

Weak Ties: Subtle Role of Information Diffusion in Online Social Networks

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As a social media, online social networks play a vital role in the social information diffusion. However, due to its unique complexity, the mechanism of the diffusion in online social networks is different from the ones in other types of networks and remains unclear to us. Meanwhile, few works have been done to reveal the coupled dynamics of both the structure and the diffusion of online social networks. To this end, in this paper, we propose a model to investigate how the structure is coupled with the diffusion in online social networks from the view of weak ties. Through numerical experiments on large-scale online social networks, we find that in contrast to some previous research results, selecting weak ties preferentially to republish cannot make the information diffuse quickly, while random selection can achieve this goal. However, when we remove the weak ties gradually, the coverage of the information will drop sharply even in the case of random selection. We also give a reasonable explanation for this by extra analysis and experiments. Finally, we conclude that weak ties play a subtle role in the information diffusion in online social networks. On one hand, they act as bridges to connect isolated local communities together and break through the local trapping of the information. On the other hand, selecting them as preferential paths to republish cannot help the information spread further in the network. As a result, weak ties might be of use in the control of the virus spread and the private information diffusion in real-world applications.

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I. INTRODUCTION

The emergence of the Internet has changed the way of communication radically and, especially, the development of Web 2.0 applications has led to some extremely popular online social sites, such as Facebook [1], Flickr [2], YouTube [3], Twitter [4], LiveJournal [5], Orkut [6] and Xiaonei [7]. These sites provide a powerful means of sharing information, finding content and organizing contacts [8] for ordinary people. Users can consolidate their existing relationships in the real world through publishing blogs, photos, messages and even states. They also have a chance to communicate with strangers that they have never met on the other end of the world. Based on the development and prevalence of the Internet, online social sites have reformed the structure of the traditional social network to a new complex system, called the online social network, which attracts a lot of research interests recently as a new social media.

Recent works about online social networks mainly focus on probing and collecting network topologies [8, 9], structural analysis [8–11], user interactions [12–14] and

content generating patterns [13, 15]. At the same time, some concepts and methods of traditional social networks have also been introduced into current researches: The strength of ties is one of them. The strength of ties was first proposed by Granovetter in his landmark paper [16] in 1973, in which he thought the strength of ties could be measured by the relative overlap of the neighborhood of two nodes in the network. It was interesting that different from the common sense, he found that loose acquaintances, known as weak ties, were helpful in finding a new job [17]. This novel finding has become a hot topic of research for decades. In [18], a predictive model was proposed to map social media data to the tie strength. In [19], Onnela et al. gave a simple but quantified definition to the overlap of neighbors of nodes i and j as follows:

$$w_{ij} = \frac{c_{ij}}{k_i - 1 + k_j - 1 - c_{ij}}, \quad (1)$$

where c_{ij} is the number of common acquaintances, k_i and k_j are the degrees of i and j , respectively. **In this paper, we define w_{ij} as the strength of the tie between i and j .** The lower w_{ij} is, the weaker the strength of tie between i and j is.

As a social media, the core feature of online social networks is the information diffusion. However, the mechanism of the diffusion is different from traditional

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models, such as Susceptible-Infected-Susceptible (SIS), Susceptible-Infected-Recovered (SIR) [20, 21] and random walk [22–24]. At the same time, few works have been done to reveal the coupled dynamics of both the structure and the diffusion of online social networks [25, 26]. To meet this critical challenge, in this paper, we aim to investigate the role of weak ties in the information diffusion in online social networks.

By monitoring the dynamics of

$$\bar{S} = \sum_{S < S_{\max}} \frac{nS^2}{N}, \quad (2)$$

where n is the number of connected clusters with S nodes, and N is the size of the network, a phase transition was found in the mobile communication network during the removal of weak ties first [19]. We find that this phase transition is pervasive in online social networks, which implies that weak ties play a special role in the structure of the network. This interesting finding inspires us to investigate the role of weak ties in the information diffusion. To this end, we propose a model $ID(\alpha, \beta)$ to characterize the mechanism of the information diffusion in online social networks and associate the strength of ties with the process of spread. Through the simulations on large-scale real-world data sets, we find that selecting weak ties preferentially to republish cannot make the information diffuse quickly, while the random selection can. Nevertheless, further analysis and experiments show that the coverage of the information will drop substantially during the removal of weak ties even for the random diffusion case. So we conclude that weak ties play a subtle role in the information diffusion in online social networks. We also discuss their potential use for the information diffusion control practices.

The rest of this paper is organized as follows. Section II introduces the data sets used in this paper. In Section III, we study the structural role of weak ties. The model $ID(\alpha, \beta)$ is proposed in Section IV, and the role of weak ties in the information diffusion is then investigated. Section V discusses the possible uses of weak ties in the control of the virus spread and the private information diffusion. Finally, we give a brief summary in Section VI.

II. DATA SETS

We use two data sets in this paper, i.e., YouTube and Facebook in New Orleans. YouTube is a famous video sharing site, and Facebook is the most popular online social site which allows users to create friendships with other users, publish blogs, upload photos, send messages, and update their current states on their profile pages. All these sites have some privacy control schemes which control the access to the shared contents. The data set of YouTube includes user-to-user links crawled from YouTube in 2007 [8]. The data set of Facebook contains

TABLE I: Data Sets

Data set	$ V $	$ E $
YouTube	1134890	2987624
Facebook	63392	816886

a list of all the user-to-user links crawled from the New Orleans regional network in Facebook during December 29th, 2008 and January 3rd, 2009 [14]. In both two data sets, we treat the links as undirected.

In these data sets, each node represents a user, while a tie between two nodes means there is a friendship between two users. In general, creating a friendship between two users always needs mutual permission. So we can formalize each data set as an undirected graph $G(V, E)$, where V is the set of nodes and E is the set of ties. We use $|V|$ to denote the size of the network, and $|E|$ to denote the size of ties. Some characteristics of the data sets are shown in Table I. The *Cumulative Distribution Function (CDF)* of the strength of ties is shown in Fig. 1.

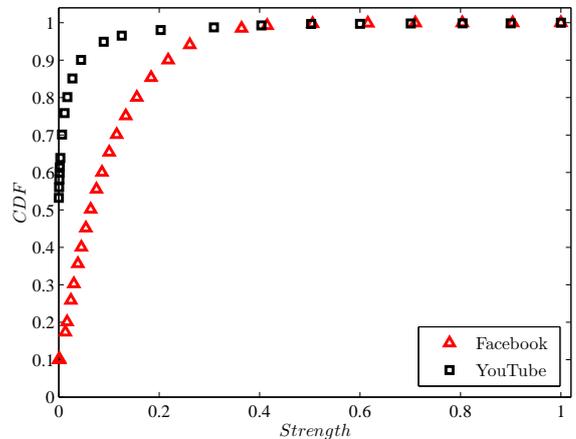


FIG. 1: (Color online) *CDF* of the strength of ties.

As we know, online social networks are divided into two types: knowledge-sharing oriented and networking oriented [15]. For the data sets we use, YouTube belongs to the former, while Facebook belongs to the latter, both of which are scale-free networks.

III. STRUCTURAL ROLE OF WEAK TIES

In this section, we study the structural role of weak ties. As shown in Fig. 2a and Fig. 2c, we find a phase transition (characterized by \bar{S}) similar to the one in [19] in online social networks during the removal of weak ties first. This phase transition, however, disappears if we remove the strong ties first. Furthermore, it is also found

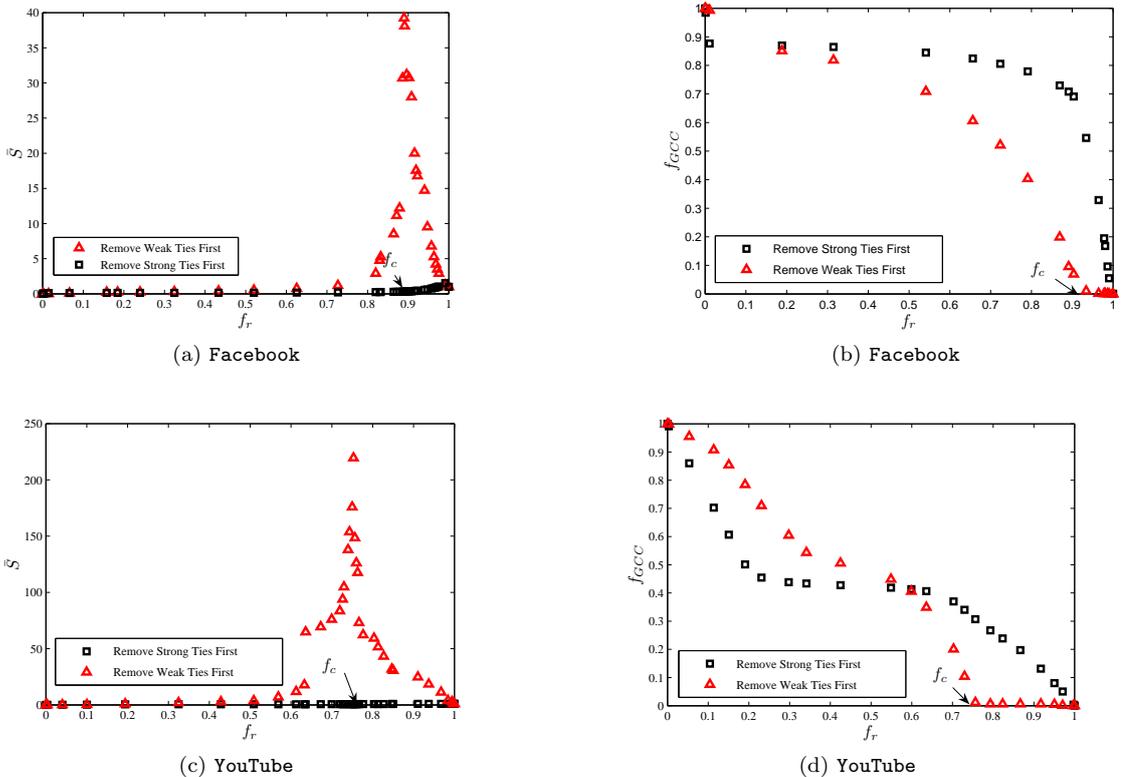


FIG. 2: (Color online) The variations of \bar{S} and f_{GCC} during the removal of weak ties first and strong ties first, respectively. f_r is the fraction of removed ties.

in Fig. 2b and Fig. 2d that the relative size of giant connected cluster (GCC), denoted by f_{GCC} , shows different dynamics between the removals of weak ties first and strong ties first. We denote the critical fractions of the removed ties at the phase transition point by f_c . It is interesting to note that $f_c = 0.753$ for YouTube and $f_c = 0.890$ for Facebook when \bar{S} reaches the submit, which are very close to the case when $f_{GCC} \approx 0$.

In the percolation theory, the existence of the above phase transition means that the network is collapsed, while the network is just shrinking if there is no phase transition when removing the ties [19]. So the above experiments tell us that weak ties play a special role in the structure of online social networks, which is different from the one strong ties play. In fact, they act as the important bridges that connect isolated communities. In what follows, we build a model that associates the weak ties with the information diffusion, to discuss the coupled dynamics of the structure and the information diffusion.

IV. DIFFUSING ROLE OF WEAK TIES

The information diffusing in online social networks includes blogs, photos, messages, comments, multimedia files, states, etc. Because of the privacy control and other

features of online social sites, the mechanism of the information diffusion in online social networks is different from traditional models, such as SIS, SIR and random walk. We start by discussing the procedure of information diffusion in online social networks.

A. The Procedure of Information Diffusion

The procedure of the diffusion in online social networks can be briefly described as follows:

- The user i publishes the information I , which may be a photo, a blog, etc.
- Friends of i will know I when they access the profile page of i or get some direct notifications from the online social site. We call this scheme as *push*.
- Some friends of i , may be one, many or none, will comment, cite or reprint I , because they think that it is interesting, funny or important. We call this behavior as *republish*.
- The above steps will be repeated with i replaced by each of those who have republished I .

It is easy to find that the key feature of the information diffusion in online social networks is that the information is pushed actively by the site and only part of friends will republish it. Take **Facebook** as an example, in which *News Feed* and *Live Feed* are two significant and popular features. *News Feed* constantly updates a user's profile page to list all his or her friends' news in **Facebook**. The news includes conversations taking place between the walls of the user's friends, changes of profile pages, events, and so on [27]. *Live Feed* facilitates the users to access the details of the contents updated by *News Feed*. It is updated in a real-time manner after the user's login to the web [28]. In fact, *News Feed* aggregates the most interesting contents that a user's friends are posting, while *Live Feed* shows to the user all the actions his or her friends are taking in **Facebook** [29].

The feature of pushing and republishing we have discussed above is indeed more obvious in **Twitter**, in which all the words you post will be pushed immediately to your followers' terminals, including a PC or even a mobile phone, and then they can republish it if they like. However, in real-world situations, the trace of the information is hard to collect [25], especially for large-scale networks. So it is quite reasonable to build a model to characterize the mechanism and simulate the diffusion.

B. The Model for Information Diffusion

Based on the procedure described above, we propose a simple model $ID(\alpha, \beta)$, where α is the navigating factor and β represents the strength of the information. In this model, α determines how to select neighbors to republish the information, while $\beta \in [0, 1]$ is a physical character of the information, which describes how interesting, novel, important, funny or resounding it is. The model is defined as follows:

- Step 1: Suppose there comes information I . Set the state of all the nodes in V to σ_0 . The state σ_0 of a node means I is not known to it, otherwise the state is σ_1 .
- Step 2: Randomly select a seed node i from the network. The degree of i is k_i . Set i to σ_1 . It publishes the information I with strength equal to β at time $T = 0$.
- Step 3: Increase the time by one unit, i.e., $T = T + 1$. Set each node in the neighborhood of i to σ_1 . Add i to the set of nodes that have published I , denoted by P . So $P = P \cup \{i\}$.
- Step 4: Calculate the number of nodes that will republish I in the next round:

$$R_i = k_i \beta. \quad (3)$$

- Step 5: Select one node j from the neighborhood of i with the probability [30]

$$p_{ij} = \frac{w_{ij}^\alpha}{\sum_{m=1}^{k_i} w_{im}^\alpha}. \quad (4)$$

If j is not in P , then add it to the set of nodes that will republish I in the next round, denoted by W . So $W = W \cup \{j\}$. Repeat this step for R_i times.

- Step 6: For each node in W , execute from Step 3 to Step 5 recursively until W is null or all the nodes in V have known I .

It is easy to find from Eq. (3) that during the diffusion, the number of republishing nodes selected from the neighborhood of i is decided by k_i and β . It is consistent with the real situation that the user with more friends tends to attract more other users to visit and republish the information. The more interesting or important the information is, the higher the chance that it will be republished. We use parameter α in Eq. (4) to associate the diffusion with the strength of the ties, which means different values of α will lead to different selections of ties as paths for republishing information in the next round. In fact, when $\alpha = -1$, weak ties are to be selected preferentially as paths for republishing. The selection is random when $\alpha = 0$, and the strong ties will be selected with higher priority when $\alpha = 1$.

C. Results and Analysis

We define the fraction of nodes with the state σ_1 as the coverage of I , denoted by C . Since it is found that only 1-2% friends will republish the information in Flickr [25], we let $\beta = 0.01$ in the simulations. Fig. 3 shows the numeric experimental results on **Facebook** and **YouTube** networks. As can be seen, C reaches the maximum when $\alpha = 0$. In other words, compared with weak or strong ties, selecting the republishing nodes randomly from the neighborhood will make the information spread faster and wider. This is indeed out of our expectation, since previous studies show that weak ties can facilitate the information diffusion in social networks.

To understand this, we further explore the process of the information diffusion in details. By Eq. (1), we can easily have

$$1/w_{ij} = (k_i - 2)/c_{ij} + k_j/c_{ij} - 1.$$

Assume that as k_j increases, c_{ij} increases proportionately, i.e., $k_j/c_{ij} = \text{const}$. Then given a node i and its neighbor node j , we have $k_j \uparrow \Rightarrow c_{ij} \uparrow \Rightarrow 1/w_{ij} \downarrow \Rightarrow w_{ij} \uparrow$, and vice versa. This implies that a neighbor node of i tends to have a higher degree if it has a stronger strength of ties with i . Therefore, when selecting the republishing nodes for the next round from the neighborhood, different α will select nodes with different degrees preferentially.

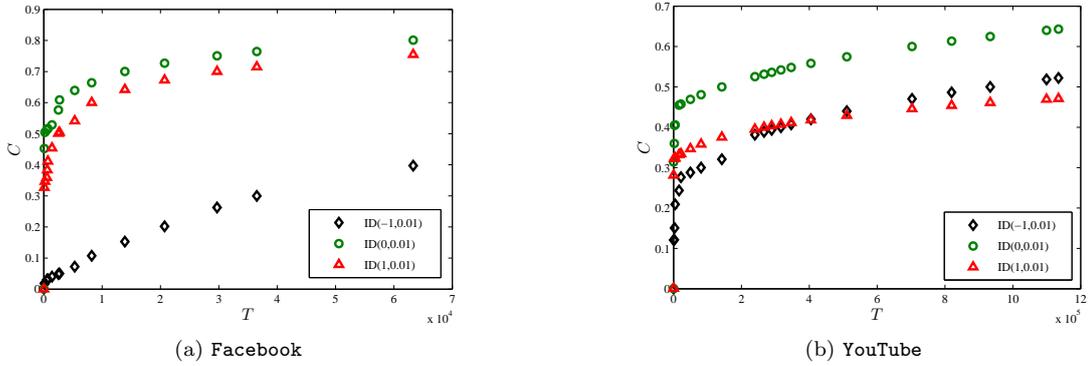


FIG. 3: (Color online) The dynamics of C during the process of the diffusion. We perform the experiments for each pair of α and β 20 times and return the mean value as the final result.

For example, when $\alpha = -1$, the weak ties will be selected with higher priority, which means that the nodes with lower degrees will be selected preferentially. However, it is easy to learn from Eq. (3) that, for the node with lower degree, the republishing nodes selected from its neighborhood will be less, which will eventually reduce the total number of republishing nodes and impede the information from further spreading in the network. As to the case of selecting strong ties preferentially, although it will tend to select the nodes with higher degrees to republish, the local trapping [19] will limit the scope of selected nodes into some local areas and make it harder to propagate the information further in the network.

To validate the analysis above, we also observe the fraction of the nodes that have published I during the diffusion, denoted by f_{pub} . As shown in Fig. 4, f_{pub} increases more slowly when $\alpha = -1$, and the time-varying properties of f_{pub} are similar to those of C in Fig. 3 for different α values, respectively. We also monitor the fraction of the nodes that have published I in each hop away from the source node, denoted by f_{local} . As shown in Fig. 5, when $\alpha = -1$, f_{local} decreases faster than other cases, in particular the $\alpha = 0$ case. It means when $\alpha = -1$, the number of republishing nodes selected from the neighborhood decreases sharply as the information spreading far away from the source, which agrees with our former analysis. As for the case of $\alpha = 1$, f_{pub} increases more and more slowly during the diffusion, because the nodes selected to republish are trapped in some local clusters. In other words, it is hard to find some new nodes to republish the information to the outer space.

Based on the above results, we can conclude that selecting weak ties preferentially as the path to republish information cannot make it diffuse faster. However, this does not mean that weak ties play a trivial role in the information diffusion in online social networks, especially when we recall its special role in the network structure in Section III. Let $\alpha = 0$ in $ID(\alpha, \beta)$, we compare the variation of C under the situation of removing weak ties first with that of removing strong ties first. As shown in

Fig. 6, for the case of removing weak ties first, the coverage of the information decreases rapidly, e.g., from 0.8 to 0.4 in Facebook when the fraction of removed weak ties reaches about 0.4. This implies that weak ties are indeed crucial for the coverage of information diffusion in online social networks.

To further study the effect of β , we conduct experiments with different β values, as shown in Fig. 7. As can be seen, no matter what the β value is, random selection ($\alpha = 0$) is still the fastest mode for the information diffusion, although the gap tends to shrink with higher β values. It is also shown that when β grows, C will also rise for all α values. That is, the greater the strength of the information is, the more nodes will be attracted to republish it, and the wider it will spread in the network.

Until now we can conclude that weak ties play a subtle role in the information diffusion in online social networks. On one hand, they are bridges that connect isolated communities and break through the trapping of information in local areas [19]. On the other hand, selecting weak ties preferentially as the path of republishing cannot make the information diffuse faster and wider.

V. DIFFUSION CONTROL

The growing popularity of the online social networks does not mean that it is safe and reliable. On the contrary, the virus spread and the private information diffusion have made it become a massive headache for IT administrators and users [31, 32]. For example, “KooFace” is a Trojan Worm on Facebook, which spreads by leaving a comment on profile pages of the victim’s friends to trap a click on the malicious link [33]. About 63% of system administrators worry that their employees will share too much private information online [34]. So as time goes by, it becomes more and more important and urgent to control the virus spread and the private information diffusion in online social networks.

In the light of this, we can make use of the weak ties

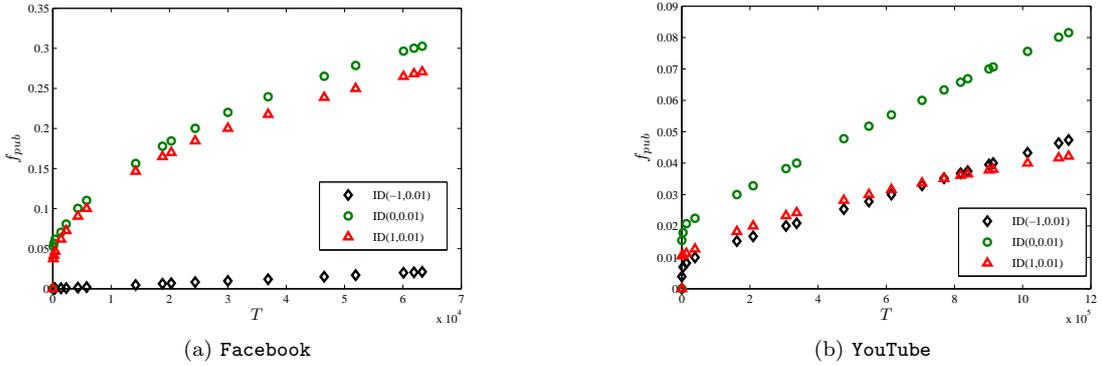


FIG. 4: (Color online) The dynamics of f_{pub} during the process of the diffusion. We perform the experiments for each pair of α and β 20 times and return the mean value as the final result.

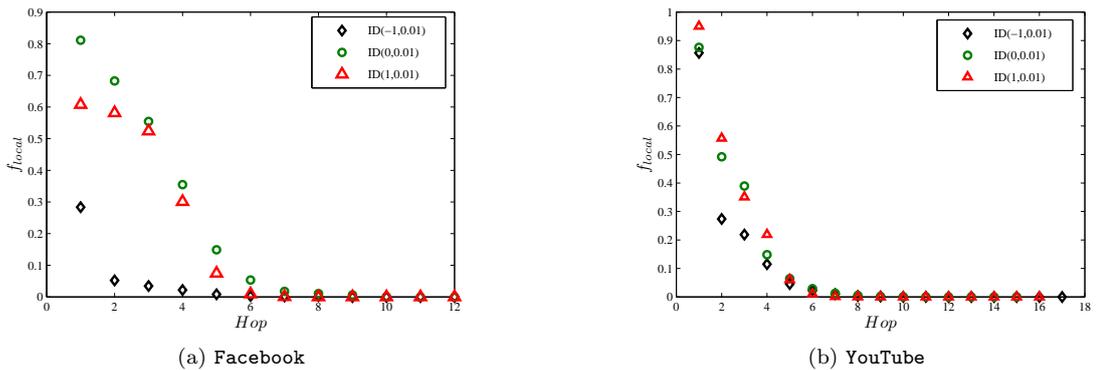


FIG. 5: (Color online) The dynamics of f_{local} during the information propagation far away from the source. We perform each experiment 20 times and get the mean value as the final result.

for the information diffusion control. That is, in the real-world practices, we can assume that the behavior of republishing information is random, i.e., $\alpha = 0$. Then according to the results in Fig. 6, we can make the virus or the private information trapped in local communities by removing weak ties and stop them from diffusing further in the network.

VI. SUMMARY

Online social sites have become one of the most popular Web 2.0 applications in the Internet. As a new social media, the core feature of online social networks is the information diffusion. We investigate the coupled dynamics of the structure and the information diffusion in the view of weak ties. Different from the recent work [25], we do not focus on the trace collection and analysis of the real data flowing in the network. Instead, inspired by [19], we propose a model for online social networks and take a closer look at the role of weak ties in the diffusion.

We find that the phase transition found in the mo-

bile communication network exists pervasively in online social networks, which means that the weak ties play a special role in the network structure. Then we propose a new model $ID(\alpha, \beta)$, which associates the strength of ties with the diffusion, to simulate how the information spreads in online social networks. Contrary to our expectation, selecting weak ties preferentially to republish cannot facilitate the information diffusion in the network, while the random selection can. Through extra analysis and experiments, we find that when $\alpha = -1$, the nodes with lower degrees are preferentially selected for republishing, which will limit the scope of the distribution of republishing nodes in the following rounds. However, even for the random selection case, removal of the weak tie can make the coverage of the information decreases sharply, which is consistent with its special role in the structure.

So we conclude that weak ties play a subtle role in the information diffusion in online social networks. On one hand, they play a role of bridges, which connect isolated communities and break through the trapping of information in local areas. On the other hand, selecting weak ties preferentially to republish cannot make the information

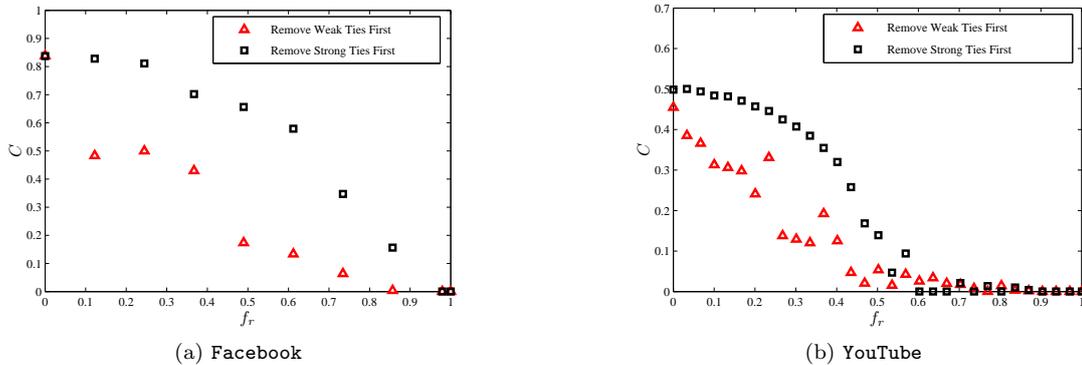


FIG. 6: (Color online) The variations of C during the removal of ties. The diffusing time is $T_{Facebook} = |V|$ and $T_{YouTube} = 10^4$. We perform the experiments 20 times for $\alpha = 0$ and $\beta = 0.01$, and return the mean value as the final result.

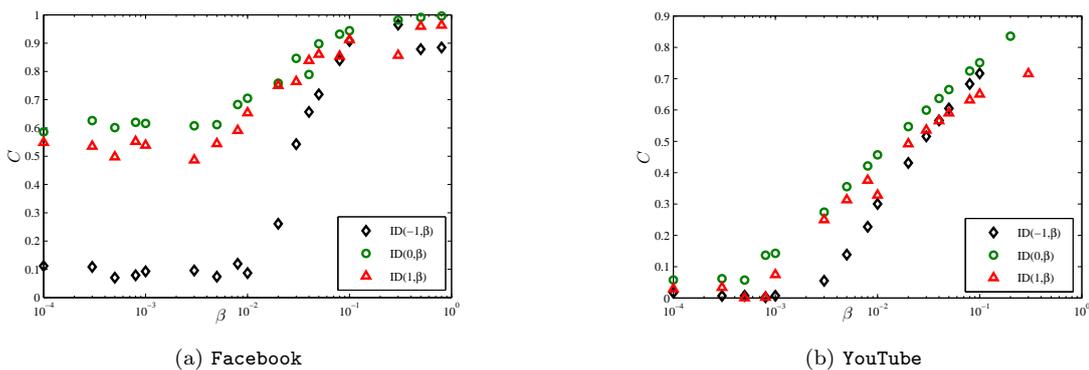


FIG. 7: (Color online) The increment of C when β grows in the log-scale. We perform the experiments for each pair of α and β 20 times and return the mean value as the final result.

diffuse faster in the network. For potential applications, we think that the weak ties might be of use in the control of the virus spread and the private information diffusion.

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