

Structural Diversity for Resisting Community Identification in Published Social Networks

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Abstract

As an increasing number of social networking data is published and shared for commercial and research purposes, privacy issues about the individuals in social networks have become serious concerns. Vertex identification, which identifies a particular user from a network based on background knowledge such as vertex degree, is one of the most important problems that has been addressed. In reality, however, each individual in a social network is inclined to be associated with not only a vertex identity but also a community identity, which can represent the personal privacy information sensitive to the public, such as political party affiliation. This paper first addresses the new privacy issue, referred to as community identification, by showing that the community identity of a victim can still be inferred even though the social network is protected by existing anonymity schemes. For this problem, we then propose the concept of *structural diversity* to provide the anonymity of the community identities. The k -Structural Diversity Anonymization (k -SDA) is to ensure sufficient vertices with the same vertex degree in at least k communities in a social network. We propose an Integer Programming formulation to find optimal solutions to k -SDA and also devise scalable heuristics to solve large-scale instances of k -SDA from different perspectives. The performance studies on real data sets from various perspectives demonstrate the practical utility of the proposed privacy scheme and our anonymization approaches.

Index Terms

social network, privacy, anonymization.

I. INTRODUCTION

In a social network, individuals are represented by vertices, and the social activities between individuals are summarized by edges. In light of the recognition of the usefulness of information in social networking data for

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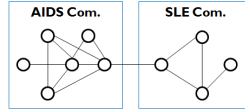


Fig. 1. Privacy violation by degree attacks.

commercial and research purposes, more and more social networking data have been published and shared in recent years. This, however, raises serious privacy concerns for the individuals whose personal information is contained in social networking data.

Each individual in a social network is associated with a vertex identity, which can represent the user name or Social Security number (SSN)¹. Vertex identification, where malicious attackers utilize their background knowledge to associate an individual with a specific vertex in published social networking data, is one of the most important privacy issues that has emerged in recent year [24], [29]. Due to the complexity of social networks, the resistance of vertex identification has been studied against different background knowledge from various perspectives [1], [12], [17], [28], [30]. Backstrom et al. in [1] first showed that as long as an attacker knows a piece of information about an individual, it is insufficient to protect privacy by only removing the vertex identities. Liu and Terzi in [17] later proposed k -degree anonymity that guarantees the privacy protection against degree information. Given the degree information, k -degree anonymity ensures that there are at least k vertices with the same degree in a social network, such that the probability of an individual being associated with a specific vertex is limited to $1/k$. Similar concepts have also been applied to provide protection against attackers with stronger background knowledge. The work in [28] considered the case where an attacker's knowledge is the 1-neighborhood connectivity around an individual and proposed k -neighborhood anonymity as a solution. The studies in [5], [30] introduced k -automorphism anonymity and k -isomorphism anonymity against attacks of arbitrary subgraphs related to an individual. Alternatively, a generalization technique is another approach. Hay et al. [12] were able to hide privacy details about each individual by grouping a set of vertices into a super-vertex and inferring the relationships between super-vertices from super-edges.

Note that, however, each individual in a social network is inclined to be associated with a community identity [7], [14]. The community identity of a vertex can represent the personal privacy information sensitive to the public, such as on-line political activity group, on-line disease support group information, or friend group association in a social network. Different from the other vertex features such as gender or salary, community identity is a kind of structural information that can be derived by the community detection techniques from a social network. The existing vertex anonymity schemes thus cannot ensure the privacy protection for the community identities since it is possible that the vertices with the same information known to an attacker gather closely in a subgraph (community) of the whole social network.

Specifically, this paper addresses a new privacy issue, referred to as community identification, and shows that k -degree anonymity is not sufficient. Consider the 2-degree anonymity in Figure 1 as an example. Suppose that an attacker knows that John has 5 friends in this network. In the case of explicit communities, the attacker is able to infer that John has AIDS since all vertices with degree 5 are associated with the AIDS community. Moreover, even in another case of implicit communities (i.e., without explicit community label), the attacker can infer the

¹SSN is a nine-digit number issued to U.S. citizens, permanent and temporary residents in the United States.

neighborhood of John with only a distance one inaccuracy by identifying the dense subgraph in which John resides. This example demonstrates that even though an attacker cannot precisely identify the vertex corresponding to an individual, private and sensitive community information and neighborhood information can still be revealed.

To prevent community identification in published social networks by degree attacks, therefore, we propose k -structural diversity, which ensures that for each vertex, there are other vertices with the same degree located in at least $k - 1$ different communities. The rationale is that the probability for an attacker to associate a victim with the correct community identity is limited to at most $1/k$. We then formulate a new problem, k -Structural Diversity Anonymization (k -SDA), which ensures the k -structural diversity with minimal semantic distortion. For k -SDA, we propose an Integer Programming formulation to find optimal solutions for small instances. In addition, we also devise scalable heuristics to solve large-scale instances of k -SDA with different perspectives. To demonstrate the practical utility of the proposed privacy scheme and our anonymization approaches, various evaluations are performed on real data sets. The experimental results show that the social networks anonymized by our approaches can preserve much of the characteristics of the original networks.

II. RELATED WORK

Privacy is always a crucial factor in releasing or exchanging data. In the past decade, issues on privacy-preserving data publishing (PPDP) on transaction data, such as record linkage, sensitive attribute linkage, and table linkage, have attracted extensive research interest [9]. Record linkage refers to the identification of a record's owner, and its corresponding privacy model, k -anonymity [21], prevents record linkage by ensuring that at least k records share the same quasi-identifier. That is, there are at least k records in a *qid* group. Following this initial research, a group of studies, such as MultiRelational k -anonymity [20], extended k -anonymity to improve and support privacy protection under various scenarios and attacks. In contrast to the record, the attribute value associated with each individual is more important in sensitive attribute linkage, and l -diversity [18] ensures that at least l sensitive values appear in every *qid* group. However, as Li et al. [15] observed, l -diversity is not sufficient to provide privacy protection, especially when the overall distribution of the sensitive attribute is skewed. In other words, an attacker is able to issue a *skewness attack* when a sensitive attribute is associated to a *qid* group with higher confidence than other *qid* groups. This problem is remedied by t -Closeness [15] by demanding that the distribution of a sensitive attribute in every *qid* group is similar to each other among the whole dataset. It is worth noting that both l -diversity and t -closeness mainly focus on categorical sensitive attributes. For numerical sensitive attributes, a *proximity attack* [16] identifies the interval in which the sensitive value s of an individual is located, while (ε, m) -anonymity is proposed to ensure that the probability to infer an interval $[s - \varepsilon, s + \varepsilon]$ is limited to at most $1/m$. Moreover, table linkage is concerned about whether the record associated with an individual is presented in a released table, and δ -presence [19] limits the probability of the above inference within a specified range.

With the explosive growth of information from social networking applications, privacy concerns in releasing social networking data become increasingly important. Various issues, such as vertex identification and link identification, have drawn extensive research interests [24], [29]. Vertex identification [1], [5], [12], [17], [28], [30] finds the one-to-one correspondence of each individual and each vertex in a social network in order to extract sensitive personal information, and many anonymization and generalization approaches for resisting vertex identification have been introduced in Section I. This contrasts with link identification [5], [25], [26], [27], which discloses the sensitive relationship between two individuals. To resolve this issue, perturbation [25] with edge addition, edge deletion, and edge swap is proposed. To further address different privacy requirements, edges are classified into multiple

types of sensitivities and removed with different priorities [27]. Zhang et al. [26] explored a new situation where attackers possess the knowledge of vertex descriptions, such as degrees, and proposed to decrease the certainty on the existence of an edge according to the attacker's available knowledge. In addition, α -proximity [6] brings the notion of attribute privacy in transaction data to social networks by extending the concept of t -closeness. That is, α -proximity ensures that the distribution of labels in a neighborhood is similar to that in the whole social graph.

Different from all the above privacy models concentrating on varied datasets that are directly made public, *differential privacy* [8] explores the condition on the release mechanism, i.e., a randomized algorithm \mathcal{A} answering queries to release information. Specifically, a randomized algorithm \mathcal{A} follows ϵ -differential privacy if for all datasets x and x' that differ on at most one element, and any subset of outputs $S \subset \text{Range}(\mathcal{A})$,

$$\Pr[\mathcal{A}(x) \in S] \leq \exp(\epsilon) \Pr[\mathcal{A}(x') \in S],$$

where ϵ is a privacy parameter. Intuitively, the privacy protection increases with a smaller ϵ . Thus, differential privacy aims to introduce noises into query results and provide robust privacy guarantee without any assumption on the data and background knowledge possessed by an attacker. In the past few years, the great promise of differential privacy has mainly been demonstrated on statistical database [9]. Very recently, a few studies [10], [11], [13] have also proposed its application to social networks. To meet the privacy guarantee, those approaches focus on specific data utility of social networks. Specifically, Hay et al. [11] proposed constrained inferences to provide provable privacy for the degree distribution of a social network; Karwa et al. [13] studied the privacy-preserving problem for subgraph counting queries, e.g., a triangle, k -star and k -triangle, while Gupta et al. [10] addressed the cut function of a graph that answers the number of correspondences between any two sets of individuals.

III. PROBLEM FORMULATION

In this paper, we formulate a new anonymous problem, k -Structural Diversity Anonymization (k -SDA), to protect the community identities of individuals in a network. The network is represented as an undirected simple graph $G(V, E, C)$, where V is the set of vertices corresponding to the individuals, E is the set of edges representing the relationship between individuals, and C is the set of communities. These communities can be either explicitly given as input or derived through clustering on the social network graph. Each vertex v has a community ID², c_v , in C , and each edge in E can span two vertices in either the same or different communities. Let d_v denote the degree of vertex v , and k -SDA is also given a positive integer parameter k , $1 \leq k \leq |C|$, to represent the structural diversity, which is formally defined as follows.

Definition 1. A graph $G(V, E, C)$ is k -structurally diverse, i.e., satisfying k -SDA, if for every vertex $v \in V$, there exist at least k communities such that each of the communities contains at least one vertex with the degree identical to d_v ³.

²For simplicity, we focus on the one-community case in this paper while the multi-community scenario is studied in our ICDM paper [23].

³From the viewpoint of privacy protection, the concept of structural diversity proposed in this paper can be extended to support the multi-community scenario [23]. For protecting a *single* community, the structural diversity anonymization (k -SDA) specifies that the vertices of the same degree need to appear in at least k different communities. In contrast, to support the scenario that each individual belongs to a community set with one or more than one community, the key factor for extending k -SDA is to ensure that the vertices of the same degree in the anonymized graph appear in at least k different mutually exclusive *community sets*. For example, if two vertices A and B of the same degree in the anonymized graph belong to community sets $\{C1\}$ and $\{C2, C3\}$, respectively, those two vertices follow 2-SDA since the two community sets are mutually exclusive. On the other hand, if A and B reside in community sets $\{C1\}$ and $\{C1, C3\}$, respectively, it is easy for an attacker to infer that A and B must participate in community C1.

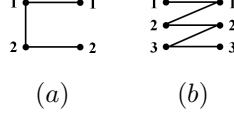


Fig. 2. Examples of two 2-structurally diverse graphs.

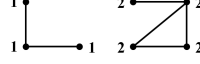


Fig. 3. Examples of limit of operation Adding Edge.

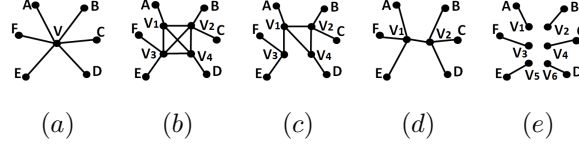


Fig. 4. Examples of operation Splitting Vertex

In other words, for each vertex v , there must exist at least $k - 1$ other vertices located in at least $k - 1$ other communities. Figure 2 shows an example with the graphs that are 2-structurally diverse, where the community ID is indicated beside each vertex. In Figure 2(a), both communities contain a vertex with the degree as 1 and a vertex with the degree as 2. Therefore, the graph is 2-structurally diverse. In Figure 2(b), two communities contain vertices with the degree as 1, and three communities contain vertices with the degree as 2. For each degree, we can find at least two communities containing vertices with the same degree. The graph is thus 2-structurally diverse.

Proposition 1. If $G(V, E, C)$ is k -structurally diverse, then it also satisfies k -degree anonymity, which implies that for every vertex, there exist at least $k - 1$ other vertices with the same degree.

Proposition 2. If $G(V, E, C)$ is k_1 -structurally diverse, then it is also k_2 -structurally diverse for every $k_2, k_2 \leq k_1$.

The problem is to anonymize a graph $G(V, E, C)$ such that the graph is k -structurally diverse. To limit the semantic distortion in the corresponding applications, we define two operations, *Adding Edge* and *Splitting Vertex*. Operation Adding Edge connects two vertices belonging to the same community. Adding an edge for two vertices in different communities is prohibited because it may lead to improper distortion. For example, it is inappropriate to artificially connect an individual in the liberal political action community to another individual in the anti-abortion community to achieve k -structural diversity. Although operation Adding Edge alone can fulfill k -structural diversity in some cases, k -structural diversity cannot often be solely achieved with this operation. Consider the example in Figure 3. There is one vertex with the degree as 3 in community 2. However, by operation Adding Edge alone, it is impossible to make any vertex in community 1 have a degree as 3 since there are only three vertices in community 1.

Therefore, operation Splitting Vertex is proposed to ensure that any arbitrary input instance can be anonymized to achieve k -structural diversity. Each vertex v involved in this operation is split into multiple *substitute vertices*, where each substitute vertex is a clone for the corresponding individual. Each clone represents the relationship of at least one neighbor of v , such that all substitute vertices of v as a whole share the same relationships with the neighbors of v before the splitting. Specifically, let E_v denote the set of incident edges of v , where v is replaced

with a set S_v of substitute vertices such that (1) each substitute vertex is connected with at least one edge in E_v , and (2) every edge in E_v is incident to a substitute vertex in S_v . Thus, S_v includes at most $|E_v|$ vertices. Figures 4(b)-4(e) present several possible results for Splitting Vertex on vertex v of Figure 4(a). For the connectivity between substitute vertices, a simple approach is to enforce that all substitute vertices of v must be mutually connected. However, Splitting Vertex does not restrict that S_v must form a clique because an attacker can regard the clique as a hint to identify the corresponding individual. Therefore, Splitting Vertex allows a substitute vertex to freely connect to any other substitute vertex in S_v , and the flexibility inherited in Splitting Vertex enables our algorithm to achieve k -structural diversity for any arbitrary input instance.

Note that in the previous study on the privacy preservation of databases [9], it was pointed out that maintaining the original information stored in the database is important for some applications that are required to extract the attribute values associated with the data tuples. For this reason, several database anonymization schemes [9], [15], [18], [22] avoid removing a tuple or even any of its attribute values in order to preserve all corresponding information. Similarly, for preserving the attribute values of a tuple to some extent, many existing anonymization schemes [15], [18], [22] adopt generalization or suppression to hide a specific attribute value into its specific attribute range or generalize the concepts of the attribute values, while the hiding ranges and generalization concepts are optimized to reduce the distortion.

In this paper, the proposed algorithms with operations Adding Edge and Splitting Vertex can be regarded as the above type of anonymization schemes that aims to preserve the attribute values to some extent. As such, the information in the social networks is not removed by deleting or swapping the existing edges, even though the above two strategies allow the proposed algorithms to be more flexible in anonymizing a graph. Nevertheless, the concept of swapping an edge has been incorporated in our algorithm design. The proposed heuristics redirect an edge added at the previous iteration, instead of always adding a new edge, in order to reduce the number of created edges. However, redirecting added edges does not affect the original edges in the network, and hence does not violate our objective of preserving the original edges in the network. Specifically, the objective of k -SDA is to minimize the semantic distortion during the anonymization via Adding Edge and Splitting Vertex. We formally define k -SDA as follows.

Problem k -SDA. Given a graph $G(V, E, C)$ and an integer k , $1 \leq k \leq |C|$, the problem is to anonymize G to satisfy k -structural diversity with operations Adding Edge and Splitting Vertex such that $n_a + \omega n_s$ is minimized, where n_a denotes the number of edges created in operation Adding Edge, n_s denotes the number of vertices added in operation Splitting Vertex, and ω is a positive weight for operation Splitting Vertex.

In this paper, we set ω as $|V|^2$ (the maximum number of edges in a graph) to consider the case that operation Splitting Vertex is performed only if the graph cannot be anonymized with operation Adding Edge alone.

IV. INTEGER PROGRAMMING

In the following, we propose the Integer Programming formulation for k -SDA. Our formulation together with any commercial software for mathematical programming can find the optimal solutions, which can be used as the benchmarks for the solutions obtained by any heuristic algorithm. We first derive the formulation for k -SDA with only operation Adding Edge in Section IV-A to capture the intrinsic characteristics of this optimization problem and to avoid initially including complicated details. Thereafter, we extend the formulation to incorporate both operations in IV-B.

TABLE I
THE INPUT OF k -SDA.

Notation	Description
V	the set of vertices
C	the set of communities
E	the set of the original edges
E_v	the set of the original edges incident on v $v \in V, E_v \subseteq E$
\overline{E}	the set of candidate edges that are allowed to be added in operation Adding Edge
\overline{E}_v	the set of adding edge candidates incident on v , $v \in V, \overline{E}_v \subseteq \overline{E}$
S_v	the set of substitute vertices of $v, v \in V$
D	the set of degrees, i.e., $D = \{d \in \mathbb{N} \mid 1 \leq d \leq V \}$
k	the size of structural diversity
c_u	the community of vertex $u, u \in V, c_u \in C$

TABLE II
THE DECISION VARIABLES OF k -SDA WITH OPERATION ADDING EDGE.

Notation	Description
$\alpha_{u,v}$	binary variable; $\alpha_{u,v} = 1$ if edge $e_{u,v}$ is added in operation Adding Edge; otherwise, $\alpha_{u,v} = 0$, $e_{u,v} \in \overline{E}_u$
$\delta_{u,d}$	binary variable; $\delta_{u,d} = 1$ if the degree of u is d ; otherwise, $\delta_{u,d} = 0, u \in V, d \in D$
$\theta_{c,d}$	binary variable; $\theta_{c,d} = 1$ if there exists at least one vertex in c with its degree as d ; otherwise $\theta_{c,d} = 0, c \in C, d \in D$

A. Formulation with Adding Edge

As an initial basis, consider the formulation for k -SDA with only operation Adding Edge. Tables I and II summarize the input and decision variables of k -SDA. In our formulation, $e_{u,v}$ and $e_{v,u}$ correspond to the same edge. The objective function of k -SDA with only operation Adding Edge is formulated as

$$\min \sum_{e_{u,v} \in \overline{E}} \alpha_{u,v}.$$

The objective function minimizes the number of added edges. The problem has the following constraints,

$$\forall u \in V, \tag{1}$$

$$\sum_{d \in D} \delta_{u,d} = 1,$$

$$\forall u \in V, \forall d \in D, \quad (2)$$

$$\text{where } d < |E_u| \text{ or } d > |E_u| + |\overline{E}_u|,$$

$$\delta_{u,d} = 0,$$

$$\forall u \in V, \quad (3)$$

$$|E_u| + \sum_{e_{u,v} \in \overline{E}_u} \alpha_{u,v} = \sum_{d \in D} d \delta_{u,d},$$

$$\forall u \in V, \forall d \in D, \quad (4)$$

$$\delta_{u,d} \leq \theta_{c_u,d},$$

$$\forall c \in C, \forall d \in D, \quad (5)$$

$$\theta_{c,d} \leq \sum_{u \in V: c_u = c} \delta_{u,d},$$

$$\forall c \in C, \forall d \in D, \quad (6)$$

$$(k-1) \theta_{c,d} \leq \sum_{\bar{c} \in C: \bar{c} \neq c} \theta_{\bar{c},d}.$$

Constraint (1) ensures that the degree of each vertex is unique, and constraint (2) prunes unnecessary candidate degrees for each vertex. The degree for each vertex u must be no smaller than the number of originally incident edges. In addition, it cannot exceed the sum of the number of originally incident edges and the number of adding edge candidates. The left-hand-side of constraint (3) represents the degree of vertex u , and constraint (1) guarantees that $\delta_{u,d}$ is 1 for only a single d . In this way, constraint (3) together with constraint (1) ensure that binary variable $\delta_{u,d}$ can find the correct degree of each vertex.

Constraints (4) and (5) collect the degrees of the vertices in each community. If the degree value of vertex u is p , i.e., $\delta_{u,p} = 1$, then constraint (4) states that the corresponding community must have at least one vertex with the degree as p , i.e., $\theta_{c_u,p} = 1$. In contrast, for any other degree value q , $q \neq p$, constraints (1)-(3) ensure that $\delta_{u,q} = 0$ must hold. In this case, $0 \leq \theta_{c_u,q}$ must be true when $\theta_{c_u,q}$ is either 0 or 1. Note that this constraint does not limit the value of $\theta_{c_u,d}$ in this case. However, if the degree value of every vertex u in community c is not q , i.e., $\delta_{u,q} = 0$, then the right-hand-side of constraint (5) is 0 and thereby ensures that $\theta_{c,d}$ in the left-hand-side must be 0. Therefore, constraints (4) and (5) ensure that binary variable $\theta_{c,d}$ can find and represent the degrees of the vertices in each community.

Constraint (6) implements the k -structural diversity. Specifically, if community c has at least one vertex with the degree d , i.e., $\theta_{c,d} = 1$, then this constraint guarantees that there must exist at least $k-1$ other communities, where each of them also has a vertex with the degree as d . In this case, for each community \bar{c} with $\theta_{\bar{c},d}$ as 1, constraint (5) will assign the degree of at least one vertex u in community \bar{c} to be d , and constraint (3) will then add several edges to u to fulfill the degree requirement. Therefore, constraint (6) is able to achieve the k -structural diversity in k -SDA.

TABLE III
THE DECISION VARIABLES OF k -SDA.

Notation	Description
$\alpha_{u,v,i,j}$	binary variable; $\alpha_{u,v,i,j} = 1$ if an edge is added to connect substitute vertex i of u and j of v ; otherwise, $\alpha_{u,v,i,j} = 0$, $u \in V$, $e_{u,v} \in \overline{E}_u$, $i \in S_u$, $j \in S_v$
$\beta_{u,i,j}$	binary variable; $\beta_{u,i,j} = 1$ if an edge is added to connect the substitute vertices i and j of u ; otherwise, $\beta_{u,i,j} = 0$, $u \in V$, $i, j \in S_u$, $i \neq j$
$\eta_{u,v,i,j}$	binary variable; $\eta_{u,v,i,j} = 1$ if the original edge $e_{u,v}$ connects the substitute vertex i of u and j of v ; otherwise, $\eta_{u,v,i,j} = 0$, $u \in V$, $e_{u,v} \in E_u$, $i \in S_u$, $j \in S_v$
$\pi_{u,i}$	binary variable; $\pi_{u,i} = 1$ if the substitute vertex i of u is active; otherwise, $\pi_{u,i} = 0$, $u \in V$, $i \in S_u$
$\delta_{u,i,d}$	binary variable; $\delta_{u,i,d} = 1$ if the degree of substitute vertex i of u is d ; otherwise, $\delta_{u,i,d} = 0$, $u \in V$, $i \in S_u$, $d \in D$
$\theta_{c,d}$	binary variable; $\theta_{c,d} = 1$ if there exists at least one vertex in c with its degree as d , $c \in C$, $d \in D$

B. Formulation with Splitting Vertex as well

We now extend the Integer Programming formulation in Section IV-A to consider both operations in k -SDA. Table III shows the modified decision variables, where subscripts for substitute vertices are included in variables $\alpha_{u,v,i,j}$ and $\delta_{u,i,d}$. To ensure that each substitute vertex in S_v has at least one incident edge in E_v , we incorporate variable $\eta_{u,v,i,j}$ to assign the edges in E_v to the substitute vertices, and $\beta_{u,i,j}$ represents the edges between substitute vertices of v . Please note that we do not enforce that every substitute vertex in S_v must have an incident edge. Instead, our formulation allows some vertices in S_v to have no incident edge. In this case, these vertices are not actually split from v , and we regard these vertices *inactive* in S_v . In the extreme case, if only one vertex in S_v is *active* and has incident edges, the vertex represents v in our formulation, and v is actually not split in k -SDA. In our formulation, to avoid missing the globally optimal solutions, S_v has a sufficient number of candidate substitute vertices, and only active substitute vertices are included or added to G in the solutions for users.

The objective function of k -SDA with both operations is as follows.

$$\min \omega \left(-|V| + \sum_{u \in V} \sum_{i \in S_u} \pi_{u,i} \right) + \sum_{e_{u,v} \in \overline{E}} \sum_{i \in S_u} \sum_{j \in S_v} \alpha_{u,v,i,j} + \sum_{e_{u,v} \in E} \left[-1 + \sum_{i \in S_u} \sum_{j \in S_v} \eta_{u,v,i,j} \right].$$

The first part represents the cost from operation Splitting Vertex, and note that no cost is incurred if no such operation is performed, i.e., there is only one active substitute vertex in S_u for each $u \in V$. The second and third terms correspond to the cost from operation Adding Edge. Moreover, the edges between the substitute vertices of

the same vertex, $\beta_{u,i,j}$, induce no cost. The problem has the following constraints,

$$\forall u \in V, \forall i \in S_u, \quad (7)$$

$$\sum_{d \in D} \delta_{u,i,d} = 1,$$

$$\forall u \in V, \forall i \in S_u, \quad (8)$$

$$\begin{aligned} \sum_{e_{u,v} \in E_u} \sum_{j \in S_v} \eta_{u,v,i,j} + \sum_{j \in S_u: i \neq j} \beta_{u,i,j} + \sum_{e_{u,v} \in \bar{E}_u} \sum_{j \in S_v} \alpha_{u,v,i,j} \\ = \sum_{d \in D} d \delta_{u,i,d}, \end{aligned}$$

$$\forall u \in V, \forall i \in S_u, \forall d \in D, \quad (9)$$

$$\delta_{u,i,d} \leq \theta_{c_u,d},$$

$$\forall c \in C, \forall d \in D, \quad (10)$$

$$\theta_{c,d} \leq \sum_{u \in V: c_u = c} \sum_{i \in S_u} \delta_{u,i,d},$$

$$\forall c \in C, \forall d \in D, \quad (11)$$

$$(k-1) \theta_{c,d} \leq \sum_{\bar{c} \in C: \bar{c} \neq c} \theta_{\bar{c},d},$$

$$\forall e_{u,v} \in E, \quad (12)$$

$$\sum_{i \in S_u} \sum_{j \in S_v} \eta_{u,v,i,j} \geq 1,$$

$$\forall u \in V, \forall e_{u,v} \in E_u, \forall i \in S_u, \forall j \in S_v, \quad (13)$$

$$\eta_{u,v,i,j} \leq \pi_{u,i},$$

$$\forall u \in V, \forall e_{u,v} \in \bar{E}_u, \forall i \in S_u, \forall j \in S_v, \quad (14)$$

$$\alpha_{u,v,i,j} \leq \pi_{u,i},$$

$$\forall u \in V, i \in S_u, \forall j \in S_u, i \neq j, \quad (15)$$

$$\beta_{u,i,j} \leq \pi_{u,i}.$$

Constraints (7), (8), (9), (10), and (11) are similar to constraints (1), (3), (4), (5), and (6). The first term in constraint (8) is different from the one in (3), in which every original edge in E is connected to vertex u . In contrast, here we allow the edges in E_u to be distributed to the substitute vertices of u , while more edges are also allowed to be added. The left-hand-side of (8) thereby finds the degree of each substitute vertex i of u .

Constraints (12)-(14) allocate the original edges in E to substitute vertices, add more edges, and identify the corresponding active substitute vertices. Constraint (12) ensures that each original edge connecting vertices u and v in k -SDA must connect a substitute vertex of u and a substitute vertex of v here, while new edges are also allowed to be added. Constraints (13), (14), and (15) guarantee that a substitute vertex is active when the vertex has at least one incident edge.

V. SCALABLE APPROACHES

In this section, we solve the k -SDA problem on large scale social networks. Anonymization of large scale social networks with minimal information distortion is always challenging because directly enumerating possible solutions is computationally infeasible. Heuristically, anonymization problems can be solved by a one-step framework which directly adjusts a graph to satisfy the privacy requirements [5], [28], [30], or by a two-step framework consisting of degree sequence anonymization and graph re-construction subjected to anonymized degree sequence [17]. For k -SDA, note that the degree sequence in the first step presents limited structural information due to the dimension incurred from the community information, while deriving additional information in the first step is so computationally intensive that an algorithm becomes less scalable. Therefore, in this paper, we design the algorithms to solve the k -SDA problem based on the one-step framework.

To ensure good scalability and achieve the anonymization with minimal information distortion, we propose four algorithms based on the following concepts. First, our algorithms anonymize the vertices one-by-one such that the graph anonymization can be efficiently achieved with only one scan of the vertices. Second, to efficiently minimize the total anonymization cost, we anonymize the vertices in orders of degrees and handle a set of vertices with similar degrees to avoid searching for a large amount of combinations. Third, to consider the community information, we propose two procedures, CREATION and MERGENCE, to anonymize each vertex v efficiently. Specifically, CREATION forms a new anonymous group for protecting v , such that other similar vertices that have not been considered can be anonymized via this new group and share the same degree with v . In addition to creating new anonymous groups for anonymization, MERGENCE lets v join an existing anonymous group if joining the group only incurs a small anonymization cost. Consequently, the above two procedures enable each vertex to be anonymized efficiently, and the graph anonymization can thereby be achieved with minimal information distortion.

In this paper, we propose four algorithms to solve k -SDA. The first algorithm, named **EdgeConnect**, specially aims at minimizing information distortion. That is, EdgeConnect applies operation Adding Edge alone since adding edges within a community does not destroy existing semantic information, such as friendships, and makes limited changes over the whole graph. It should be noted that, with sole use of Adding Edge, the degrees of vertices can only increase. EdgeConnect thus considers the vertices in *decreasing order* of the degrees to first anonymize the vertices with large degrees, so that we have more chances to achieve the anonymization of subsequent vertices without affecting existing anonymous groups. Second, to provide more variety for anonymization, we then extend EdgeConnect with operation Splitting Vertex and propose the **CreateBySplit** algorithm. CreateBySplit utilizes the same anonymization flow as EdgeConnect, but leverages Splitting Vertex if the anonymization cannot be achieved by Adding Edge alone. Incorporating Splitting Vertex can not only provide more chances to achieve the anonymization but also incur less information distortion. Differing from the previous two algorithms, which focus on minimizing the information distortion, the third algorithm, named **MergeBySplit**, is designed to guarantee the anonymization for the social networks that are difficult to be anonymized with respect to a high privacy level k . For this purpose, MergeBySplit anonymizes the vertices in *increasing order* of the degrees, and the creation of new anonymous groups with small degrees thereby allows us to protect a vertex with any larger degree by operation Splitting Vertex. Finally, we propose the fourth algorithm, named **FlexSplit**, to improve Algorithm MergeBySplit and reduce the number of generated substitute vertices in the objective function of k -SDA. Specifically, in addition to anonymizing a vertex by splitting it into members of the existing anonymous groups as in Algorithm MergeBySplit, FlexSplit is endowed with a new splitting strategy, which splits a group of vertices to generate a new anonymous group of a target degree for anonymization. With the capability of looking forward k subsequence vertices for anonymization, FlexSplit is

able to reduce the substitute vertices with the two splitting strategies. FlexSplit is thus more flexible and preserves more data utilities than MergeBySplit under the same guarantee of anonymization.

Before we introduce these algorithms in detail, we first define the anonymous group, which considers not only the number of vertices of the same degree but also the distribution of the vertices over the communities.

Definition 2. An anonymous group of degree d , denoted as g_d , consists of the vertices with degree d , i.e., $g_d = \{v | d_v = d\}$. A g_d is a k -SDA group, denoted as \hat{g}_d , if $C_{g_d} = \{c_v | v \in g_d\}$ and the cardinality of C_{g_d} is no smaller than k , i.e., $|C_{g_d}| \geq k$.

Lemma 1. If every vertex v in $G(V, E, C)$ belongs to a k -SDA group, $G(V, E, C)$ must satisfy k -SDA.

Given a graph $G(V, E, C)$, the objective is to assign every vertex v to a group \hat{g}_d with minimal information distortion. In the next sections, we present the details of our algorithms.

A. Algorithm EdgeConnect

The EdgeConnect algorithm is designed for minimizing information distortion on large-scale graphs. For this purpose, the EdgeConnect algorithm incorporates operation Adding Edge to anonymize the vertices one-by-one in decreasing order of their degrees to avoid enumerating all possible combinations, which is computationally infeasible. One merit of EdgeConnect is that the existing information is never removed, and the added local new edges within each community incur few changes to the whole graph. Moreover, procedures CREATION and MERGENCE are utilized in this algorithm, and any existing k -SDA group is never removed in order to avoid re-anonymizing the vertices and increasing the computation cost. As a result, EdgeConnect has very good scalability, which is shown in our experiments.

The rationale of Algorithm EdgeConnect is to adjust the vertex degrees one-by-one with operation Adding Edge in order to let every vertex share the same degree with other vertices in at least k different communities. To avoid examining all possibilities, the anonymization begins from a not-yet-anonymized vertex v of the *largest* degree, since the power-law degree distribution demonstrated in the previous social network analysis indicates that each large degree has fewer vertices required to be anonymized. For a chosen v , EdgeConnect utilizes procedure MERGENCE and CREATION to explore the way to anonymize v with minimal number of new edges. Procedure MERGENCE aims at adjusting the degree for a vertex v to join an existing k -SDA group, while CREATION is designed to collaborate with other not-yet-anonymized vertices to generate a new k -SDA group with a new degree. In the example of Figure 5(a), the first vertex to be anonymized is vertex c because its degree is the largest one. At the beginning, procedure MERGENCE is unable to anonymize c since no k -SDA group has been generated, and procedure CREATION thus generates a new anonymous group of degree 5 by adding an edge connecting f and another vertex in the same community, such as g . At this point, the new k -SDA group is $\{c, f\}$ as shown in Figure 5(b). EdgeConnect repeats the above process until all the vertices are successfully anonymized.

The details of each step are presented as follows. First, procedure MERGENCE protects a vertex v with an existing k -SDA group g_d . As all vertices in k -SDA group g_d share the same degree d for structural diversity, the cost for v to be anonymized (by the operation Adding Edge) in g_d is

$$Cost_{MRG}(v, d) = \begin{cases} d - d_v, & \text{if } d \geq d_v \\ \infty, & \text{otherwise.} \end{cases} \quad (16)$$

The minimal MERGENCE cost for v is evaluated as $\min_{\hat{d}} Cost_{MRG}(v, \hat{d})$ to find a suitable k -SDA group for v from all existing k -SDA groups, where \hat{d} is the degree of a k -SDA group \hat{g}_d . For example, if there are three existing

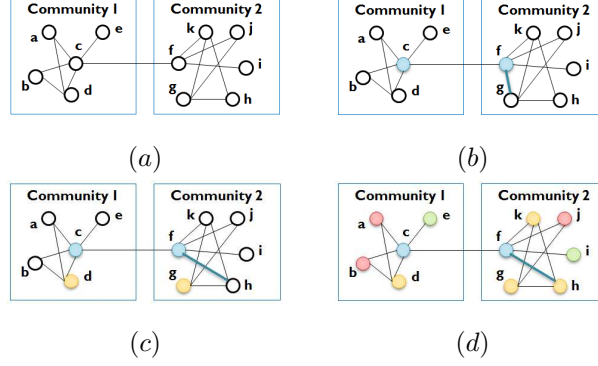


Fig. 5. Example of anonymization by EdgeConnect.

k -SDA groups with degrees 2, 5 and 6, the minimal MERGENCE cost for a vertex v of degree 4 is 1 by increasing its degree to $\hat{d} = 5$. Next, for procedure CREATION, which introduces a new k -SDA group, our algorithm finds the vertices distributed in other $k - 1$ communities to join this new group. Specifically, the diversity of a group g_d is first defined as

$$Div(g_{d_v}) = \begin{cases} 1, & \text{if } |C_{g_{d_v}}| \geq k \\ \infty, & \text{if } |C_{g_{d_v}}| < k, \end{cases} \quad (17)$$

where $C_{g_{d_v}} = \{c_u | u \in g_{d_v}\}$. Accordingly, the minimal cost for v in CREATION is

$$Cost_{CRT}(v) = \min_U \{Div(U) \times \sum_{u \in U} Cost_{MRG}(u, d_v)\}, \quad (18)$$

where U is any subset of k vertices that have not been anonymized, including v . For example, if k is 2 and not-yet-anonymized vertices v and u in different communities are of degrees 4 and 2, respectively, when g_4 has not been previously generated, a simple way for anonymizing v is to create a new k -SDA group $g_4 = \{v, u\}$ by increasing the degree of u to 4. However, to avoid exploring every possible U , we sort all not-yet-anonymized vertices of each community in the decreasing order of their degrees, and the vertex with the largest degree in each community is chosen for U since the degree difference between those vertices and v is the smallest. If $|C| > k$, only k of the above vertices with the largest degrees are selected to construct U such that $|U| = k$. Therefore, finding the anonymization costs for each vertex v is computationally efficient.

In our algorithm design, the not-yet-anonymized vertices in each community are sorted in the decreasing order of their degrees. Let s_c denote the order set of the vertices for community c , and $s_c(i)$ be the vertex with the i -th largest degree in c . We anonymize the vertices one-by-one with MERGENCE and CREATION as follows. We first choose the largest degree vertex v among $s_1(1), \dots, s_{|C|}(1)$. If $\min_{\hat{d}} Cost_{MRG}(v, \hat{d})$ is smaller than $Cost_{CRT}(v)$, procedure MERGENCE increases the degree of v by adding $(\hat{d} - d_v)$ edges connecting v and the $(\hat{d} - d_v)$ subsequent vertices, which are not yet connected to v , in s_{c_v} . We then update s_{c_v} , and note that the update of s_{c_v} is efficient given that only $(\hat{d} - d_v)$ vertices increase their degrees by 1. Otherwise, procedure CREATION finds U , increases the degree of each vertex u in U to d_v in the same way, and updates the corresponding s_{c_u} as well. We present the proceeding illustrative example.

Example 1. Consider the graph in Figure 5(a) with k as 2. In the decreasing order of the degrees, the vertex orders are $s_1 = cdabe$ and $s_2 = fgkhji$. Accordingly, the first considered vertex (the largest degree vertex) is c . From Formula (16), the MERGENCE cost for c is infinity as there is no 2-SDA group. According to Formula (18),

the CREATION cost for c is 1, and the set U corresponding to the minimal cost consists of c and f (the first vertex in s_c). Therefore, vertex c is anonymized by CREATION and an edge is added between f and g . Consequently, a new 2-SDA group of degree 5 is generated, and the vertex orders are updated to $s_1 = dabe$ and $s_2 = gkhji$. Figure 5(b) shows the result after this iteration, where the anonymized vertices are shaded. ■

The above two procedures can anonymize every vertex with a minimal cost at each iteration. However, Since adding an edge increases the degrees of two vertices, the newly added edge (f, g) in Figure 5 not only increases the degree of vertex f for creating a 2-SDA group of degree 5 but also increases the degree of vertex g simultaneously. Nevertheless, this increment of the degree on g incurs additional cost to anonymize the not-yet-anonymized vertex g . To avoid the above case, we define redirectable edges and propose edge-redirection operation, so that edge (f, g) can be properly replaced by another edge, such as (f, h) , without revoking the anonymization of vertices c and f examined previously.

Definition 3. An added edge (w, v) , where w is an anonymized vertex and v is a not-yet-anonymized vertex in the same community, is said redirectable away from v if there is another not-yet-anonymized vertex x in the same community not yet connecting to w . Defined on such an edge, the edge-redirection operation performs

$$\hat{E} \leftarrow \hat{E} / (w, v) \cup (w, x),$$

where \hat{E} is the set of existing added edges.

Let R_v denote the set of edges that are redirectable away from v . The edge-redirection operation allows us to reduce the degree of v without changing the degree of any vertex w that has been anonymized in a k -SDA group. Therefore, we can modify procedure MERGENCE in the following way to allow v to join the group with a smaller degree, by redirecting some added edges incident to v .

$$Cost_{MRG}(v, d) = \begin{cases} 0, & \text{if } d_v \geq d \geq d_v - |R_v| \\ d - d_v, & \text{if } d > d_v \\ \infty, & \text{otherwise.} \end{cases} \quad (19)$$

Thus, to find a suitable k -SDA group, we derive the minimal MERGENCE cost for v as $\min_{\hat{d}} Cost_{MRG}(v, \hat{d})$, where \hat{d} is the degree of a k -SDA group \hat{g}_d . Similarly, we modify procedure CREATION and derive the minimal cost of creating a new k -SDA group for v as

$$Cost_{CRT}(v) = \min_U \{Div(U) \times \sum_{u \in U} Cost_{MRG}(u, d_v - |R_v|)\}, \quad (20)$$

where U is any subset of k vertices that have not been anonymized, including v . As a result, with the edge-redirection operation and the two modified procedures, we are able to reuse the edges added previously to further reduce the anonymization cost.

In the following, we propose Algorithm EdgeConnect (Algorithm 1 in Figure 6) based on the modified MERGENCE and CREATION. For each vertex v , EdgeConnect first finds the set R_v of added edges that can be redirected away from v . More specifically, R_v is a subset of new edges incident to v added during operation Adding Edge. For every edge (w, v) in R_v , there must exist a vertex x in the same community of v such that x shares no edge with the anonymized w . To calculate R_v efficiently, Algorithm EdgeConnect examines every new edge (w, v) incident to v to find $V_{C_v} - N_w$, where V_{C_v} is the set of not-yet-anonymized vertices in the same community of v , and N_w is the set of neighboring vertices of w . We add (w, v) to R_v if $V_{C_v} - N_w$ is not an empty set. For vertex g in Figure 5(b) following Example 1, (f, g) is in R_g since $\{g, h, i, j, k\} - \{g, i, j, k\} \neq \emptyset$. In Community 2, there is a vertex

Algorithm 1. EdgeConnect	Function AddE(v, \hat{G}, k)
Input: $G(V, E, C), \{s_c\}$ and k Output: $\hat{G}(V, \hat{E}, C)$ or "No"	1. $R_v \leftarrow \text{RedirectableESet}(v)$ 2. If $\min_{\hat{d}} \text{Cost}_{\text{MRG}}(v, \hat{d}, R_v) < \min_U \text{Cost}_{\text{CRT}}(v, k, R_v)$ 3. $d \leftarrow \hat{d}: \min \text{Cost}_{\text{MRG}}(v, \hat{d}, R_v)$ 4. $\text{anon} = \text{AdjustDeg}(v, d, \hat{G})$ 5. $\text{Update}(s_{c_v})$ 6. Else if $\min_U \text{Cost}_{\text{CRT}}(v, k, R_v) \neq \infty$ 7. $U \leftarrow U: \min \text{Cost}_{\text{CRT}}(v, k, R_v)$ 8. For $u \in U$ 9. $\text{anon} = \text{anon} \cup \text{AdjustDeg}(u, d_v - R_v , \hat{G})$ 10. $\text{Update}(s_{c_u})$ 11. return anon
1. $\hat{G} \leftarrow G$ 2. $v \leftarrow \text{LargestDegV}(\{s_c(1)\})$ 3. While $v \neq \emptyset$ do 4. $\text{anon} = \text{AddE}(v, \hat{G}, k)$ 5. If anon = "No" 6. return "No" 7. $v \leftarrow \text{LargestDegV}(\{s_c(1)\})$ 8. return \hat{G}	

Fig. 6. The pseudo code of EdgeConnect.

h that does not connect to the anonymized vertex f . After identifying R_v , the costs induced from MERGENCE and CREATION for v are evaluated by (19) and (20). If the MERGENCE cost is smaller than the CREATION cost, the degree of v is increased by Adding Edge or decreased by the edge-redirection operation. Otherwise, EdgeConnect anonymizes v by creating a new k -SDA group with the vertices in U that minimizes the cost in (20). EdgeConnect returns the anonymized graph $\hat{G}(V, E \cup \hat{E}, C)$ and obtains the anonymization cost.

Example 2. We continue the example in Figure 5. However, procedures MERGENCE and CREATION utilize (19) and (20) here, instead of (16) and (18) as in Example 1. In this case, c is still the first vertex to be anonymized. However, at the next iteration as shown in Figure 5(b), without the edge-redirection operation, g can only be anonymized by adding another edge to increase its degree to 5 (by MERGENCE), or by adding an edge between d and e to create a new 2-SDA group of degree 4 (by CREATION). In both ways, we need to add an edge to the graph. In contrast, the edge-redirection operation is able to avoid this additional edge. Specifically, for vertex g , EdgeConnect first finds $R_g = \{(f, g)\}$. The CREATION cost for g is thus 0, and the set U that minimizes this cost is $\{d, g\}$. The MERGENCE cost for g is 1 because the only 2-SDA group is of degree 5. Therefore, EdgeConnect anonymizes g by creating a new 2-SDA group consisting of d and g , and redirecting the edge (f, g) to (f, h) . Consequently, the edge-redirection operation enables us to anonymize g with zero cost. Figure 5(c) shows the result after the second iteration of anonymization, where the anonymized vertices belonging to the same 2-SDA groups are shaded in the same color. When EdgeConnect terminates, the final anonymous result is shown in Figure 5(d). ■

B. Algorithm CreateBySplit

In this subsection, we extend Algorithm EdgeConnect with operation Splitting Vertex and propose Algorithm CreateBySplit. Compared to EdgeConnect, CreateBySplit is a more realizable solution because Splitting Vertex will increase the number of vertices in a community and provide a greater number of chances to achieve the anonymization.

Specifically, Splitting Vertex replaces a vertex v with a set S_v of substitute vertices, and redistributes incident edges of v to substitute vertices so that each substitute vertex presents partial truths of v . Splitting Vertex will thus increase the number of vertices and incur higher information distortion than Adding Edge. To minimize the information distortion, Splitting Vertex is always regarded as the second choice and will be applied only if Adding Edge is not able to anonymize the social network.

In addition, to avoid creating too many vertices and increasing information distortion, we always use two substitute

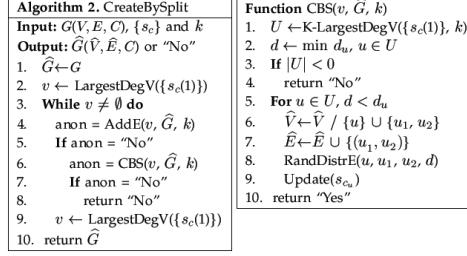


Fig. 7. The pseudo code of CreateBySplit.

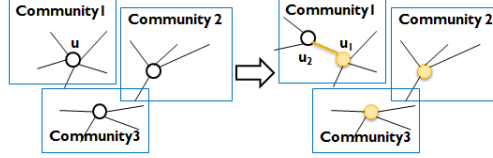


Fig. 8. Example of splitting strategy of CreateBySplit.

vertices v_1 and v_2 to replace v , and connect v_1 and v_2 with an edge. This approach can limit the incrementation of the length for the shortest path between any pair of vertices due to the split of a vertex.

In other words, when Adding Edge is not able to anonymize the social network (Algorithm 2 in Figure 7), CreateBySplit anonymizes a given vertex v with Splitting Vertex in the following way. Let U denote the vertex set consisting of k not-yet-anonymized vertices with the largest degrees in k different communities. CreateBySplit generates a new k -SDA of degree d in the following steps, where d is the maximal degree satisfying $d \leq d_u$ for every $u \in U$. When $d_u > d > 2$, CreateBySplit (1) replaces u with two substitute vertices u_1 of degree $d_{u_1} = d - 1$ and u_2 of degree $d_{u_2} = d_u - d + 1$, and then (2) connects u_1 and u_2 with an additional edge (u_1, u_2) , so that $d_{u_1} = d$ and $d_{u_2} = d_u - d + 2$ eventually. In the 2nd step, the edge (u_1, u_2) is added not only to ensure $d_{u_1} = d$ but also reduce the information distortion such as the split of connected components and the impact in the shortest paths (and their lengths). On the other hand, when $d_u > d = 2$, connecting u_1 and u_2 with an additional edge (u_1, u_2) in the 2nd step will enforce $d_{u_2} = d_u - 2 + 2 = d_{u_2}$ and thus make u_2 just another u of the same degree to be anonymized. Similar situation occurs for $d = 1$. To tackle those special cases with $d \leq 2$, CreateBySplit assigns $d_{u_1} = d$ and $d_{u_2} = d_u - d$ and no longer connects u_1 and u_2 with an additional edge. Consequently, in both general and special cases, u_1 will be anonymized in the newly generated k -SDA group of degree d , while u_2 is a not-yet-anonymized vertex to be subsequently anonymized as with other vertices.

C. Algorithm MergeBySplit

Here, we propose Algorithm MergeBySplit for the social networks that are difficult to be anonymized with respect to a high privacy level k . In CreateBySplit, even though Splitting Vertex can generate vertices to increase the possibility of anonymization for the social networks, the algorithm still cannot guarantee finding the solution of every instance of k -SDA. In contrast, MergeBySplit can anonymize every social network, even for the most difficult one.

In more detail, MergeBySplit anonymizes the vertices one-by-one in the increasing order of the degrees, and performs Splitting Vertex by allowing each vertex v to be split into more than two substitute vertices protected by

Algorithm 3. MergeBySplit	Function MBS(v, \hat{G})
Input: $G(V, E, C)$, $\{\bar{s}_c\}$ and k	1. $S_v = DP(d_v)$
Output: $\hat{G}(\hat{V}, \hat{E}, C)$	2. $\hat{V} \leftarrow \hat{V} / \{v\} \cup S_v$
1. $\hat{G} \leftarrow G$	3. RandDistrE2Groups(v, S_v)
2. $v \leftarrow \text{SmallestDegV}(\{\bar{s}_c(1)\})$	4. Update(s_{c_v})
3. While $v \neq \emptyset$ do	
4. anon = AddE(v, \hat{G}, k)	
5. If anon = "No"	
6. MBS(v, \hat{G})	
7. $v \leftarrow \text{SmallestDegV}(\{\bar{s}_c(1)\})$	
8. return \hat{G}	

Fig. 9. The pseudo code of MergeBySplit.

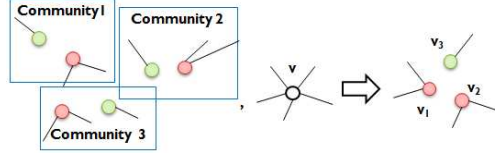


Fig. 10. Example of splitting strategy of MergeBySplit.

the existing k -SDA groups. The rationale of this algorithm is that, the creation of k -SDA groups with small degrees allows us to protect any vertex v by splitting v into many cohorts of the generated k -SDA groups. In the worst case, we can split a vertex v of degree d_v into d_v substitute vertices of degree 1 to achieve the anonymization for an arbitrary k , $1 \leq k \leq |C|$.

However, to reduce the information distortion, when we split a vertex v to cohorts of the existing k -SDA groups, we create the least number of substitute vertices based on the following dynamic programming.

$$\begin{aligned}
 |S_v| &= DP(d_v) \\
 &= \min\{D(d_v), \min_{1 \leq d < d_v} DP(d_v - d) + D(d)\},
 \end{aligned} \tag{21}$$

where $D(d) = 1$, if there is a k -SDA group \hat{g}_d of degree d ; otherwise, $D(d) = \infty$.

We now describe the details of Algorithm MergeBySplit (Algorithm 3 in Figure 9). MergeBySplit sorts the not-yet-anonymized vertices in each community in the *increasing order* of the degrees. Let \bar{s}_c denote the order set of vertices in community c , and $\bar{s}_c(i)$ be the vertex with the i -th smallest degree. At each iteration, we anonymize a vertex v with the *smallest degree* d_v with procedures MERGENCE or CREATION as specified in Algorithm CreateBySplit. If it is too restrictive to anonymize v by Adding Edge and edge-redirection operations, we perform Splitting Vertex operation to anonymize v . That is, we replace v with a set S_v of substitute vertices as shown in Figure V-C, i.e.,

$$V \leftarrow V / \{v\} \cup S_v,$$

where the size of S_v is determined by Formula (21). Afterward, the edges incident to v are randomly redistributed to the substitute vertices $v_1, v_2, \dots, v_{|S_v|}$ such that each substitute vertex v_j , $j = 1, \dots, |S_v|$, is a cohort of some existing k -SDA group \hat{g}_d , i.e., $d_{v_j} = d$. As shown above, anonymizing v by Splitting Vertex in this way can always succeed. When all the vertices belong to k -SDA groups, Algorithm MergeBySplit returns the anonymized graph \hat{G} .

D. Algorithm FlexSplit

In this subsection, we propose Algorithm FlexSplit that improves MergeBySplit and preserves more utilities of the social networks under the same guarantee of anonymization. FlexSplit outperforms MergeBySplit by introducing a new splitting strategy and the capability of looking forward.

To elaborate, in addition to splitting a vertex into substitutes protected by the existing anonymous groups as MergeBySplit, FlexSplit is endowed with a new splitting strategy, which identifies a group of vertices and splits these vertices to generate a new anonymous group of a target degree. In this way, the degrees of substitute vertices are not constrained to be the same as those of the existing anonymous groups. FlexSplit is better able to preserve the degree distribution by setting a large target degree for the newly generated anonymous group. Moreover, when splitting a group of vertices together, FlexSplit introduces new edges to connect the substitute vertices to effectively prevent the partitioning of connected components in a social network.

With Vertex Splitting operation, FlexSplit is thus more flexible and is able to anonymize a selected vertex v in the following strategies, for reducing the number of generated substitute vertices. The first strategy is *Single Splitting*, which splits v into multiple substitute vertices as in MergeBySplit. Let S_v^M denote the minimal set of substitute vertices generated by Single Splitting, and S_v^M can be derived by Formula (21). The second strategy is *Group Splitting*, which identifies a group of vertices and splits those vertices to generate a new anonymous group of the target degree for anonymization. To create minimal number of substitute vertices, this strategy splits each vertex into at most two substitute vertices. The minimal set S_v^C of substitute vertices generated by Group Splitting is thus determined as

$$S_v^C = 2 \times \{u | d_u > d_v, u \in W\}, \quad (22)$$

where W is the vertex set consisting of k not-yet-anonymized vertices with the smallest degrees in k different communities. Since each node is split into two substitute nodes, we have a multiplier of 2 in Formula (22). One of the substitute vertex is anonymized with the target degree d_v of the newly generated anonymous group and the other has the remaining degree $d_u - d_v + 2$ with an additional edge added to connect the two substitute vertices.

Furthermore, FlexSplit is also endowed with the capability of looking forward, to reduce the number of generated substitute vertices in the objective function of k -SDA. In other words, it should be noted that Single Splitting usually generates fewer substitute vertices than Group Splitting, especially when k is large. If we simply compare $|S_v^C|$ and $|S_v^M|$ and choose the strategy that introduces fewer substitute vertices to anonymize each selected vertex v , Single Splitting will be performed most of the time for anonymizing v at each iteration, which may result in generating more substitute vertices in total after many iterations.

To sidestep this trap, FlexSplit looks forward by identifying, from W , the subset X consisting of the vertices that cannot be anonymized by Adding Edge alone, and compares the numbers of substitute vertices $|S_v^C|$ and $\sum_{u \in X} |S_u^M|$, instead of $|S_v^C|$ and $|S_v^M|$, to choose the splitting strategy. Specifically, recall that the vertex set involved in procedure CREATION is W , and X is the subset of vertices in W such that X cannot be anonymized by Adding Edge alone in both CREATION and the subsequent MERGENCE. FlexSplit first examines every vertex of W and initializes X as the set of vertices that cannot be anonymized by Adding Edge alone in CREATION. Let u' denote the vertex of the largest degree among the vertices that cannot be anonymized in CREATION. X includes the vertices in W whose degrees are smaller than or equal to $d_{u'}$, since the CREATION process of these vertices will also involve u' . Afterward, FlexSplit removes some vertices from X such that every remaining vertex in X cannot be anonymized by Adding Edge alone in MERGENCE, neither. Let d_{\max} denote the largest degree of the existing

Algorithm 4. FlexSplit Input: $G(V, E, C), \{s_c\}$ and k Output: $\hat{G}(\hat{V}, \hat{E}, C)$ 1. $\hat{G} \leftarrow G$ 2. $v \leftarrow \text{SmallestDegV}(\{s_c(1)\})$ 3. While $v \neq \emptyset$ do 4. $\text{anon} = \text{AddE}(v, \hat{G}, k)$ 5. If $\text{anon} = \text{"No"}$ 6. $\text{FS}(v, \hat{G}, k)$ 7. $v \leftarrow \text{SmallestDegV}(\{s_c(1)\})$ 8. return \hat{G}	Function $\text{FS}(v, \hat{G}, k)$ 1. $W \leftarrow \text{K-SmallestDegV}(\{s_c(1)\}, k)$ 2. $S_v^C = 2 \times \{u d_u > d_v, u \in W\}$ 3. $X = \{u u \in W, \text{AddE}(u, \hat{G}, k) = \text{"No"}\}$ 4. $S^M = \sum_{u \in X} S_u^M$ 5. If $ W > 0$ and $ S_v^C < S^M $ 6. For $u \in S_v^C$ 7. $\hat{V} \leftarrow \hat{V} / \{u\} \cup \{u_1, u_2\}$ 8. $\hat{E} \leftarrow \hat{E} \cup \{(u_1, u_2)\}$ 9. $\text{RandDistrE}(u, u_1, u_2, d_v)$ 10. $\text{Update}(s_{c_u})$ 11. Else 12. $\hat{V} \leftarrow \hat{V} / \{v\} \cup S_v^M$ 13. $\text{RandDistrE2Groups}(v, S_v^M)$ 14. $\text{Update}(s_{c_v})$
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Fig. 11. The pseudo code of FlexSplit.

k -SDA groups. According to Formula (19), FlexSplit calculates the MERGENCE cost of every vertex u in X with respect to d_{\max} and removes u from X if $\text{Cost}_{MRG}(u, d_{\max}) > |C_u| - |N_u| - 1$, where C_u denotes the set of all vertices in the same community of u , and N_u represents all the neighbors of u . After that, FlexSplit compares the numbers of substitute vertices $|S_v^C|$ and $\sum_{u \in X} |S_u^M|$, and anonymizes v by Group Splitting if $|S_v^C| < \sum_{u \in X} |S_u^M|$ and by Single Splitting otherwise.

We now give the complete picture of Algorithm FlexSplit (Algorithm 4 in Figure 11). FlexSplit first sorts the not-yet-anonymized vertices in each community in increasing order of the degrees. Thereafter, at each iteration, the algorithm tries to anonymize a vertex v of the smallest degree d_v with procedures MERGENCE and CREATION as in MergeBySplit. If it is too restrictive to anonymize v by operations Adding Edge and edge-redirection, FlexSplit discovers the set W of k not-yet-anonymized vertices with the smallest degrees among all communities, and computes the minimal set of substitute vertices S_v^C required for Group Splitting. In addition, FlexSplit also discovers the subset X of W and computes $\sum_{u \in X} |S_u^M|$, where each vertex u in X cannot be anonymized by Adding Edge. If $|S_v^C| < \sum_{u \in X} |S_u^M|$, FlexSplit anonymizes v by Group Splitting. Otherwise, Single Splitting is performed. When all vertices belong to k -SDA groups, FlexSplit returns the anonymized graph \hat{G} .

E. Complexity Analysis

We will now show that the complexities of the four heuristic algorithms. Let n , m and l denote the numbers of vertices, edges and communities of the input graph G , and d_{\max} represents the largest vertex degree in G , $d_{\max} \leq n$.

We derive the space complexity of the four heuristics as follows. First, storing the whole input graph requires $O(n + m)$ space. For each of the four heuristics, maintaining a sorted list of not-yet-anonymized vertices in each community according to their degrees during the anonymization process takes $O(n)$ space due to each vertex being involved in only one community. In addition, since operations Adding Edge and Splitting Vertex create new edges and vertices during anonymization, to anonymize a vertex v , Adding Edge introduces at most d_{\max} new edges to protect v in a k -SDA group of the largest degree, while Splitting Vertex generates at most d_{\max} substitute vertices given $|E_v| \leq d_{\max}$. Consequently, the space complexity of the four heuristics is $O(m + nd_{\max})$.

After this, we can determine that the time complexity of each of the four heuristics is $O(kn^2 \log n)$ in the following manner. Firstly, EdgeConnect achieves the graph anonymization by processing the vertices one-by-one. For each selected vertex v to be anonymized, the number of redirectable edges is bounded by the number of new

edges incident to v , which is at most d_{\max} . Finding the minimal MERGENCE cost for v involves a test of all generated anonymous groups, which is bounded by $O(n/k)$. Computing the minimal CREATION cost is $O(l \log l)$ since the set U consists of k not-yet-anonymized vertices with the largest degrees from l communities. The adjustment of v 's degree and the update of vertices' order in a community can be achieved within $O(n \log n)$ time. As such, MERGENCE and CREATION take $O(n \log n)$ and $O(kn \log n)$ time, respectively. The time complexity of anonymizing v is then $O(d_{\max} + n/k + l \log l + n \log n + kn \log n)$. Consequently, since $l < n$, the graph anonymization is achieved in $O(kn^2 \log n)$ time.

Second, with the Vertex Splitting operation, CreateBySplit can also anonymize a selected vertex v by generating a new anonymous group of a smaller degree. The discovery of the k vertices with the largest degrees in different communities costs $O(l \log l)$ time. The splitting of v , including the re-distribution of the incident edges to the two substitute vertices is upper bounded by $O(d_{\max})$. The update of the vertex order is $O(n \log n)$. Therefore, the anonymization process of v takes $O(kn \log n)$ time. As an extension of EdgeConnect, the complexity of CreateBySplit is thus $O(kn^2 \log n)$.

Third, as with EdgeConnect, MergeBySplit achieves the anonymization of each selected vertex v in $O(kn \log n)$ time by operation Adding Edge alone. By Vertex Splitting operation, MergeBySplit anonymizes a selected vertex v in $O(n \log n)$ time because the minimal number of substitute vertices of v can be determined in $O(n)$, and the re-distribution of incident edges and the update of vertex order is upper bounded by $O(n \log n)$. Consequently, the whole graph anonymization is achieved in $O(kn^2 \log n)$ time.

Finally, by the operation Adding Edge alone, FlexSplit also anonymizes each selected vertex v in $O(kn \log n)$ as the MergeBySplit algorithm. By operation Splitting Vertex, FlexSplit computes S_v^C in $O(k)$ since there are k vertices in W . To find $X \subseteq W$, it takes $O(kn)$ time to check whether the vertices in W can be anonymized by CREATION and MERGENCE, because there are k vertices in W and for each vertex u , it scans $O(n)$ subsequence vertices in the same community of u to adjust the vertex degree of u . After finding X , FlexSplit calculates $\sum_{u \in X} |S_u^M|$ in $O(kn)$ as the minimal number of substitute vertices of every u in X can be determined in $O(n)$ according to Formula (21). Thereafter, FlexSplit chooses between Single Splitting and Group Splitting. Single Splitting takes $O(n \log n)$ time as in MergeBySplit. Given W , Group Splitting splits the vertices in W in $O(kn)$, and updates the vertex order in the corresponding communities in $O(kn \log n)$. Consequently, the overall anonymization time is bounded by $O(kn^2 \log n)$.

VI. EXPERIMENTS

In this paper, we conduct the experiments on both real and synthetic data sets. All the social graphs are pre-processed into simple graphs, i.e. unweighted undirected graphs without self-loops and multiple edges. The community identities of the vertices are either known as background knowledge or derived by community detection techniques⁴.

DBLP: From the DBLP data set, we select authors who have ever published their papers in the 20 top conferences, such as AAAI, SIGIR, and ICDM. The selected data set consists of 30,749 authors, and there are 157,058 edges representing the co-author relationships. As people usually publish their papers in the conferences related to their interests, we regard the conference where an author published most of his papers as the community of the author.

ca-CondMat: This data set shows the scientific collaborations between authors of papers in the Condense Matter category from January 1993 to April 2003. The graph is available at the SNAP (Stanford Network Analysis Package)

⁴METIS graph partition tool, <http://glaros.dtc.umn.edu/gkhome/views/metis>.

web page, and consists of 23,133 vertices and 186,936 edges. An edge is built between two authors if they had co-authored a paper in that period. Note that the community (conference) information for this data set is not provided on the website. We then derive the community identifications by the METIS graph partition tool, as people in the same social network group or cluster tend to interact more intensely, i.e., each group or cluster often forms a dense subgraph.

AirPort: This graph is built by considering the 500 busiest US airports⁵. In the graph, there are 500 vertices representing the airports and 2,980 edges between airports that have air travel connections. We also derive the community identities by the METIS graph partition tool.

LesMis [2]: LesMis is a small pseudo social network that simulates the relationships between 77 characters in Victor Hugo’s novel “Les Miserables.” Two characters are linked by an edge if they appear in the same chapter. There are 254 edges in total. The community information is derived by the METIS graph partition tool.

In addition, we also use R-MAT graph model [3] to generate synthetic data sets. R-MAT graph model takes four parameters a , b , c and d , where $a + b + c + d = 1$, to generate graphs that match power-law degree distributions and small-world properties, observed from many real social networks. In this paper, we use the default values of 0.45, 0.15, 0.15 and 0.25 for the four corresponding parameters, and generate graphs with the number of vertices ranging from 20,000 to 100,000 for testing the scalability of our algorithms.

A. Privacy Violation in Real Social Networks

In this paper, we show that the structural diversity is a real privacy protection issue against degree attacks in publishing social networks. The experiments are conducted on two real data sets, DBLP and ca-CondMat.

First, we study the problem of “whether many vertices of the same degree tend to gather in the same dense subgraph (community)”. Note that if an attacker finds all the vertices of a particular degree appearing in a certain subgraph (community), he can obtain the privacy information such as the neighborhood and connectivity properties of a target. Privacy will thus be violated. Figures 12(a) and 12(b) show the percentages of vertices violating k -structural diversity (k -SD), i.e., the anonymized group that does not spread over k communities, on the DBLP and ca-CondMat data sets, respectively. Consider the DBLP data set with k set as 10. In both the original graph and the 20-degree anonymized graph, there are at least 2552 (8.3%) vertices violating 20-SD. As the value of k increases, the number of vertices violating k -SD grows significantly. Figure 12 also shows that k -degree anonymity sometimes makes this problem more serious, because k -degree anonymity is designed to minimize the additional edges and does not aim to widely distribute the anonymous vertices of the same degree. This problem is even more serious for the ca-Condmat data set.

Next, we study the problem of “what the degrees are of the vertices violating k -SD”. In this experiment, we test the DBLP data set without anonymization and with 10-degree anonymization. Figure 13 shows the number of communities containing vertices of a particular degree. Consider the case of 10-SD. The data points with the community numbers smaller than 10 (below the horizontal dashed line) violate 10-SD. It is worth mentioning that the vertices violating 10-SD have large degrees. This means that active people are more likely to have higher risks of privacy violation.

In summary, the experimental results show that the structural diversity is a real privacy protection issue against degree attacks, especially for the vertices of large degrees. Moreover, graphs protected by k -degree anonymity may still violate k -SD as k -degree anonymity is not designed for the k -SDA problem.

⁵<http://www.db.cs.cmu.edu/db-site/Datasets/graphData/>

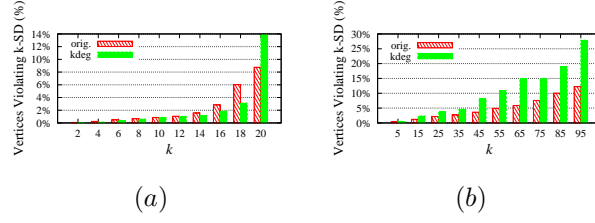


Fig. 12. Vertices violating k structural diversity on (a) DBLP and (b) ca-CondMat data sets.

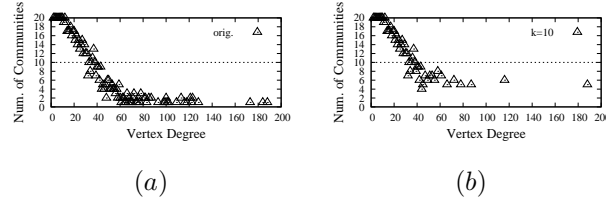


Fig. 13. Vertices with the same degree over the number of communities in (a) original DBLP and (b) DBLP protected by 10-degree anonymity.

B. Anonymization Performance

In this subsection, we evaluate the performance of the EdgeConnect (EC), CreateBySplit (CBS), MergeBySplit (MBS) and FlexSplit (FS) algorithms compared with the optimal solution, k -degree anonymity⁶, Algorithm Inverse EdgeConnect (IEC)⁷ and SplittingOnly (Sonly)⁸.

1) *Utility Studies*: We now study the utility of anonymized graphs from the clustering coefficients (CC), average shortest path lengths between vertex pairs (ASPL), betweenness centralities (BC), degree centralities (DC), eigenvector centrality correlations with respect to original graphs (EC-correlation), degree frequencies, the accuracy of community detection and connected query results on the DBLP and ca-CondMat data sets. In all of the above evaluations, we also compare our four heuristic algorithms with k -degree anonymity.

Clustering Coefficient (CC): Figures 14(a) and 15(a) show the clustering coefficients of the anonymized DBLP and ca-CondMat as a function of k , respectively. The CC values of the original DBLP and ca-CondMat are about 0.781 and 0.706. It should be first pointed out that EC can almost perfectly preserve the clustering coefficient of the original graphs on both data sets. This is because EC only adds new edges within communities for anonymization and thus preserves many of the community structures. The trade-off, however, is that on ca-CondMat, EC anonymizes the graph successfully only when k is (relatively) small. As an extension, CBS has a greater chance to achieve the anonymization when k becomes larger, as is evident from Figure 15(a), while the cost is a small decrease in the CC values due to the splitting of some vertices. To guarantee the anonymization, MBS does not connect the substitute vertices of each split vertex and, therefore, weakens the cohesiveness of the communities especially when k grows closer to the total number of communities in the graphs. Compared to MBS, FS has the CC values closer to the original value as FS reduces the numbers of substitute vertices in the objective function of k -SDA. Finally, note

⁶We implement the Priority algorithm in [17].

⁷EC increases the degree of a vertex v from d_v to \hat{d} by connecting v with not-yet-anonymized vertices of the largest degrees, while IEC connects v and the last $(\hat{d} - d_v)$ vertices in the sequence with the smallest degrees.

⁸Sonly extracts only the capabilities of the flexible splitting strategy in FlexSplit and does not apply operation Adding Edge.

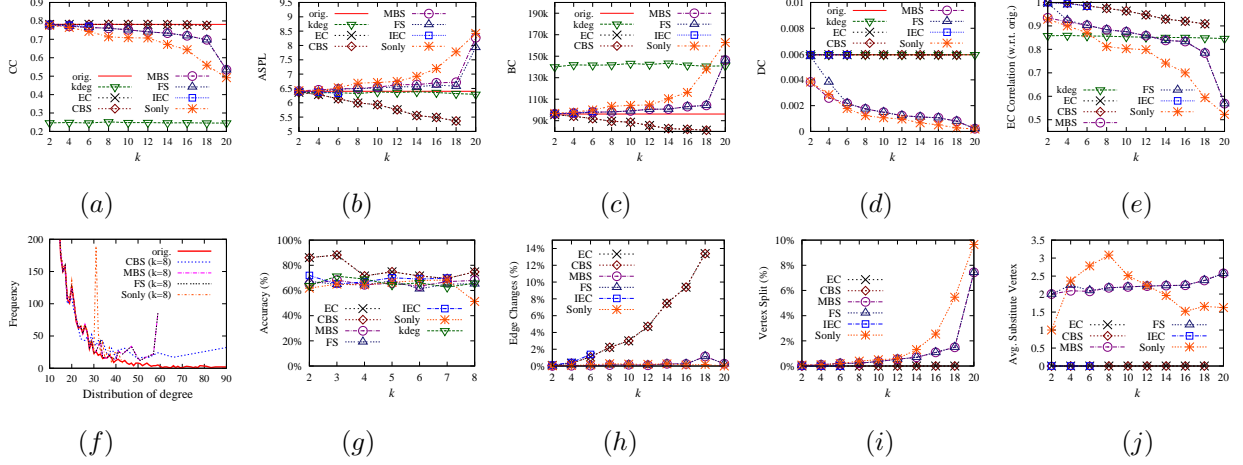


Fig. 14. Performance evaluations on DBLP.

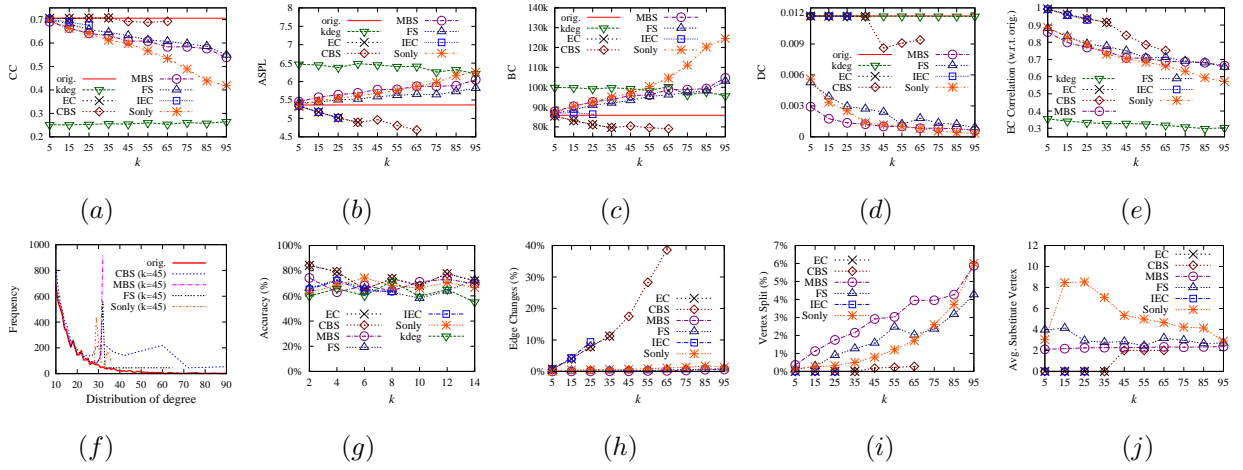


Fig. 15. Performance evaluations on ca-CondMat.

that our four algorithms all outperform k -degree anonymity in preserving the community structures.

Average Shortest Path Lengths (ASPL): Figures 14(b) and 15(b) show the average shortest path lengths between vertex pairs of the anonymized DBLP and ca-CondMat as a function of k , respectively. The ASPLs of the original DBLP and ca-CondMat are about 6.4 and 5.36. EC monotonically decreases the ASPL values as k grows because edges within communities are added for anonymization. CBS has better EC while the ASPL values neither monotonically decrease nor increase. This is because CBS not only introduces new edges within communities but also splits vertices and connects the substitute vertices of each split vertex. The cost of MBS for the guarantee of anonymization is the increase of the ASPL values, as the substitute vertices do not directly connect to each other. By reducing the numbers of substitute vertices, FS has the ASPL values closer to those of the original graph than those of MBS. Finally, k -degree anonymity performs quite well on the DBLP data set, as depicted in Figure 14(b), because k -degree anonymity provides less protection and requires only a few additional edges for anonymization. On ca-CondMat, however, the proposed methods all perform better than k -degree anonymity. The reason for this is that we consider the community structures and connect only the vertices in the neighborhoods.

Betweenness Centrality (BC): Figures 14(c) and 15(c) show the betweenness centralities, i.e., the frequency of a vertex on the shortest paths between pairs of vertices, of the anonymized DBLP and ca-CondMat as a function of k , respectively. For similar reasons mentioned in the ASPL measurement, here we observe that the BC values of the four proposed algorithms have similar trends (with respect to the original value) as the ASPL values, and the proposed methods preserve BC better than the k -degree method.

Degree Centrality (DC): For a graph, a large degree centrality, which is usually used to measure the influential vertices in social network analysis, indicates the existence of vertices with relatively large degrees. The DC comparisons of the anonymized DBLP and ca-CondMat obtained by the proposed four methods and k -degree anonymization are presented in Figures 14(d) and 15(d). The original DC values of DBLP and ca-CondMat are 0.00594 and 0.011713, respectively. On both data sets, EC, CBS and k -degree anonymization perform perfectly. This indicates that the three methods can effectively preserve the strong leaders and influential vertices in the social networks. In contrast, MBS and FS sacrifice the precision of DC in order to guarantee the anonymization. In other words, anonymizing the vertices in increasing order of the degrees tends to make the vertices have similar small degrees by the Splitting Vertex operation. Nonetheless, FS still outperforms MBS for many cases.

Eigenvector Centrality Correlation (EC-Correlation): Eigenvector centrality, another common measurement of influential vertices in the social networks, estimates the influence of a vertex based on the influence of the vertices to which the directed neighbors connect. Figures 14(e) and 15(e) show the EC-correlations of the anonymized DBLP and ca-CondMat (with respect to the original graph). It can be seen that EC has the EC-correlations above 0.9 and achieves the best preservation of influential vertices. The other three methods have the EC-correlations above 0.7 for most cases. Differing from the results in the DC measurement, here the four proposed methods all outperform the k -degree anonymity, as a result of the structural information being taken into account in the anonymization.

Degree Frequency (DF): Figures 14(f) and 15(f) compare the degree distributions of anonymized DBLP and ca-CondMat with the original graph, respectively. Although the distributions in small degrees are similar to the original distributions, due to the different splitting strategies, CBS performs better than FS, and FS outperforms MBS in preserving the distributions in large degrees.

Community Detection: Figures 14(g), 15(g), 16(g) and 17(g) present the accuracy of community detection on the anonymized graphs with respect to the original DBLP, ca-CondMat, AirPort, and LesMis graphs, respectively. The results indicate that all heuristics achieve comparable performance to the optimal solution (in Figures 16(g) and 17(g)) and k -degree anonymity (in Figures 14(g) and 15(g)), while the heuristics are able to provide stronger privacy protection than k -degree anonymity. EC always outperforms k -degree anonymity on maintaining the community structures, demonstrating that adding edges within a community can preserve semantic meanings. More interestingly, EC slightly outperforms the optimal solution on AirPort in Figure 16(g). This may indicate that, in addition to the number of new edges involved, the selection of the vertices to be connected and the vertices to be split is also crucial for preserving communities in anonymized graphs. In Figure 15(g), the heuristics still outperform k -degree anonymity in most cases when Splitting Vertex is incorporated. When a vertex can be split, the accuracy of all heuristics is not lowered as k increases.

Connected Query: In addition to the measurements above, it is worth specifically mentioning that FS also outperforms MBS in the capability of answering queries for pairs of vertices. For the ca-CondMat data set, about 0.01% to 0.03% (among two hundred million) pairs of connected vertices will be disconnected in the anonymization process of MBS when k varies from 5 to 95, while none is disconnected by FS. This is because MBS does not directly link the substitute vertices, and FS is able to reduce the numbers of substitute vertices with Group Splitting,

which connects substitute vertices.

In light of the above evaluations, CreateBySplit outperforms EdgeConnect in guaranteeing the anonymization, while FlexSplit can preserve the utility of a social network better than MergeBySplit. Therefore, we recommend CreateBySplit for the cases of (relatively) small k and FlexSplit for more challenging cases.

2) *Vertex Change and Edge Change*: We now report on the three findings of (a) the percentage of the number of new edges to the original number of edges, (b) the percentage of the number of vertices being split to the original number of vertices, and (c) the average number of substitute vertices for a vertex split, of the anonymized graphs as functions of k .

For DBLP, first, Figure 14(g) shows that when the value of k is smaller than 50% of the number of communities, EC and CBS achieve the k -structural diversity by adding less than 5% new edges in the anonymized graph. Second, the results in Figures 14(g) and 14(h) show that when k becomes larger, CBS tends to add new edges rather than to split the vertices, while MBS and FS are prone to splitting vertices rather than to adding new edges. This difference in tendency is caused by the reverse order of creating the anonymous groups of particular degrees, as we have more chances to add new edges for the anonymization when the vertices are anonymized in the decreasing order of the degrees. Third, Figures 14(h) and 14(i) show that MBS and FS use a similar number of substitute vertices for a similar percentage of vertices that have been split. On DBLP, MBS and FS thus achieve comparable performances for most k .

For ca-CondMat, the four algorithms have similar trends of adding edges and splitting vertices as those for DBLP. However, Figure 15(h) shows that FS splits 1% to 2% fewer vertices than MBS under the same guarantee of anonymization. Moreover, in Figure 15(i), FS uses more substitute vertices on average for a vertex that has been split. This indicates that a vertex being split is likely to be a vertex with a large degree. The results also conform to those described in Figure 15(f).

3) *Comparison with Optimal Solution*: Here we compare the heuristics with the Integer Programming method, while the optimal solution is obtained with the proposed formulation using CPLEX⁹. Note that finding the optimal solutions is very computationally intensive (e.g., for the AirPort dataset consisting of 500 vertices and 2,980 edges, it takes at least one hour for the simplest instance and at least one day for more challenging instances). The optimal solutions are not able to be returned within a reasonable time frame for large social networks, such as DBLP and ca-CondMat. Therefore, the solutions from the proposed algorithms are compared with the optimal solutions of AirPort and LesMis, with k from 2 to 4.

Figures 16(a)-16(g) and 17(a)-17(g) respectively present the data utility of the anonymized graphs of AirPort and LesMis in terms of the clustering coefficients (CC), average shortest path lengths between vertex pairs (ASPL), betweenness centralities (BC), degree centralities (DC), eigenvector centrality correlations with respect to the original graphs (EC-correlation), degree frequency distributions, and community detection accuracy. It can be observed that EC is close to the optimal solution in all evaluations but fails to anonymize LesMis when k is set as 3 and 4, because EC applies only Adding Edge with edge-redirection to reduce the number of new edges. Moreover, for AirPort with all k and LesMis with $k = 2$, CBS is very close to the optimal solution because CBS applies Splitting Vertex only when Adding Edge alone cannot achieve the anonymization. In contrast, MBS and FS deviate from the optimal solutions, because these heuristics apply Splitting Vertex and begin the anonymization from vertices of small degrees in order to guarantee the success of anonymization for any instance. Here the results are consistent

⁹<http://www-01.ibm.com/software/integration/optimization/cplex/>.

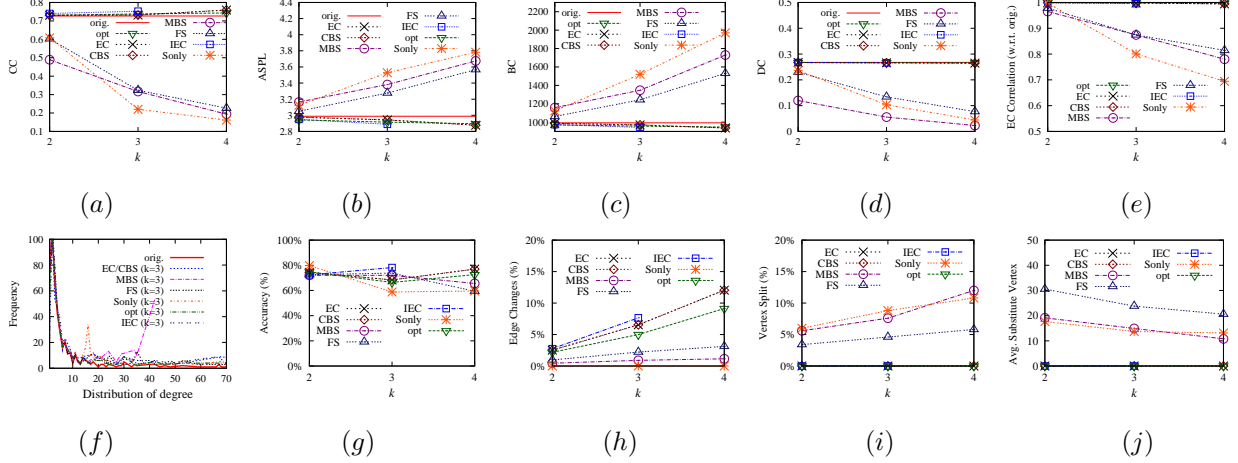


Fig. 16. Performance evaluations on AirPort.

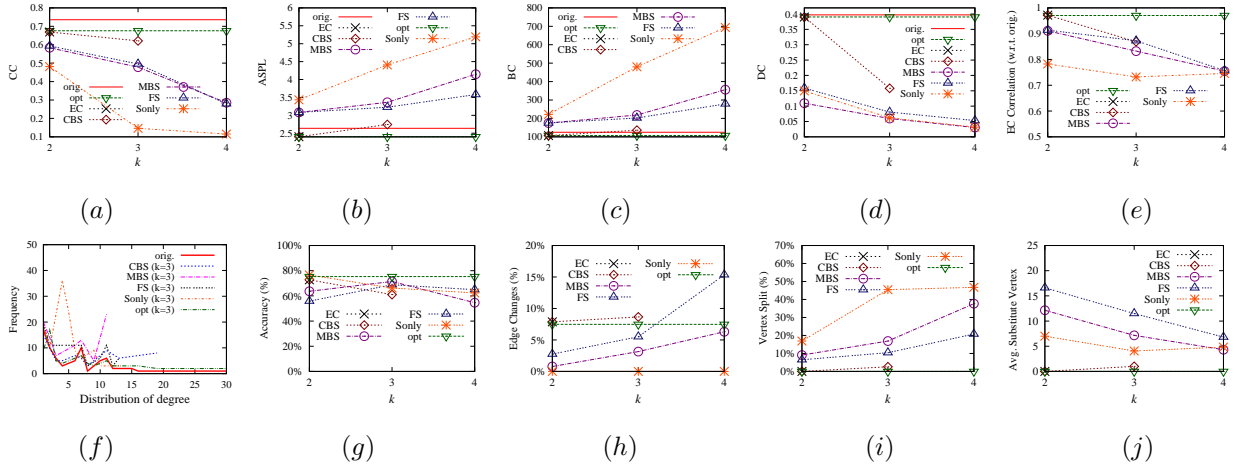


Fig. 17. Performance evaluations on LesMis.

with those obtained on the large social networks of DBLP and ca-CondMat.

4) *Comparison of EC with IEC and Sonly*: We compare EdgeConnect (EC) with Inverse EdgeConnect (IEC) and SplittingOnly (Sonly) to explore the intuition beyond the design of Algorithm EdgeConnect and the extensions.

First, EC is compared with IEC on DBLP in Figure 14, ca-CondMat in Figure 15, and AirPort in Figure 16¹⁰. Indeed, the results indicate that IEC outperforms EC in terms of the average shortest path length (ASPL) and betweenness centrality (BC) (for the cases IEC returns a feasible solution, i.e., when $k = 2, 4, 6$ in Figure 14, $k = 5, 15, 25$ in Figure 15, and $k = 2, 3$ in Figure 16), because EC takes as its priority choosing the vertices with large degrees. As those vertices are more inclined to participate in the shortest paths of any two vertices, EC reduces ASPL and BC in the anonymized graph. Therefore, IEC is suitable for the application scenarios in which the characteristics of shortest paths are the major properties required to be preserved during anonymization.

On the other hand, the clustering coefficient (CC) of the anonymized graph from EC is closer to the CC value of

¹⁰The comparison is not performed on LesMis, because IEC is not able to return feasible solutions on LesMis.

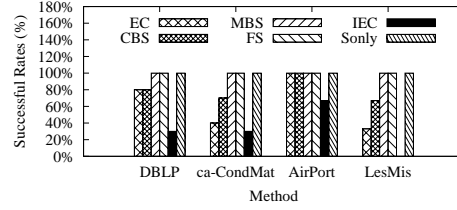


Fig. 18. Successful rates of heuristics.

the original graph, and EC is able to achieve better accuracy in community detection for most cases, as demonstrated in Figures 14(g), 15(g) and 16(g). It is noteworthy that EC incurs fewer new edges than IEC in Figures 14(h), 15(h) and 16(h), and generates a higher successful rate in anonymization, as seen in Figure 18. The reason is that a new edge involved in the edge-redirection operation of EC has more opportunities to be reused in the anonymization of other vertices considered later, as EC adds new edges between anonymizing vertex v and vertices of large degrees prior to being anonymized. EC is thus more capable of handling the input instances that are difficult to be anonymized by introducing only new edges.

The comparisons of EC and Sonly being conducted on DBLP are presented in Figure 14, on ca-CondMat in Figure 15, on AirPort in Figure 16, and on LesMis in Figure 17. Whereas Sonly preserves ASPL and BC better than EC in DBLP and ca-CondMat when k is small, for AirPort and LesMis, EC significantly outperforms Sonly. This is because the degree differences between the vertices of the largest degree and the other vertices are more significant in DBLP and ca-CondMat datasets, and EC is prone to connecting the vertices of large degrees to the others, which thereby significantly shortens many of the shortest paths among the vertices. In contrast, for a small k , Sonly only needs to split a few vertices of the largest degree to fulfill k -structural diversity. This results in the lengths of the shortest paths increasing slightly. For the other parameters, such as CC, DC, EC-correlation, degree frequency distribution, and community detection in most cases, the findings indicate that EC outperforms Sonly because Splitting Vertex not only decreases the vertex degrees but also tends to change the community structure. Nevertheless, as demonstrated in Figure 18, operation Splitting Vertex is necessary in our algorithm design for the social graphs that are difficult to anonymize.

5) *Anonymization Successful Rate:* Here we compare the successful rates of the heuristics on DBLP, ca-CondMat, AirPort and LesMis datasets. The results in Figure 18 show that MBS, FS, and Sonly are guaranteed to anonymize any social graph thanks to operation Splitting Vertex. Those approaches begin the anonymization process from the vertices of small degrees to generate anonymous groups. For this reason, the anonymous group of degree 1 will be generated first, and Splitting Vertex can thus partition a vertex of any degree into multiple substitute vertices of degree 1, even in the most challenging case in anonymization. In contrast, EC, CBS and IEC may not always be able to anonymize a graph. The vertices of large degrees usually appear in the same community (e.g., a clique), and not every community contains sufficient vertices of small degrees for anonymization. Therefore, when anonymous groups of large degrees are generated prior to those of small degrees, the added new edges within a community may significantly increase the degrees of the not-yet-anonymized vertices originally with small degrees, such that it becomes difficult afterward to anonymize other vertices with small degrees. Compared with the other schemes, the successful rate of IEC is smaller because IEC takes priority to add new edges connecting to the vertices with small degrees, thereby further increasing the difficulty to anonymize those vertices.

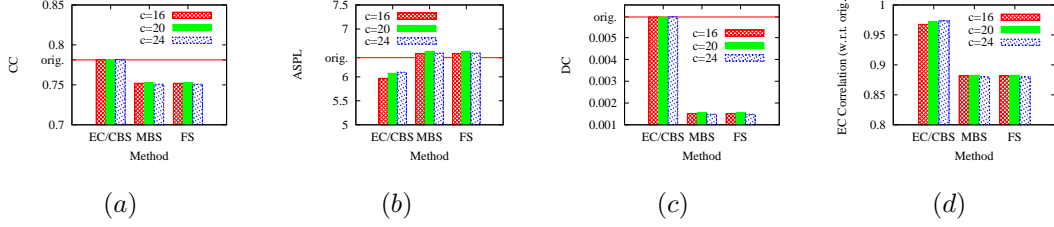


Fig. 19. Sensitivity studies given different numbers of communities.

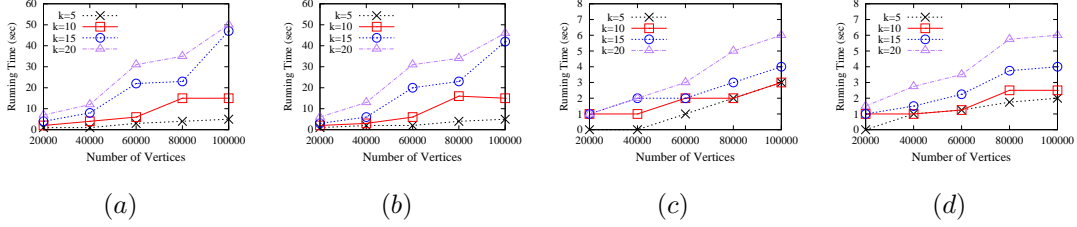


Fig. 20. Scalability of Algorithm (a) EdgeConnect, (b) CreateBySplit, (c) MergeBySplit and (d) FlexSplit.

6) *Sensitivity*: Consider the case that the communities are not given explicitly and, instead, community detection techniques are used to obtain the community information for structural diversity. We then explore the sensitivities of Algorithm EC, CBS, MBS and FS to the number of communities obtained by community detection techniques. In these experiments, we conduct the analysis on DBLP as we know the ground truth of the communities in the data set. Figure 19 presents the CC, ASPL, DC and EC-correlation, respectively, for $|C| = 16, 20$ and 24 . Specifically, EC and CBS show a little bit of sensitivity on the evaluation of ASPL because these two algorithms perform more Adding Edge operations than Splitting Vertex, and as such will connect distant vertices in a large community, when the number of detected communities is small. Nonetheless, the influence of the number of communities detected is quite small for the four algorithms.

7) *Scalability*: We demonstrate the execution efficiency of our algorithms on synthetic data sets with the number of vertices ranging from 20,000 to 100,000. The experimental environment is a Debian GNU/Linux server with double dual-core 2.4 GHz Opteron processors and 4GB RAM. Although Figure 20 shows that the execution time grows as the value of k increases, the proposed algorithms can anonymize the graph to satisfy k -structural diversity in a linear-time scale of the graph size.

VII. CONCLUSION

In this paper, we addressed a new privacy issue, community identification, and formulated the k -Structural Diversity Anonymization (k -SDA) problem to protect the community identity of each individual in published social networks. For k -SDA, we proposed an Integer Programming formulation to find optimal solutions, and also devised scalable heuristics. The experiments on real data sets demonstrated that our approaches can ensure the k -structural diversity and preserve much of the characteristics of the original social networks.

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REFERENCES

- [1] L. Backstrom, C. Dwork, and J. M. Kleinberg, "Wherefore art thou r3579x?: Anonymized social networks, hidden patterns, and structural steganography," WWW, 2007.
- [2] A. Bettinelli, P. Hansen, and L. Liberti, "Algorithm for parametric community detection in networks," Physical Review E, 2012.
- [3] D. Chakrabarti, Y. Zhan, and C. Faloutsos, "R-mat: A recursive model for graph mining," SDM, 2004.
- [4] S. Chawla, C. Dwork, F. McSherry, A. Smith, and H. Wee, "Toward privacy in public databases," TCC, 2005.
- [5] J. Cheng, A. W. Fu, and J. Liu, "K-isomorphism: privacy preserving network publication against structural attacks," SIGMOD, 2010.
- [6] S. Chester and G. Srivastava, "Social Network Privacy for Attribute Disclosure Attacks," ASONAM, 2011.
- [7] A. Clauset, M. E. J. Newman, and C. Moore, "Finding community structure in very large networks," Physical Review E., 70(6), 2004.
- [8] C. Dwork, "Differential privacy: A survey of results," TAMC, 2008.
- [9] B. C. M. Fung, K. Wang, R. Chen, and P. S. Yu, "Privacy-preserving data publishing: A survey of recent developments," ACM Comput. Surv., 42(4), 2010.
- [10] A. Gupta, A. Roth, and J. Ullman, "Iterative constructions and private data release," Manuscript, 2011.
- [11] M. Hay, C. Li, G. Miklau, and D. Jensen, "Accurate estimation of the degree distribution of private networks," ICDM, 2009.
- [12] M. Hay, G. Miklau, D. Jensen, D. F. Towsley, and P. Weis, "Resisting structural re-identification in anonymized social networks," VLDB, 2008.
- [13] V. Karwa, S. Raskhodnikova, A. Smith, and G. Yaroslavtsev, "Private analysis of graph structure," VLDB, 4(11), 2011.
- [14] J. Leskovec, K. J. Lang, A. Dasgupta, and M. W. Mahoney, "Statistical properties of community structure in large social and information networks," WWW, 2008.
- [15] N. Li, T. Li, and S. Venkatasubramanian, "t-Closeness: privacy beyond k-Anonymity and l-Diversity," ICDE, 2007.
- [16] J. Li, Y. Tao, and X. Xiao, "Preservation of proximity privacy in publishing numerical sensitive data," SIGMOD, 2008.
- [17] K. Liu and E. Terzi, "Towards identity anonymization on graphs," SIGMOD, 2008.
- [18] A. Machanavajjhala, D. Kifer, J. Gehrke, and M. Venkatasubramanian, "L-diversity: privacy beyond k-anonymity," TKDD, 1(1), 2007.
- [19] M. E. Nergiz, M. Atzori, and C. Clifton, "Hiding the presence of individuals from shared databases," SIGMOD, 2007.
- [20] M. E. Nergiz, C. Clifton, and A. E. Nergiz, "Multirelational k-Anonymity," IEEE TKDE, 21(8), 2009.
- [21] P. Samarati and L. Sweeney, "Generalizing data to provide anonymity when disclosing information," PODS, 1998.
- [22] L. Sweeney, "k-anonymity: A model for protecting privacy," IJUFKS, 10(5), 2002.
- [23] C.-H. Tai, P.-J. Tseng, P. S. Yu and, M.-S. Chen, "Identity Protection in Sequential Releases of Dynamic Social Networks," ICDM, 2011.
- [24] X. Wu, X. Ying, K. Liu, and L. Chen, *A Survey of Privacy- Preservation of Graphs and Social Networks*, Springer US, 2010.
- [25] X. Ying and X. Wu, "Randomizing social networks: a spectrum preserving approach," SDM, 2008.
- [26] L. Zhang and W. Zhang, "Edge anonymity in social network graphs," CSE, 2009.
- [27] E. Zheleva and L. Getoor, "Preserving the privacy of sensitive relationships in graph data," PinKDD, 2007.
- [28] B. Zhou and J. Pei, "Preserving privacy in social networks against neighborhood attacks," ICDE, 2008.
- [29] B. Zhou, J. Pei, and W. Luk, "A brief survey on anonymization techniques for privacy preserving publishing of social network data," SIGKDD Explorations, 10(2), 2008.
- [30] L. Zou, L. Chen, and M. T. Özsu, "K-automorphism: a general framework for privacy preserving network publication," VLDB, 2009.