the influential opinion of individuals on neighbors in finding influential individuals is never studied in any of the approaches. (4) Seed spreaders should enable the faster spreading of anti-rumors. But many approaches do not guarantee that initial spreaders are influential. So, the proposed approach addresses these issues by spreading true information from the inspiration of social immunization approach of the social insects, a bio-inspired approach, as a spreading approach. Specifically, the seed nodes to spread true information are selected in two ways: (1) within the community and (2) from the nodes that connect communities. This allows a cooperative rumor containment among communities. The user constraints such as rumor containment cost and rumor severity are also examined in the proposed approach.

3 Social immunity

Social insects such as honeybees, ants lead a group living rather than a solitary lifestyle. These insects forage food sources as a group activity. Same way, insects act against the parasites as a colony. These colonies have evolved to be collectively immunized systems. This kind of protecting the part of the susceptible population against the parasites is called Social Immunity. So, social immunity can be defined as a collective anti-parasite approach carried over by social insects to mitigate the disease spread in the colony. After encountering a parasite infection to one or more colony members, increasing the protection of the colony with the help of affected individuals is followed in social immunization.

Social fever and social transfer immunity are major social immunity approaches followed by social insects to reduce the susceptibility of the insects [42]. Social fever immunization approach is seen in honey bees [19]. Honeybee colonies maintain an elevated temperature in their nests for reasons such as (1) accelerating brood development, and (2) defense against parasites. The Chalkbrood is a disease caused by a heterothallic fungus, Ascosphaera apis, that affects the larvae in honey bee colonies [43]. Once larvae affected by this heat-sensitive pathogen, larvae die and these mummies dry into white lumps that resemble chalk. This act is beneficial for other colony members to recognize the pathogenic effect. Once it recognizes, the honeybees increase the brood-comb temperature and it limits the pathogenic effect.

Social transfer immunity [44] is an adaptive immunization approach followed by dampwood termites to control a fungus disease. If any of the individual termites in the group immunize itself from fungus, there is a high chance that immunization spreads through contact with others in the group. This contact immunization increases the survivorship of termites. This kind of 'transferring' of immunization is termed as social transfer immunity.

Susceptibility reduction of insects followed in [19, 44] is explained in Fig. 1. Susceptibility reduction is transferring of fever to other insects to improve the immunity against the parasite infection. This approach can be summarized as follows: On the encounter of parasite infection, the temperature of the brood camp is increased to avoid further spread through the chalkbrood effect. In case of the disease to be transferred to other broods, then contact immunity is activated to transfer the fever to other brood camps. If the camp is immunized from parasite infection, then the transfer stops. Otherwise, immunity transfer continues. In this paper, a rumor control approach is developed by the inspiration of this susceptibility reduction approach of social insects.

Social immunity for susceptible reduction approach.

4 Model and problem formulation

In this section, a Competitive Cascade model (CC) is introduced based on the SIR epidemic model. This model impersonates the real-world rumor propagation and its respective true information propagation in OSNs. Under the CC model, the Rumor Containment via Social Immunity (RC-SI) problem is studied.

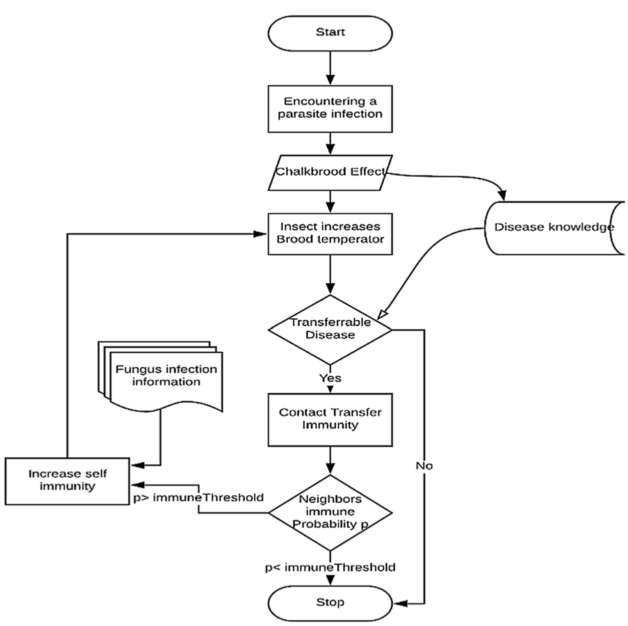


Fig. 1 Social immunity for susceptibility reduction of insects

This paper aims to propagate true information against the rumor to suppress the spread of the rumor. So, the CC model tries to model the two opposite information spreading and study its nature in order to suppress one against the other.

4.1 Competitive cascade model

The competitive Cascade (CC) model is derived from the SIR epidemic model. An undirected graph $G = (V, E, B)$ is used to represent OSNs in this paper. Here, nodes in V represent individuals in the network, edges in E represent the social connection between individuals and B is the belief influence of each node on other nodes. This social connection is a pair-wise connection. $b(u)$ is a belief influence value of node u. This belief influence of u is updated on every pair-wise interaction between $u's$ neighboring nodes. Let $C = \{C_1, C_2, C_3, \dots, C_n\}$ be the communities available in network G with few nodes overlapping between communities and the number of communities is n.

Each node in this model can be in one of four states: Ignorant (I), Spreader (S), Protector (PR), and Prosocial (P). Ignorant is neutral to both rumor and true information and target for both true and rumor information spreading. They are naïve, prone to be affected by any information sent by others. Spreader spreads the rumor in the network, Protector sends the true information in the network, and Prosocial are the individuals who recover from the rumor and will not be affected anymore. The proposed CC model is explained in Fig. 2.

Let a random variable $X_i(t)$ represents the state of node i at time t. At time 0, all the nodes in the network are assumed to be in the Ignorant state. If an arbitrary user i believes the rumor and decided to spread, then the state of the user will be $X_i(t) = Spreader$. If the user believes the true information and decided to spread, then the state of the user will be $X_i(t) = Protector$. A user can become *Protector* from the state *Ignorant* and *Prosocial*. At any given time, the user tries to send information to neighbors, either be it rumor or true information. For simplicity, it is assumed that a

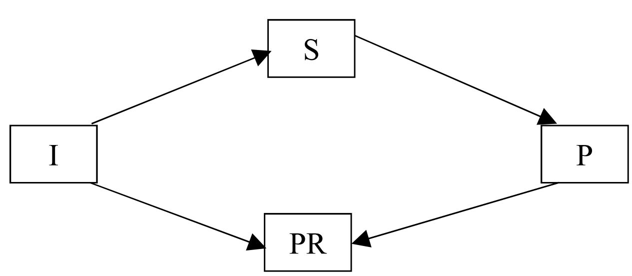


Fig. 2 Competitive cascade model

user can spread information only once to his/her neighbor. The spreader goes to prosocial in either of these two ways: They treated by the protector or they loss interest in sending rumor. Then the state of such users will be $X_i(t) = Prosocial$.

4.2 Belief update

To update the belief of every individual in the network, an extended HK model is derived from Li et al. [22]. This is a non-linear update model that updates the individual's belief influence synchronously based on the interactions. A confidence trust value € is defined as a base belief value between neighbors for the information propagation process. The belief influence of an individual updated only if the value is greater than the trust value. Otherwise, the belief update is ignored. It is assumed that each time step t = 0, 1, 2, …, the belief influence of node $u \in [V]$ can be represented by a vector $b_u(t) = [b_1, b_2, \dots, b_q]$. Here q is the possible number of outcomes of any interaction in the network. With this, the neighborhood function is defined as,

$$N_u(t) = \left\{ v \in [V] \middle| \left| b_u(t) - b_v(t) \right| > € \right\} \quad (1)$$

Using Eq. (1), the belief update model can be defined as,

$$b_u(t+1) = \frac{1}{|N_u(t)|} \sum_{v \in N_u(t)} b_v(t) \quad (2)$$

To calculate the belief influence of an individual, a measure called belief closeness is defined

$$BC_u(t) = \frac{1}{\sum_{v \in C/u} b_v(t)} \quad (3)$$

In reality, individuals have their own judgments about the information they receive. Before they decide about whether to propagate/share the information, they judge it. This is called as the individual interest threshold $\rho \epsilon (0,1)$. For simplicity, it is assumed that the value to be the same for everyone.

4.3 Problem definition

In this section, the paper defines the problem and related definitions of the proposed CC model. Every online social network possesses some common behavior: people with shared interests are connected as neighbors and share information among their connection. This phenomenon creates more communities in the network and the clustering coefficient gets higher in such networks. So, people from the same community tend to have common interests rather than people between communities. That is, people within the same community have more interactions than with people outside. Most of the time, the information spread in OSNs can be viewed as a sequence of decisions in which the following people act based on the actions of earlier people. This approach of one person influencing decisions of others is known as *social influence*. So, information spread in a network is a chain reaction on an influence.

4.3.1 Herding process

In an information diffusion process, actions of an individual heavily been influenced by the actions of previous persons. The individual tries to imitate the same action as the previous person. This individual may or may not impose his judgment on the information. e.g., Information spread from famous personalities spread without much questioning by others. This kind of herding information diffusion is called as Herding Process.

4.3.2 Cascading process

Cascading is an information streamlining process in which individuals imitate almost the same as the previous person. The chain of actions will imitate the initiator in most of the times. Mostly, the individuals in this process will not impose his judgment on the information. e.g., Authentic information from the government or official body during emergency situations will not be questioned by civilians.

4.3.3 RC-SI

Given rumor R and true information P in network G, this problem aims to increase the spread of P such that the spread of R gets reduced by finding the k set of prosocial or ignorant individuals as protectors to enable the herding and cascading process.

5 Rumor containment—a social immunity approach

In this section, the rumor containment approach is discussed as follows: First, identify the most influential persons in every community who can enable the herding/cascading process. Second, the gateway influential spreaders are identified to increase the true information reach across communities. Then, true information is spread to reduce the susceptibility of the individuals in the network.

Rumor intensity describes the severity of the rumor transmission in the network i.e., the proportion of the rumor affected in the network. The intensity of the rumor is not broadly studied while combating rumors in previous researches. In the proposed approach, the intensity of rumor affection in the network is calculated by tracking the amount of population affected by the rumor. The measure rumor depth ($r_d(t) \in [0,1]$) is calculated as,

$$r_d(t) = \frac{Number\ of\ rumor\ affected\ nodes}{Number\ of\ total\ nodes} \tag{4}$$

This value is used to find a number of people needed to find as an initial seed to combat the rumor.

5.1 Herding influencer

OSNs follow power-law degree distribution and having a higher cluster coefficient. The higher cluster coefficient implies that the people from the same community share almost the same interest. An influential person from the same community has the ability to impact more numbers of people in the community. i.e., People from the same community has more believing rate than people from different communities. We use this approach to propagate the true information faster which tries to block the rumor propagation. People from the same cluster share a common interest and an influential person from this cluster has a higher trust factor compared to others in the network. When information being broadcasted from such an influential person, it will transfer to others easily and social transfer of true information faster and people get immune very fast. Prosocial are the people who got immunized from rumor and not going to affect by rumor anymore. Prosocial and Ignorant influencers from a cluster can be considered for protecting the network from rumor.

Algorithm 1 Herding Influence Finder

INPUT: $G = (V, E, B)$, a n set of communities $C = \{C_1, C_2, C_3, \ldots, C_n\}$, rumor depth $r_d(t)$
OUTPUT: Herding Influencer set S.
$S \leftarrow \theta, U' \leftarrow V - S,$
foreach $Comm$ in C do:
    $Seed_{Comm} = Round(rd(t) * \gamma(|Pros(t) + Ign(t)|))$
    for $range(Seed_{Comm})$):
        $v = \arg max_{u \in Comm/S}\{(BC_u) | u \in [Prosocial, Ignorant]\}$;
        $S = S \cup v$;
    endfor
endforeach
return set S

S is the first $Seed_{Comm}$ set of influential persons from every community in the network. The number of influential persons from each community is retrieved based on the intensity of the rumor. So, when the number of people affected by rumor is higher, then the number of true information spreader is more. This selection approach helps to reduce or eradicate the rumor faster from the network. Through this scalable approach, the cost incurred in identifying and true information spreading is controlled based on the intensity of the rumor.

$$|S| = \sum_{Comm \in C} Seed_{Comm} \tag{5}$$

$$Seed_{Comm} = Round\left(rd(t) * \gamma\left(\left|Pros_{Comm}(t) + Ign_{Comm}(t)\right|\right)\right) \tag{6}$$

The $Seed_{Comm}$ is a number of initial seeds from every Community $Comm \in C$. This value is derived from rumor intensity and γ fraction of prosocial and ignorant individuals from the community $Comm$.

5.2 Gateway influencer

A bridge connector between two clusters will be influencing both the clusters. This person can introduce the information from one cluster to the other. In this way, a bridge person acts as a gateway between the clusters. Finding this influencer has a greater impact in wider acceptance of information between clusters.

In this approach, finding influencer seed is a process of finding a person who is not a rumor spreader and has the ability to enable the herding behavior. So, the influential person can be selected from prosocial and ignorant individuals. This gateway influencers are transferring the information between communities. Since the person is influential among neighbors with herding behavior, this person can send true information faster between communities.

Algorithm 2 Gateway Influencer Finder

INPUT: $G = (V, E, B)$, a n set of communities $C = \{C_1, C_2, C_3, \ldots, C_n\}$,
OUTPUT: Gateway influence set GI
$GI \leftarrow \theta, U' \leftarrow V - S$,
foreach $Comm$ in C do
    foreach node i in $Comm$:
        if $\exists\, e \mid (i, u)$ & $u \nexists$ $in\ Comm$:
            $PN = PN \cup i$;
        endif
    endforeach
    $w = \arg max_{u \in PN}\{(BC_u) \mid u \in [Prosocial, Ignorant]\}$;
    $GI = GI \cup w$;
endforeach
return set GI

GI is the set of individuals for every community who has more belief closeness as a bridge connector. The number of individuals in *GI* is equal to the number of communities since the true information should pass between communities to control the rumor spreading.

$$|GI| = |C| \tag{7}$$

Influencer set

$$IF = S \cup GI \tag{8}$$

$$|IF| = \sum_{Comm \in C} Seed_{Comm} + n \tag{9}$$

5.3 Rumor containment—susceptibility reduction

Susceptibility of individuals is reduced by increasing the immunized population in the network. To immunize the population against the rumor, the true information is spread by the government or official body. The true information should reach a maximum number of individuals in the network faster than rumor to ensure the rumor is suppressed. This objective is achieved by enabling true information to spread as a herding process within the community and increasing the information spread across communities. Algorithm 3 explains the process of transmitting true information in the network.

Here, cascading is happening through the inspiration of the social immunity approach. The initial spreaders are the herding and gateway influencers who are identified in the previous step. On the occurrence of rumor, with the help of influential people, the true information is propagated in the network. With this approach, the information broadcasted for susceptibility reduction.

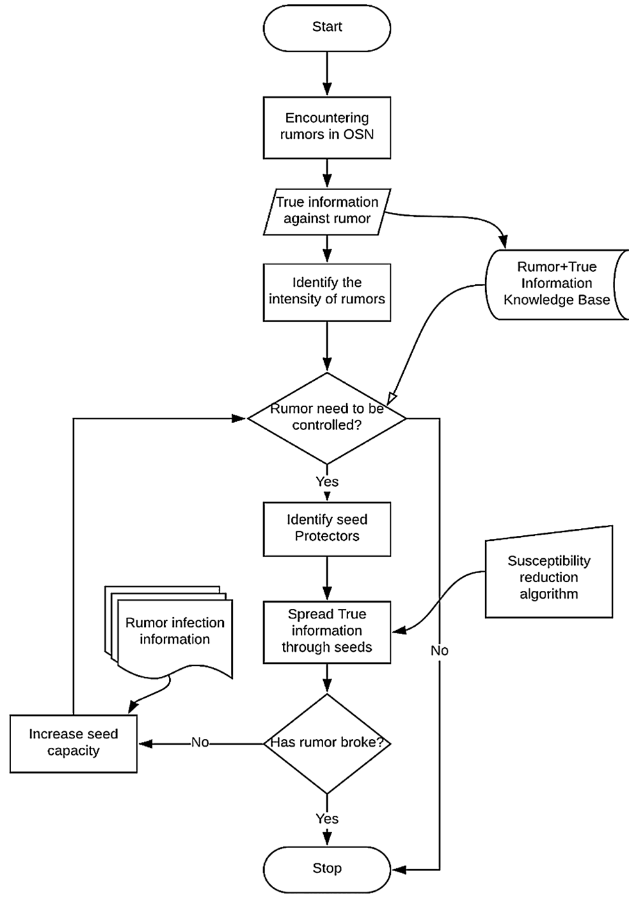


Fig. 3 Social immunity for susceptibility reduction (rumor control) in OSNs

Algorithm 3 – Susceptibility Reduction

Input: $G = (V, E, B)$, a n set of communities $C = \{C_1, C_2, C_3, \ldots, C_n\}$
Input: $IF = \{IF^1, IF^2, IF^3, \ldots, IF^u \mid IF \in V\ \&\ |IF| \leq |V|\}$
Input: $S(t) \subseteq V, I(t) \subseteq V, Pro(t) \subseteq V, PS(t) \subseteq V$,
    $|S(t) + I(t) + Pro(t) + PS(t)| = V$
Output: *Updated* $S(t) \subseteq V, I(t) \subseteq V, Pro(t) \subseteq V, PS(t) \subseteq V$,
    $|S(t) + I(t) + Pro(t) + PS(t)| = V$
foreach node i in IF:
    if $i \in I(t)$ then:
        $I(t) = I(t) - i$
        $Pro(t) = Pro(t) \cup i$
    elseif $i \in PS(t)$ then:
        $PS(t) = PS(t) - i$
        $Pro(t) = Pro(t) \cup i$
    endif
endforeach

The flow chart in Fig. 3 describes the bio-inspired social immunity approach in containing rumor from OSNs. The rumor containment approach starts when the rumor is encountered and visible to others in the network. This is the same as social fever in honeybees in response to chalkbrood infection. Once the immunization process starts, true information needs to reach maximum people in the network. This paper ensures reachability by finding herding influencers and finding bridging influencers in the network. So, true information spreads in the network through contacts. This approach is similar to Social fever/Social Transfer immunity in social insects, detailed in Fig. 1.

Susceptibility reduction steps shown in Fig. 3 are as follows: The process starts when a rumor is encountered in the network. The respective true information is identified to counter the rumor. Next, the intensity of the rumor is measured using Eq. (4). This rumor intensity is one of the inputs in selecting the number of seed spreaders for true information. Next, the algorithm decides whether to contain the rumor at the current level. This step involves the user input constraints such as the cost of rumor containment, the severity of rumor in the network. Equation (10) shows the rule applied to decide on continuing the rumor containment. Once rumor needs to be contained, the susceptibility reduction process goes into iteration until rule in Eq. (10) satisfies or rumor breaks. That is, the seed spreaders are identified using the algorithms 1 and 2. The final set of influential spreaders for the current iteration is calculated as *IF* in Eq. (8). Next, the true information is spread through *IF* spreaders. If this breaks the rumor, the susceptibility reduction stops. Otherwise, the cost incurred in the current iteration is calculated and move to the next iteration by checking Eq. (10). This process continues till Eq. (10) satisfies or rumor is removed from the network.

$$\text{Rumor Control Rule } RC_i : c_i < C_t AND r_d(t) > r_{dt} | RC_i \in \{True, \ False\} \tag{10}$$

here, C_t and r_{dt} are user input constraints namely planned total cost to reduce the rumor and tolerable rumor depth respectively. RC_i is the rumor control decision for *i*th iteration which is a Boolean value {True, False}. c_i cost incurred till *i*th iteration.

6 Experimental evaluation

In this section, six social networking datasets are considered for the experiments to prove the effectiveness of the proposed approach. The proposed approach is compared with recent and well-known rumor containment algorithms.

6.1 Datasets

To evaluate the effectiveness of the proposed rumor containment approach, we apply it on two synthesized datasets and four real-world datasets from public large dataset library SNAP [45]. The sizes of these datasets are ranging from small to large. Datasets and topological features of those are summarized in Table 1.

ego-Facebook, ego-Twitter, and ca-Condmat have higher clustering coefficient and degree heterogenicity compared to Karate Club, RandNW_1, and RandNW_2. ego-Facebook and ego-Twitter are from the online social networks Facebook and Twitter respectively. These platforms allow users to share messages and interact with people. ca-Condmat is a scientific collaboration network, collected from ArXiv (an e-print repository of manuscripts). These three datasets are available in SNAP [45]. RandNW_1 and RandNW_2 are synthesized networks. Karate Club [46] is a friendship network consists of friends from university-based karate club.

The datasets are not containing the community structure by default. The community structure is derived through our opinion update model discussed in Sect. 4.2. The neighborhood function in Eq. (1) is used for this task. Most closed neighborhood nodes with a positive opinion on each other are clustered into one community.

Table 1 Topological features of datasets

Dataset name	Network features					
	n	e	<k>	H	β_{th}	β
Karate club	34	78	4.5882	1.6895	0.129	0.242
RandNW_1	1000	5178	13	2.11	0.08	0.24
RandNW_2	2000	14,324	20	2.33	0.11	0.14
ego-Facebook	4,039	88,234	34	3.22	0.12	0.24
ego-Twitter	81,306	1,768,149	42	3.45	0.134	0.15
ca-Condmat	21,363	196,972	22	2.99	0.02	0.035

Here <k> is average degree, H = <k2>/<k>2 is Degree Heterogenicity index, β_{th} = <k>/<k2> is epidemic threshold

6.2 Competing methods

State-of-the-art rumor containing approaches need to be compared to prove the effectiveness of the RC-SI model in controlling the rumor. The proposed rumor containment approach is compared with the Delayed Start model (DS) [28], SEIR model [34], and a recent rumor-containing model RC model [39]. Also, a rumor blocking approach [14] is considered for the comparison and it is called wmSIR ("wise man" SIR) in the experiments. All the competing models are well-known approaches in controlling the rumors***.

Delayed start model It is an independent cascade model. This anti-rumor spreading technique starts the spreading process of anti-rumor after a time-delay of rumor propagation. The initial spreaders for this model are selected randomly from infected nodes.

SEIR model Spreader-Educated-Ignorant-Recovered model is based on the SIR epidemic model. SEIR spreading model focuses on ignorant people and studies their behavior. Authors argue that educating the ignorant population can reduce the rumor propagation. i.e., the more educated individuals in the network weaken the rumor in a higher degree.

RC model Rumor-containment (RC) model defines the rumor suppressing problem as an optimization problem with budget constraints. RC model spreads anti-rumor information to suppress the rumor in the network. This model examines the forgetting rate, rumor duration for containing the rumor. This method propagates true information in a model called uncertain-rumor-truth-uncertain (URTU). In experiments, the URTU model is implemented which considers the budget constraints while propagating true information. The budget constraint is set to be directly proportional to the number of seeds.

wmSIR model This approach extends the SIR epidemic model by considering the 'wise men' in the population. The idea of this approach is that a considerable number of 'wise man' always exist in the network and upon learning the falseness of rumor, they stop participating in the spreading process. This kind of node-level blocking influences the network and controls the rumor spreading. In experiments, the wise men are randomly chosen and applied for evaluation.

6.3 Experimental setup

Throughout this evaluation the spreading rate of spreader and protector is set to 1. i.e., spreader and protector can spread the information only once to their neighbors, irrespective of the state of the neighbors. The experiments are performed on a server with 16 GB ram and a 4.0 GHz octa-core processor running 64-bit JAVA VM 1.8. NetworkX [47] is used to load/generate the networks discussed in this section. The information diffusion is simulated using the Competitive Cascade model discussed in Sects. 4.1 and 4.2. For the experiments of competing methods independent cascade, URTU, and the SIR models are implemented. The spreading rate of these existing methods is the same as the proposed method. In the experiments, the intensity of rumors is set to a maximum of 50% of the total population to avoid the rumor occupy the whole network before the anti-rumor spread start. The cost of rumor containment is set between 1 and 20 which is proportional to the intensity of rumors. All the simulations are averaged at least for 50 runs for fair simulation results.

Three experiments are conducted to evaluate the effectiveness of the anti-rumor method in controlling the rumors. In the first experiment, the evaluation focuses on rumor final size against the time. The final size of the rumor is the number or percentage rumor left in the network after a certain time period of true information being spread. This explains how effectively the proposed approach controls the rumor. The second experiment directly evaluates the effectiveness of initial seeds in controlling the rumors. This evaluation compares the percentage of rumors left in the network against the number of initial spreaders selected. The third experiment evaluates the effectiveness of the truth spreading method in controlling the rumor. The average influence of truth spreaders in rumor control is compared in this evaluation.

6.4 Results

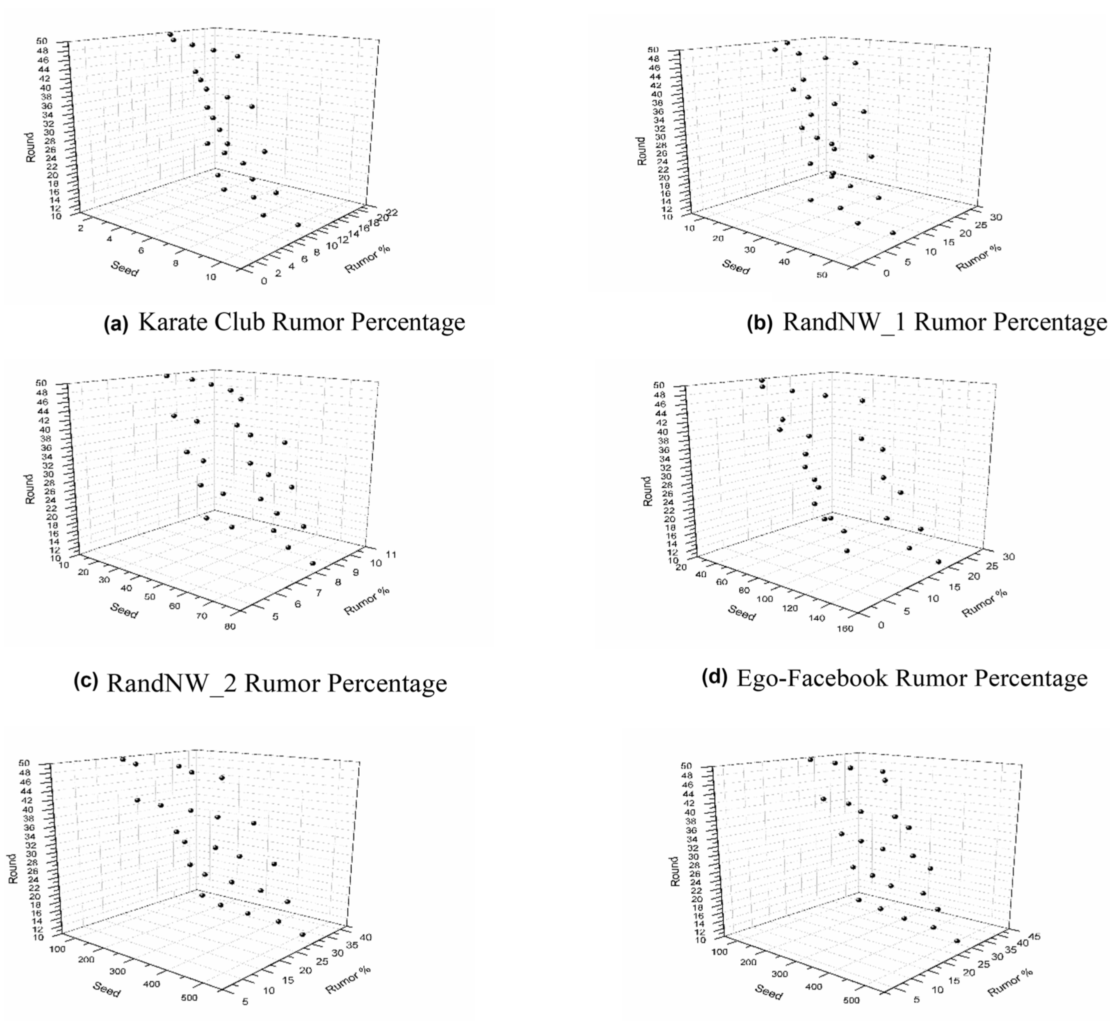
Analysis of the evaluation results of all three experiments is discussed in the following subsections, respectively. Each subsection also elaborates on the results that contribute to the effectiveness of all methods in rumor control.

6.4.1 Rumor final size

In the first experiment, the size of the rumor is measured for each round of time with varying seed sizes. To generalize the measurement, the rumor size is measured as the percentage of nodes affected by the rumor at a given time.

Figure 4a–f shows the percentage of rumor available in the network for six different datasets. The rumor percentage is shown for a different number of initial spreaders for timeframe 10–50. The timesteps are represented as round in Fig. 4a–f. The number of initial spreaders and the number of timesteps are the two different aspects analyzed in this experiment.

Rumor percentage is decreased from 12 to 2% for Karate Club and RandNW_1 when seeds are higher during the timestep varying from 10 to 50. Rumors in RandNW_2 has decreased from 8.6 to 5%. These three datasets are small which has a lesser clustering coefficient. But the rumor percentage is decreased drastically for ego-facebook (21–3%), ego-twitter (33–9%), and ca-Condmat (31.38–7.32%) in



(a) Karate Club Rumor Percentage **(b)** RandNW_1 Rumor Percentage **(c)** RandNW_2 Rumor Percentage **(d)** Ego-Facebook Rumor Percentage **(e)** Ego-Twitter Rumor Percentage **(f)** ca-Condmat Rumor Percentage

Fig. 4 **a** Karate club rumor percentage. **b** RandNW_1 rumor percentage. **c** RandNW_2 rumor percentage. **d** Ego-facebook rumor percentage. **e** Ego-twitter rumor percentage. **f** ca-Condmat rumor percentage

Table 2 Percentage of rumors

Dataset name	Lower seed	Higher seed
Karate Club	12	2
RandNW_1	18	2
RandNW_2	8.1	5
ego-Facebook	12	3
ego-Twitter	18.1	9.3
ca-Condmat	24.59	7.32

timesteps 10–50. These three datasets have a higher clustering coefficient and a higher average degree. This indicates that the proposed approach works well for scale-free networks with a higher clustering coefficient.

Table 2 indicates the percentage of rumor available in the network at lower seed and higher seed for round 50. This implies that the number of initial truth spreaders is also played a significant role in combating the rumor. i.e., The influence of initial truth spreaders is significant in reducing the influence of rumors.

6.4.2 Rumor control comparison

Next, the experiments evaluate the state-of-the-art approaches elaborated in Sect. 6.2 to compare the rumor containment efficiency of these approaches against the proposed approach. The results shown in the figures are for 50th timestep and varying seed sizes.

Figure 5a–f show the comparison of the proposed approach with various other recent and well-known rumor containment approaches. The proposed approach provides better results for datasets Karate Club, ego-facebook, and ego-twitter for all seed levels compared to

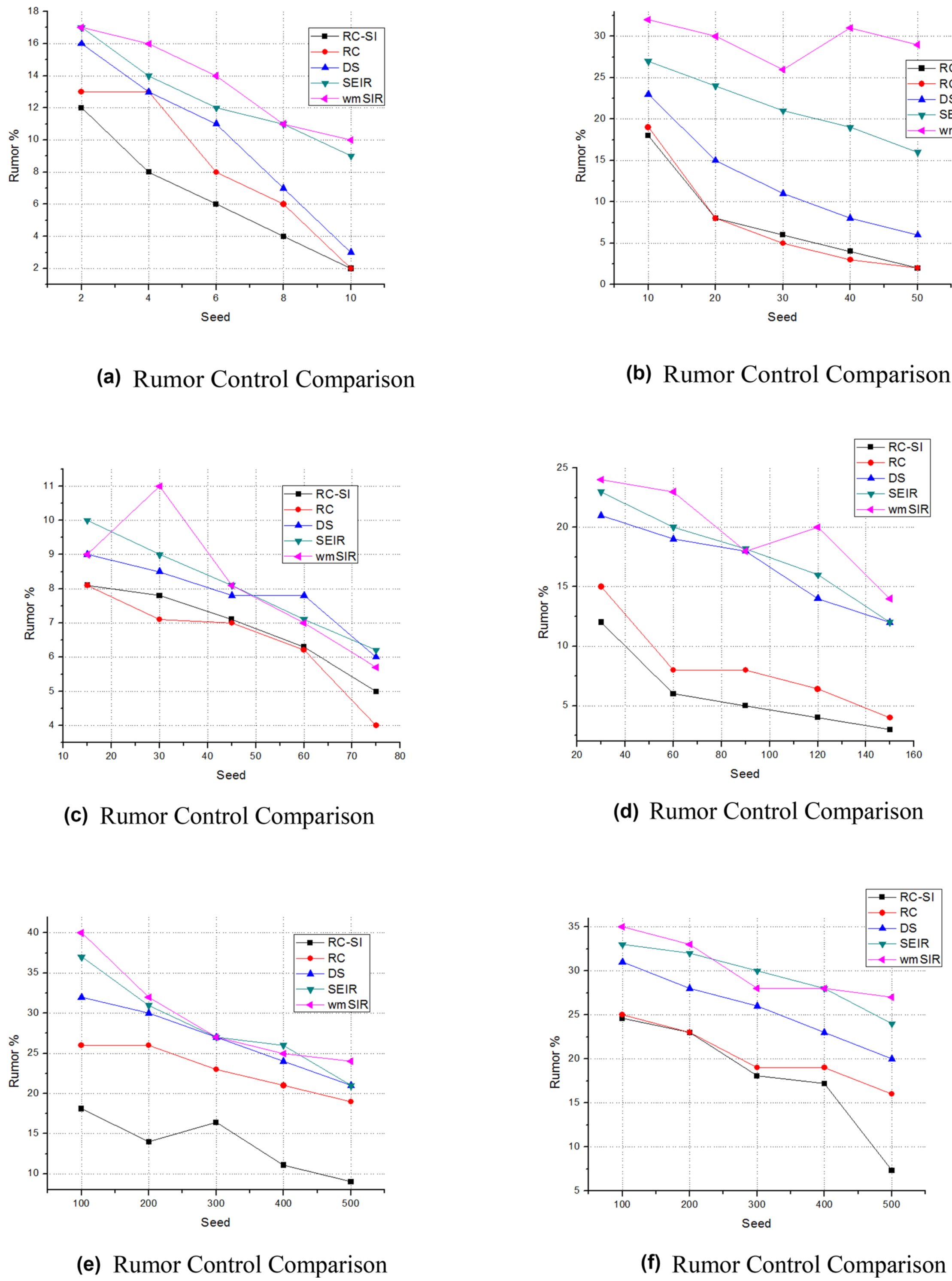


Fig. 5 **a**–**f** Rumor control comparison

competing methods. In most of the cases, the rumor containing approaches DS, SEIR and wmSIR are performing almost similar. Rumor percentage of the proposed approach is performing along with RC for the ca-Condmat dataset for smaller seeds. In this scenario, the number of initial spreaders is lesser and not proportional to the intensity of rumors. In ego-Facebook, ego-Twitter, and ca-Condmat, when the number of seeds is increasing, the proposed approach provides better results. But the competing approaches are struggling to control the rumor. This also implies the proposed approach working well for scale-free networks. Overall RC-SI is performing better than other competing approaches in terms of reducing rumors with chosen influential initial spreaders. i.e., The initial spreaders identified in the proposed approach effectively enable the herding process which provides the group inoculation.

6.4.3 Rumor influence containment

In this subsection, the effectiveness of true information propagation is compared among all competing methods. To do this, an average rumor containment degree or average protector degree is defined.

$$IC_a(G;t) = \frac{1}{|PR|} \sum_{v \in PR} \sigma_v(t) \tag{11}$$

In this equation, at any time t, $\sigma_v(t)$ is influence degree [33] of node v and PR is the set of protectors. In this case, the number of connections of the node is considered as influence degree. This measure shows the average number of influential individuals received true information at given time t which results in rumor control. This shows the statistical significance of the proposed approach on true information propagation. For experiments, in the RC method, the number of truth spreaders from the uncertain-rumor-truth-uncertain model of [39] are treated as protectors. In the SEIR model, E-state nodes are treated as protectors and for the DS model, the protectors are identified at the beginning of truth propagation.

Figure 6a–f shows the rumor containment ability comparison of all true information spreading approaches for all datasets. The average protector degree will be lesser when the rumor containment approach starts since the number of protectors is lesser, and it gradually increases as the number of nodes becomes the protector. In this comparison also DS and SEIR are performing almost similar. According to Fig. 6a–c, the average influence degree of the proposed method is always higher in comparison to other competing methods with an exception of equal to RC method at some points in Fig. 6c. These networks are small and synthesized where the influential spreaders are mostly higher degree individuals. For scale-free networks, in Fig. 6d–f, the average protector degree is higher when rumor contained.

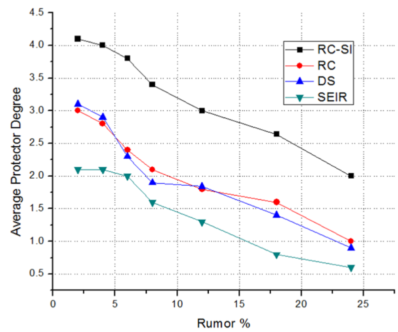
In Fig. 6d–f, for the RC-SI method, when the rumors are higher in the network i.e., at the beginning of rumor combating, the degree of protectors is slightly above than competing methods. The protectors of the proposed method are the influential initial spreaders. This implies that for large and scale-free networks, the influential spreaders are not needed to be higher degree individuals. But as time proceeds, the higher number of individuals are becoming protectors in the proposed method compared to the competing methods which help in reducing the rumor faster using RC-SI.

The overall results of all three experiments indicate that the proposed approach contains the rumor well, compared to other approaches. So, the collective approach performs well and eradicate rumor from the network faster than other truth spreading techniques.

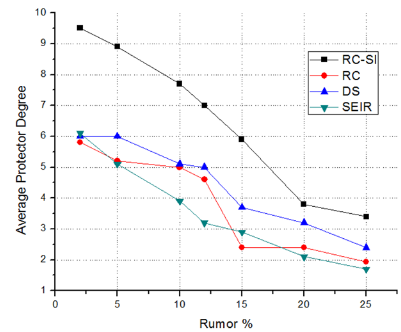
7 Discussions

In the proposed approach, A collective rumor containment approach is deployed by utilizing the opinion dynamics in identifying influential anti-rumor spreaders. Key findings obtained from the study are (1) the initial spreaders identified in this method enable the herding process through which the rumor is controlled at the earliest. As per the experiments in Sects. 6.4.2 and 6.4.3, the initial spreaders quickly increase the number of protectors which implies it enabled the herding process. This helps in controlling the rumor spread as a greater number of individuals know the true information. (2) The rumor intensity measure helps in identifying the stop condition for anti-rumor propagation. The experiment results show the rumor intensity reduces faster in the proposed approach compared to other methods for large scale networks. So, the stop condition can be reached faster in the proposed approach which increases the performance of the proposed work compared to other methods. (3) The proposed approach provides better results for large scale-free social networks compared to any other approaches as per Figs. 5e,f and 6e,f. This implies the rumor containment approach proposed in this work can be applied to large real-world social networking applications.

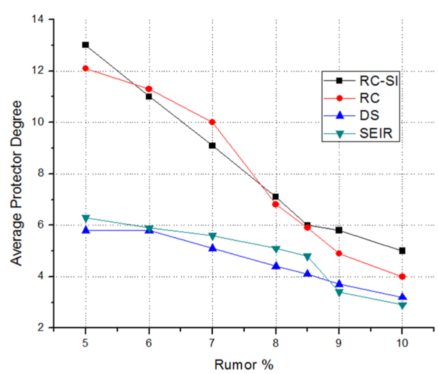
The cost of rumor containment and the rumor intensity decide whether to continue rumor control after a certain percentage of rumors are contained. In real-world applications, this method helps to identify the trade-off condition where this rumor containment approach should stop. Also, unlike other rumor containing methods, the key aspect of the proposed approach is to enable a co-operative, collective rumor containing. This kind of group anti-rumor spreading is realized through the herding influencers identified using opinion dynamics. The experiments on the percentage of rumor identified show that the proposed approach control rumors 30% better than other compared methods. In the worst case, the proposed approach gives 5% better results than competing methods. This result sheds some light on concentrating on incorporating collective rumor containment approaches will help in faster rumor control. A collective rumor identification approach will also benefit real-time users about serious threats in the network.



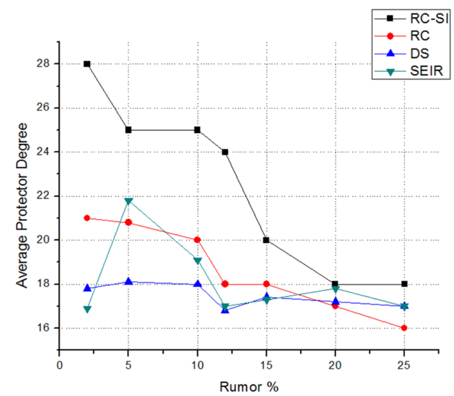
(a) Protector Influence Comparison



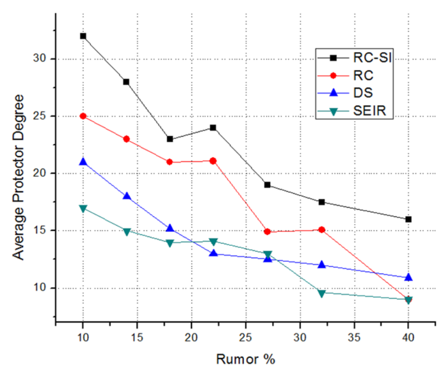
(b) Protector Influence Comparison



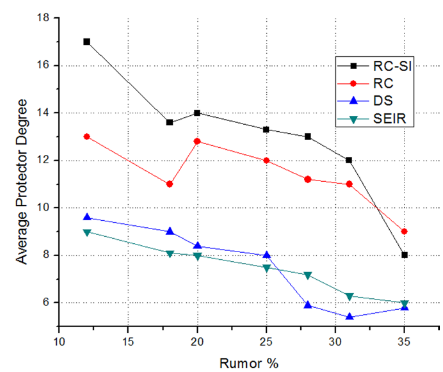
(c) Protector Influence Comparison



(d) Protector Influence Comparison



(e) Protector Influence Comparison



(f) Protector Influence Comparison

Fig. 6 **a**–**f** Protector influence comparison

8 Conclusion

Online social networks are double-edged swords, i.e., While helping to share novel information on a large scale by promoting openness, OSNs also act as a platform for the extensive spread of rumors. Rumors spread faster in OSNs than in any other medium. This urges the importance of devising a cost-effective, faster rumor containment approach as an urgent necessity. Spreading rumor can be controlled by blocking the rumor in some nodes of the network or suppressing the rumor by the effective propagation of the anti-rumor information. In this paper, an anti-rumor spread approach is proposed by the inspiration of social immunity, a collective immunization technique followed by social insects. The proposed approach is a faster collective immunization method that reduces the susceptibility of individuals in the network depending upon rumor intensity in a cost-effective way. The experimental evaluation compares our proposed approach with recent and well-known algorithms. The results indicate that the collective immunization approach is far better in combating the rumor when compared with other individual immunization approaches. The proposed approach considered the intensity of rumor in the network to select the number of protectors for controlling the cost involved in the anti-rumor spread. In future, the cost of educating the protectors and the cost incurred in the loss of information credibility can also be studied.

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