dK-Microaggregation: Anonymizing Graphs with Differential Privacy Guarantees

Masooma Iftikhar
Qing Wang
Yu Lin

Research School of Computer Science
The Australian National University

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Introduction

Motivation

- Graph data analysis has been widely performed in real-life applications. For instance,
  - online social networks are explored to analyze human social relationships;
  - election networks are studied to discover different opinions in a community.
- However, such networks often contain sensitive or personally identifiable information, such as social contacts, personal opinions and private communication records.
- Publishing graph data can thus pose a *privacy threat*.

Graph Data Release Process

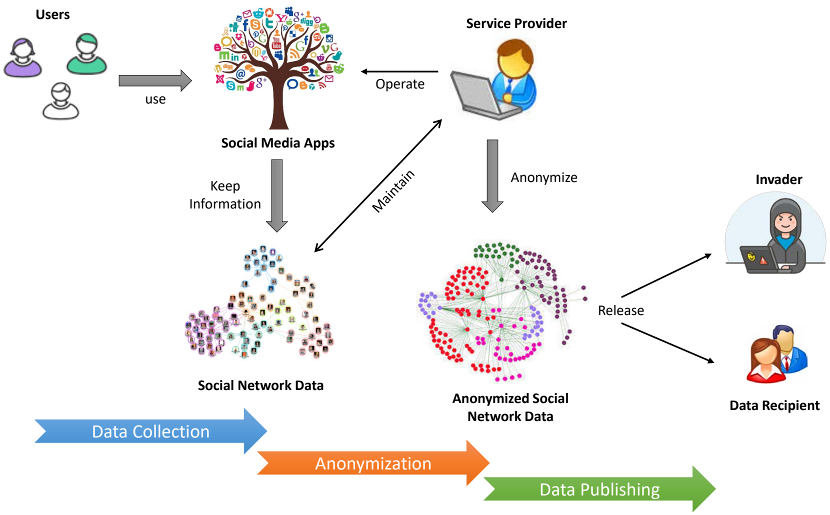

Figure 1: Graph Data Release Process (e.g. online social network)

- **Aim:** To generate anonymized graphs with ε-differential privacy guarantee for improving utility of anonymized graphs being published.

- **Key Challenges:**
  - To preserve topological structures of an original graph at different levels of granularity.
  - To enhance utility of graph data by reducing the magnitude of noise needed to achieve ε-differential privacy through adding controlled perturbation to its edges (i.e., edge privacy).

- **Key Observation:** We observe that the dK-graph model [5] for analyzing network topologies can serve as a good basis for generating structure-preserving anonymized graphs.

Problem Formulation

- The dK-graph model [5] provides a systematic way of extracting subgraph degree distributions from a given graph, i.e. *dK-distributions*.

DK-DISTRIBUTION

A *dK-distribution* $dK(G)$ over a graph G is the probability distribution on the connected subgraphs of size d in G.

- Specifically, 1K-distribution captures a degree distribution, and 2K-distribution captures a joint degree distribution. When $d = |V|$, dK-distribution specifies the entire graph.
- A dK-distribution is extracted from a graph, by using *dK function* (s.t. $\gamma^{dK}(G) = dK(G)$).

- We define *dK-graph* as a graph that can be constructed through reproducing the corresponding dK-distribution.

DK-GRAPH

A *dK-graph* over $dK(G)$ is a graph in which connected subgraphs of size d satisfy the probability distribution in $dK(G)$.

- Conceptually, a dK-graph is considered as an anonymized version of an original graph G that retains certain topological properties of G at a chosen level of granularity.
- We aim to generate dK-graphs with ε-differential privacy guarantee for preserving privacy of structural information between nodes of a graph (edge privacy).

- Two graphs $G = (V, E)$ and $G' = (V', E')$ are said to be neighboring graphs, denoted as $G \sim G'$, iff $V = V'$, $E \subset E'$ and $|E| + 1 = |E'|$.

Differentially private dK-graphs

A randomized mechanism $\mathcal{K}$ provides ε-differentially private dK-graphs, if for each pair of neighboring graphs $G \sim G'$ and all possible outputs $\mathcal{G} \subseteq range(\mathcal{K})$, the following holds

$$Pr[\mathcal{K}(G) \in \mathcal{G}] \leq e^{\varepsilon} \times Pr[\mathcal{K}(G') \in \mathcal{G}]. \tag{1}$$

- $\mathcal{G}$ is a family of dK-graphs, and $\varepsilon > 0$ is the differential privacy parameter. Smaller values of ε provide stronger privacy guarantees.

dK-Microaggregation Framework

- We incorporate microaggregation techniques [1] into the dK-graph model [5] to reduce the amount of random noise without compromising ε-differential privacy.
- Generally, dK-microaggregation works in the following steps:

  (1) Extracts a dK-distribution from each *neighboring* graph.

  (2) Microaggregates the dK-distribution and perturbs the microaggregated dK-distribution to generate ε-differentially private dK-distribution.

  (3) Generates ε-differentially private dK-graphs using a dK-graph generator [4, 5].

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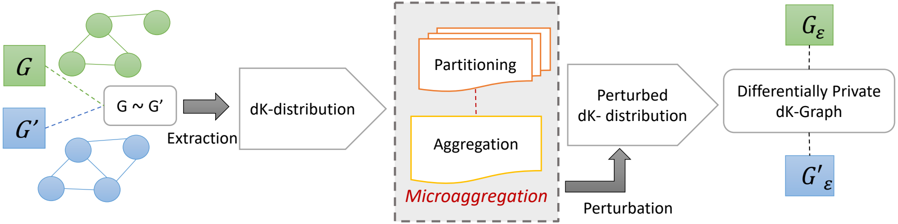


Figure 2: A high-level overview of the proposed framework (dK-Microaggregation).

Proposed Algorithm

- A microaggregation algorithm for dK-distributions $\mathcal{M} = (\mathcal{C}, \mathcal{A})$ consists of two phases:
  (a) *Partition* - similar tuples in a dK-distribution are partitioned into the same cluster;
  (b) *Aggregation* - the frequency values of tuples in the same cluster are aggregated.

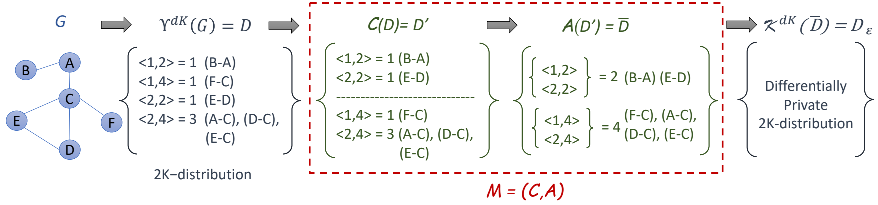


Figure 3: An illustration of our proposed algorithms.

- **MDAV-dK algorithm:** We use a simple microaggregation heuristic, called *Maximum Distance to Average Vector* (MDAV) [1], which can generate clusters of the same size k, except one cluster of size between k and $2k - 1$. Then unlike MDAV, we aggregate frequency values of tuples in each cluster.

  However, MDAV-dK would suffer significant information loss when evenly partitioning a highly skewed dK- distribution into clusters of the same size.

- **MPDC-dK algorithm:** To address this issue, we propose *Maximum Pairwise Distance Constraint* (MPDC-dK), which aims to partition a dK-distribution into a minimum number of clusters in which every pair of tuples from the same cluster satisfies a distance constraint τ.

Experiments and Results

- Three network datasets:
  (1) *polbooks* contains 105 nodes and 441 edges.
  (2) *ca-GrQc* contains 5,242 nodes and 14,496 edges.
  (3) *ca-HepTh* contains 9,877 nodes and 25,998 edges.

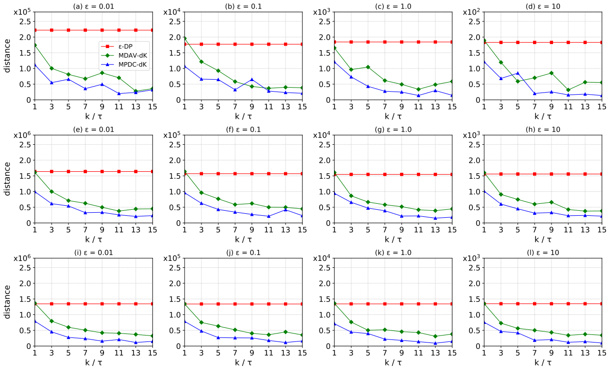
- Two measures:
  - Euclidean distance [6] measures network structural error between original and perturbed dK-distributions.
  - sum of absolute error [2] measures within-cluster homogeneity of clustering algorithms, defined as:

    $$SAE = \sum_{i=1}^{N} \sum_{\forall x_j \in c_i} |x_j - \mu_i|,$$

    where c_i is the set of tuples in cluster i and μ_i is the mean of cluster i.

Experiments I

- To verify the utility, we compare the structural error between original and perturbed dK-distributions generated by MDAV-dK, MPDC-dK and the baseline method ε-DP. Our proposed algorithms MDAV-dK and MPDC-dK lead to less structural error for every value of ε as compared to ε-DP.



- We compare the quality of clusters, in terms of within-cluster homogeneity, generated by MDAV-dK and MPDC-dK. MPDC-dK outperforms MDAV-dK by producing clusters with less SAE over all three datasets.

Table 1. Performance of MDAV-dK under different values of k.

Datasets	Measures	k=1	k=3	k=5	k=7	k=9	k=11	k=13	k=15
polbooks	SAE	0	144.6	184.67	**224.84**	273.6	292.21	299.15	334.25
	# Clusters	161	53	32	**23**	17	14	12	10
ca-GrQc	SAE	0	1073.3	1476	**1810.5**	2166.8	2313.7	2555.5	2730
	# Clusters	1233	411	246	**176**	137	112	94	82
ca-HepTh	SAE	0	968.72	1304	1599.8	**1893.9**	2063	2232.9	2389.7
	# Clusterss	1295	431	259	185	**143**	117	99	86

Table 2. Performance of MPDC-dK under different values of τ.

Datasets	Measures	τ=1	τ=3	τ=5	τ=7	τ=9	τ=11	τ=13	τ=15
polbooks	SAE	90.72	**192.15**	328.96	424.2	563.73	617.63	723.06	795.77
	# Clusters	68	**25**	13	8	7	5	3	3
ca-GrQc	SAE	725.38	**1732.1**	2630.6	3470.6	4262.9	5176.7	6170.1	7037.7
	# Clusters	483	**178**	98	61	42	35	26	20
ca-HepTh	SAE	841.87	**1761.8**	2773.3	3721.4	4719.2	5623.8	6402.6	7034.2
	# Clusters	412	**140**	73	37	34	24	19	15

Conclusion and Future work

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- **Conclusion:**
  - We present a novel framework, called *dK-microaggregation*, that can leverage a series of network topology properties to generate ε-differentially private anonymized graphs.
  - We propose a distance constrained algorithm for approximating dK-distributions of a graph via microaggregation within the proposed framework, which can reduce the amount of noise being added into ε-differentially private anonymized graphs.
  - The effectiveness of our proposed framework has been empirically verified over three real-world network.
- **Future work:** To this work will consider zero knowledge privacy (ZKP) [3], to release statistics about social groups in a network while protecting privacy of individuals.

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Thanks for your attention!

Any **Questions**