Model Inversion Attack with Least Information and an In-depth Analysis of its Disparate Vulnerability

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***Abstract*—In this paper, we study *model inversion attribute inference* (MIAI), a machine learning (ML) privacy attack that aims to infer sensitive information about the training data given access to the target ML model. We design a novel black-box MIAI attack that assumes the least adversary knowledge/capabilities to date while still performing similar to the state-of-the-art attacks. Further, we extensively analyze the *disparate vulnerability* property of our proposed MIAI attack, i.e., elevated vulnerabilities of specific groups in the training dataset (grouped by gender, race, etc.) to model inversion attacks. First, we investigate existing ML privacy defense techniques– (1) *mutual information regularization*, and (2) *fairness constraints*, and show that none of these techniques can mitigate MIAI disparity. Second, we empirically identify possible disparity factors and discuss potential ways to mitigate disparity in MIAI attacks. Finally, we demonstrate our findings by extensively evaluating our attack in estimating binary and multi-class sensitive attributes on three different target models trained on three real datasets.**

***Index Terms*—model inversion attribute inference, privacy, disparate vulnerability**

I. Introduction

In recent years, machine learning (ML) has become very popular because of its wide range of applications in real-life, including predictive modeling [1], speech and speaker recognition [2], medical diagnosis [3], and image analysis [4], [5]. These increasing applications have introduced new ways for attack vectors to perform privacy attacks [6]. Among the different existing privacy attacks against ML models, e.g., membership inference [7], model extraction [8], and property inference [6], *model inversion attribute inference attack* (MIAI) is comparatively under-explored and more challenging due to its inherent characteristics [9]. Although some research has focused on attribute inference in different contexts, e.g., in social media [10], these studies do not specifically focus on ML privacy or model inversion vulnerability. In an MIAI attack, the adversary leverages its access to the target model to infer sensitive attributes in the training instances of the target ML model [1], [11]. For instance, a social survey (e.g., National Longitudinal Surveys) dataset to model how individuals rate their lives may also include their responses to questions on sensitive topics, such as drug usage behavior, sexual activities, etc. If an attacker knows background information of a target individual and can also infer some sensitive features of that target individual by querying the ML model that predicts life ratings, a significant privacy violation could occur. In-depth analysis of the vulnerabilities of model inversion attacks in the domain of tabular datasets [1], [3], [11] is even less studied.

State-of-the-art MIAI attacks in the literature consider strong adversarial capabilities [3], [11], e.g., access to the target model's confusion matrix, marginal priors, knowledge of all training instances' non-sensitive attribute values, possible values of sensitive attribute, ground truth labels of all training data instances, etc. These capabilities are not only stronger assumptions but also might not always prevail in the real world. For example, an adversary might not have access to the ground truth labels (e.g., unlabeled data in the unsupervised learning scenario like anomaly detection), might not know all non-sensitive attribute values of individual training instances, or even might not know the training data confusion matrix. These limitations are crucial challenges to existing MIAI attacks in the literature and restrict the applicability of these attacks to a more practical scenario. Therefore, in our work, we explore the following research question: *How can we design an effective MIAI attack with the least adversarial capabilities in a more realistic scenario?* We define *least* capabilities as being able to only (i) query the black-box target model and obtain only the prediction labels (not confidence scores), and (ii) have knowledge of possible values of sensitive and non-sensitive attributes (however, no information about individual training instances). A real-life scenario of our attack can be the Amazon Fraud Detector API [12] that predicts whether an input event is a fraud. In this scenario (also for other MLasS APIs), an adversary with only these least capabilities can query the model via API with unlabeled (real or synthetic) data and perform MIAI to infer sensitive attributes, e.g., a valid user's demographic or personal information.

To investigate our research question, we design a novel black-box MIAI attack with the *least* capabilities mentioned above. Our attack, dubbed as the synthetic data-based MIAI attack (SDMIA), makes the same number of queries to the target model compared to the state-of-the-art MIAI attacks [3], [11]. We query the target model to generate synthetic data, which we then use to train the attack model. We further consider limiting the number of queries in our attack to half of the state-of-the-art (denoted as the SDMIA*) attacks and demonstrate that our proposed synthetic data-based attack still matches the state-of-the-art MIAI attacks in terms of effectiveness. Our proposed SDMIA renders the following benefits over the existing attacks– (i) novel back-box attack with the least capabilities, (ii) query-efficient attack (SDMIA* requires 50% less query), (iii) more realistic and broad applicability, (iv) performs similarly in most cases compared to existing attacks, and (v) achieves more stable attack performances than state-of-the-art MIAI attacks varying target models.

Dataset characteristics and algorithmic bias in the training process may contribute to having unfair outcomes in ML

models [13], [14]. These unfair outcomes might also impact different training instances' privacy vulnerability differently, commonly expressed as *disparate vulnerability* property in privacy attacks [11], [15]. This notion captures serious privacy concerns since there could be scenarios where MIAI attacks' average accuracy measured over the entire training dataset is not significant, but the attacks are highly effective on a particular set of training instances or subgroups, e.g., instances grouped by race, gender, ethnicity, etc. Although the existing work on ML privacy has explored this *disparate vulnerability* issue, it has only been studied in-depth in the context of membership inference attacks [15]. Since the MIAI attack is a more consequential and challenging privacy attack, in our work, we perform an extensive analysis of *disparate vulnerability* in the MIAI context.

We extend our study to explore potential disparity contributing properties of training dataset/ target model (e.g., correlation, marginal priors, etc.) termed as *'factors'* in this paper. First, we investigate two popular ML privacy defense techniques against the *disparate vulnerability* property of the MIAI attack– *mutual information regularization* [16] and *fairness constraints* [15]. We analyze the impacts of these techniques on (i) individual subgroup vulnerability, (ii) disparity among subgroup vulnerabilities, and (iii) target model utility. Our experiments show that although these techniques do not significantly affect target model utility, they fail to perform consistently in reducing disparity and subgroup vulnerability. Second, we expand our MIAI disparity analysis and empirically identify possible factors for the *disparity* in MIAI. We consider two types of disparity factors– factors dependent on the target model (e.g., overfitting) and factors largely dependent on training data distribution (e.g., skewness, kurtosis, etc.). We further explore how these factors contribute towards *disparity* in MIAI, i.e., their normalized weights. Finally, based on our findings, we discuss potential ways to design effective defense for mitigating disparity in MIAI attacks.

We experimentally show our findings by evaluating our SDMIA and SDMIA* on three different target models (decision tree (DT), logistic regression (LR), and deep neural network (DNN)) trained on three real datasets (Adult [17], NLSY [18], and FiveThirtyEight [19]). Our analysis shows that SDMIA can achieve more stable and similar performances (even better in some metrics in some scenarios) compared to the existing MIAI attacks, despite assuming the least capabilities for the adversary and even with fewer queries. Our in-depth disparity factor analysis demonstrates that while the target model impacts the most influential disparity factor (e.g., mutual information in the deep neural network, correlation in the decision tree), the overall disparity in MIAI results from the holistic impact of multiple factors. This finding calls for designing robust multi-factor-based disparity mitigation strategies to adopt in the future for effective MIAI disparity mitigation.

The contributions of this paper are as follows:

1) We design a novel black-box MIAI attack that considers the *least* adversarial knowledge/capabilities to date while performing similarly to the state-of-the-art MIAI attacks.
2) We formally define and analyze our proposed MIAI attack's *disparate vulnerability* property and introduce two metrics for *disparity* measures.
3) We investigate existing ML privacy defense techniques– *mutual information regularization* and *fairness constraints*, and show that none of these techniques can mitigate MIAI *disparity* consistently.
4) We empirically identify the factors behind the *disparity*, their contributions, i.e., their importance/weights towards *disparity*, and discuss possible directions for disparity mitigation.
5) We extensively evaluate the proposed SDMIA using three different target models trained on three real datasets.

II. Preliminaries

MIAI Attack. Let f be a deterministic function representing the target ML model. The input of f is a d-dimensional vector $x = [x_s, x_2, ..., x_d]$, where d signifies the number of input attributes. Without loss of generality, let x_s be the sensitive attribute and $\{x_2, ..., x_d\}$ be the set of the non-sensitive attributes. In MIAI attacks, an adversary exploits available auxiliary information to infer the training data sample's sensitive attribute (x_s) value. Adversaries can query the target models through APIs made available by the ML-as-a-service (MLaaS) providers [20]–[22]. The auxiliary information may include full or partial knowledge of the non-sensitive attribute values $\{x_2, ..., x_d\}$ in the training dataset, confusion matrix, marginal priors, confidence scores, and predicted labels returned by the target model, etc.

A comparative analysis of the adversarial capabilities assumed in Fredrickson et al. attack on decision tree (FJRMIA) [3], LOMIA [11], and our SDMIA is illustrated in Table I. In FJRMIA, an adversary has access to the confusion matrix, all non-sensitive attribute values of target individuals' training instances, and marginal priors. It queries the target model with all possible sensitive attribute values and predicts the one that maximizes the posterior value computed by $cm[y, y'] * p_s$, where cm is the confusion matrix, y, and y' are the true label and the model's predicted label, respectively, and p_s denotes marginal prior of the sensitive attribute value. LOMIA [11] considers similar adversarial capability assumptions except access to the marginal priors.

Attribute Importance. An ML model, either classification or regression, predicts output y' based on input attributes $\{x_s, x_2, ..., x_d\}$. However, all input attributes might not be equally impactful towards prediction. Therefore, the attribute/feature importance is commonly considered to assign scores to all input attributes [23]. Importance of an attribute x_d in the DT model can be formally defined [24] as below:

$$\mathcal{I}mp_{AI}(x_d) = \mathcal{M}_A(x_d) * \mathcal{S}_{x_d} - \mathcal{M}_A(L_c) * \mathcal{S}_{L_c} - \mathcal{M}_A(R_c) * \mathcal{S}_{R_c} \quad (1)$$

where the $\mathcal{I}mp_{AI}(x_d)$ is the importance of attribute x_d (i.e., node in DT), $\mathcal{M}_A$ is the metric value (e.g., Entropy or Gini),

$\mathcal{S}_{x_d}$ is number of samples at the node, and R_c, L_c indicate right and left child, respectively. So, importance in DT is computed by multiplying the attribute's (node) metric value with the number of samples at the node and subtracting scores (metric value * samples) of its left and right child.

III. Related Work

The concept of model inversion (MI) attack is fairly recent. Fredrickson et al. [1] proposed the concept of MI attack in 2014 by successfully conducting an attack on linear regression models to uncover genomics information about target individuals. MI attacks are applicable to a wide range of data domains including image, tabular, text, or audio data [1], [5]. MI attacks in the image domain (i.e., image reconstruction) have been a central research focus [3], [5], [25]. However, MIAI attacks on tabular data are underexplored [3], [11]. Fredrickson et al. [3] conducted MI attacks on both image and tabular data. They evaluated the maximum a posteriori (MAP) algorithm from [1] for black-box MIAI attacks on tabular data (decision tree target). We denoted this baseline by FJRMIA. Another baseline MIAI attack on tabular data is LOMIA, proposed by Mehnaz et al. [11], where the adversary trains an attack model querying the target. Both baselines consider a wide range of adversarial capabilities.

In the privacy research domain, membership inference attack [7], [26], [27] and MIAI attack [3], [11] have different goals. While the membership inference infers whether a sample is in the target model training dataset (i.e., binary classification), MIAI infers the sensitive attribute value of a training sample. Several works have explored the membership inference attack based on only the predicted label [26], [27]. Christopher et al. [27] proposed three label-only membership inference attacks leveraging the robustness of the model in prediction, which can achieve comparable performance as the confidence score-based attack. Zheng et al. [26] proposed two decision boundary-based label-only membership inference attacks and showed that these attacks are effective even with defenses. However, recent research shows that membership inference attack has quite different characteristics than MIAI attack, and MIAI does not show any consistent pattern [9]. For example, dataset complexity and training epochs positively impact membership inference attack performance, whereas these have no such impact on the MIAI attack. Similarly, higher overfitting leads to better membership inference, whereas there is no explicit relationship between overfitting and MIAI attacks. All these distinct characteristics and inconsistent patterns make an MIAI attack more challenging than other privacy attacks, including membership inference.

Commonly used privacy attack defense techniques include *regularization, differential privacy, fairness constraints,* and *rounding confidence score* [3], [16]. Wang et al. [16] proposed a *mutual information regularization* technique to defend against MI attacks (both image and tabular data). However, this work did not explore the impact of the *mutual information regularization* technique on *disparate vulnerability* property in MIAI. Therefore, we extend the technique in [16] to investigate its impact on MIAI *disparate vulnerability* and whether it can consistently reduce disparity in MIAI without worsening individual subgroup vulnerability magnitudes. Another work by Kulynych et al. [15] investigates *fairness constraints* and *differential privacy* as techniques to reduce disparity in membership inference attacks. *Differential privacy* is not effective against MIAI attacks without significantly compromising model utility [1], [28]. Also, our proposed attack does not require confidence scores, so *rounding confidence* is not applicable. Therefore, we only investigate *mutual information regularization* and *fairness constraints* as two viable MIAI disparity mitigation techniques.

Kulynych et al. perform the first in-depth analysis on disparate vulnerability in membership inference attacks [15]. Their investigations offer various insights regarding subgroup vulnerability, e.g., they identified *overfitting* and subgroup size as factors impacting *disparity* in membership inference attacks. In our work, we perform an in-depth analysis of *disparity* in MIAI attacks to identify possible disparity factors with their impacts on MIAI disparity. We also discuss potential ways to mitigate MIAI disparity based on our findings.

IV. Model Inversion Attack with the Least Adversary Capabilities

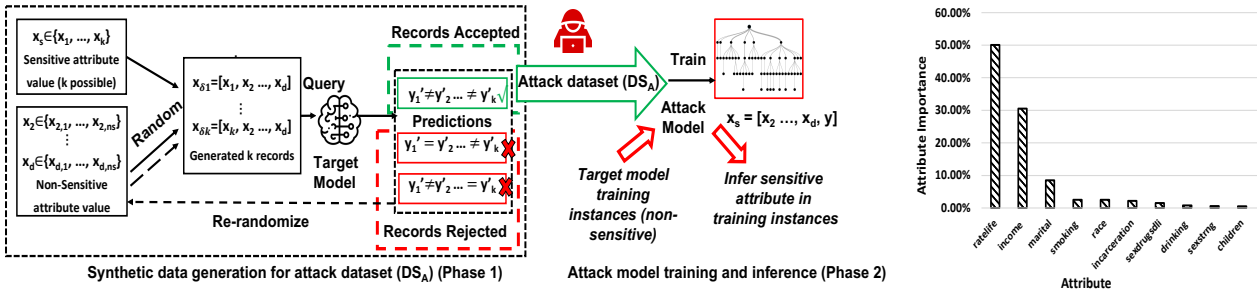
In this section, we first present the threat model and then illustrate our proposed synthetic data-based MIAI attack (SDMIA) with the least adversary capabilities.

TABLE I: Comparison among different attacks in terms of adversary capabilities.

Capability	FJRMIA [3]	LOMIA [11]	SDMIA
(1) Target model's confusion matrix	●	●	
(2) Marginal prior (sensitive attribute)	●		
(3) Marginal prior (non-sensitive attributes)	●		
(4) Possible values of attributes	●	●	●
(5) Training data instances' non-sensitive attribute values	●	●	
(6) Training data instances' actual labels	●	●	
(7) Target model's prediction labels	●	●	●

A. Threat Model

In our threat model, two parties are involved– the model owner and the adversary. Individual training data instances are an adversary's targets. The adversary aims to infer an individual's sensitive attribute in the training data. We assume the adversary does not impact the target model training process or performance; the adversary only interacts with the model owner by issuing API queries to the black-box model with the least capabilities, thereby designing the attack model to infer target individual's sensitive attribute in the training data. The attack is considered successful if the adversary can accurately infer the target individual's sensitive attribute value. In Table I, we illustrate the adversarial capabilities of existing attacks and our proposed MIAI attack. In our attack, the adversary has black-box access to the target model and can only obtain the predicted labels (y') by querying the model. Also, the adversary knows the possible values of sensitive and non-sensitive attributes. Unlike the existing attacks, our attack does not assume knowledge of marginal priors, target model



(a) *SDMIA Overview* (b) *Attribute Importance*

Fig. 1: (a.) Overview of our proposed SDMIA. It works in 2 phases– phase 1: Synthetic data generation for attack dataset (DS_A), and phase 2: Attack model training and inference. (b.) Importance of attributes in attack model, while estimating *drug_marijuana* in NLSY dataset.

confusion matrix cm, or any knowledge about the target model training dataset instances.

B. Our Proposed Synthetic Data-based Model Inversion Attack (SDMIA)

In this section, we introduce our synthetic data-based MIAI attack (SDMIA). We also consider an instance of the SDMIA (SDMIA*) that uses half the number of queries as all of the existing attacks (i.e., LOMIA [11] and FJRMIA [3]). For each instance in the training dataset, the adversaries in LOMIA [11] and FJRMIA [3] query k times (k is the number of possible values of the sensitive attribute), meaning they require $k * m$ queries in total, where m is the number of instances in the training dataset. Unlike these attacks, we generate random queries in SDMIA but constrain the query numbers to $k * m$, which is further reduced to $\frac{k*m}{2}$ in SDMIA*. SDMIA and SDMIA* follow the same attack steps; the only difference is the number of queries to the target model. Our attack works for both binary ($k = 2$) and multi-class ($k > 2$) sensitive attributes. We consider $k <$ number of classes (label), which holds for different real-life datasets and is consistent with the baseline [11]. SDMIA has two phases: (1) Synthetic data generation for the attack dataset (DS_A) and (2) attack model training and inference. In Fig. 1a, we present the overview of our proposed SDMIA strategy.

1) Phase 1: Synthetic Data Generation: The core component of our proposed SDMIA is the synthetic data generation algorithm (Algorithm 1 in Appendix A). This algorithm is inspired by the synthetic data generation technique proposed in [7] for membership inference attacks. However, unlike the existing algorithm, our algorithm is designed for MIAI attacks only considering access to prediction labels (without confidence scores). Also, our algorithm generates k query instances varying k possible sensitive attribute values in each iteration. The complexity of our algorithm is $O(c_2 + c_1 * m)$, where m, c_1, and c_2 stand for loop counter (number of instances), array access time, and outside loop run time. Therefore, our algorithm has linear time complexity.

Our synthetic data generation algorithm consists of three steps: i) *initialization*, ii) *querying*, and iii) *selection*. In *initialization*, the algorithm randomly initializes values for $d - 1$ non-sensitive attributes to form the partial query x^-. It also initializes d_{max} and d_{min}, which denote the max and min number of non-sensitive attributes that would change in every iteration, respectively. Additionally, we initialize max record rejection threshold r_{max}. In *querying*, the adversary varies the sensitive attribute value and generates k query instances from x^-, i.e., $x_{\delta_1}, \ldots, x_{\delta_k}$, where k is the number of unique possible values of the sensitive attribute. The target model f_{tar} is then queried with these generated instances, and the adversary receives the corresponding predictions (y's).

In *selection*, the adversary either includes the generated query instances to the attack model training dataset (DS_A) or rejects them based on the returned predictions. If all the k predictions using k possible values of the sensitive attribute (where $k \geq 2$) are different, we accept the instances to form DS_A; otherwise, we reject them (Fig. 1a). In the above scenario, k query instances set $x_{\delta_1}, \ldots, x_{\delta_k}$ is accepted to form DS_A if all the k predictions $y'_1, \ldots, y'_k$ are different (green marked in Fig. 1a). If at least two predictions are same, the set of instances is rejected (red marked in Fig. 1a). Regardless of acceptance/rejection, in every iteration we re-randomize non-sensitive attribute values by changing d_{max} non-sensitive attributes (chosen uniformly at random from $d-1$ non-sensitive attributes). However, in case of consecutive rejections, we update d_{max}. If the number of consecutive rejections exceeds the max rejection threshold (r_{max}), we update d_{max} by $max\ (d_{min}, \lceil d_{max}/2 \rceil)$. We reduce d_{max} to control the search diameter around the accepted records while re-randomizing. This enhances search speed and ensures accepted records vary in the least number of attributes. Therefore, it better captures the correlation between the sensitive attribute and the label.

The goal of generating synthetic data is to capture the dependency between the input attributes and the output (label). Since we initialize the non-sensitive attributes randomly (controlling search diameter) and vary the sensitive attribute values, the synthetically generated DS_A dataset primarily emphasizes the correlation between the sensitive attribute and the label of target model (varying the sensitive attribute yields different

TABLE II: Sensitive attributes (binary) distribution in the training datasets.

Dataset	Training Instances	Sensitive attribute	Positive class label	Positive class count	Positive class %
NLSY	5096	drug_marijuana	dm_yes	961	18.9%
Adult	35222	marital	married	16893	47.9%
FiveThirtyEight	331	alcohol	yes	266	80.36%

target model predictions). In Fig. 1b, we demonstrate attribute importance in the attack model to infer *drug_marijuana* sensitive attribute in NLSY dataset, where the target model label *ratelife* has the highest importance in the attack model (at 50.1%). Also, in the Adult dataset, among 18,329 *single* individuals, only 1208 have $\geq 50K$ label, i.e., *income*, whereas among the remaining 16,893 *married* individuals, 7565 have $\geq 50K$ label. Therefore, to capture this strong dependency, we consider accepting the set of instances to form DS_A only when all the k predictions from the target model using k possible sensitive attribute values are different.

2) Phase 2: Attack Model Training and Inference: In this phase, we train an attack model f_{adv} using the generated synthetic dataset DS_A from phase 1 (Section IV-B1). This attack model performs the model inversion, i.e., it predicts sensitive attribute values when given the non-sensitive attributes as the input. More specifically, we train the f_{adv} attack model with non-sensitive attribute values ($x_{ns} = x_2, ...x_d$) and y' (i.e., prediction) in DS_A dataset as the input features where the output label is the sensitive attribute x_s, i.e., $x_s = f_{adv}(y' \cup x_{ns})$, as shown in Fig. 1a. Once the f_{adv} model is trained, it can be deployed to infer the sensitive attribute of any target model training dataset instance. We evaluate the performance of SDMIA and SDMIA* in Section IV-C4.

C. SDMIA Evaluation

This subsection describes datasets, SDMIA experimental setup, performance metrics, and comparison among our proposed SDMIA and the existing MIAI attacks.

1) Dataset Description: We use publicly available datasets described below for our experiments in this paper.

Texas. This dataset is based on Texas Hospital discharge data [29]. We consider 1st quarter hospital data of consecutive five years (2006-2010) and extract features related to patient status, length of hospital stays, illness severity, and demographic information[1]. We use *pri_proc* as the label, indicating the primary procedure the patient has undergone (e.g., type1, type2, type3 classes). First, we apply stratified sampling to randomly select 20K instances from each year, based on the most frequent *pri_proc*. We then combine instances and obtain a dataset of 100K instances. After additional pre-processing (removing all duplicate instances), we end up with 89,924 instances which we split into 67,443 ($\sim$ 75%) and 22,481 ($\sim$ 25%) for training and testing, respectively.

NLSY. The National Longitudinal Survey of Youth (NLSY) dataset consists of responses from the survey conducted in 1997 [18] on 8984 individuals born between 1980-1984 living in the US. We extract features related to participant demographic information, including age, marital status, race, habits (e.g., smoking, drinking), and ratings of life (participants rate their life into classes, e.g., *excellent, very good, good, fair, poor*) [18]. The dataset has 15 attributes and we consider ratings of life, i.e., *ratelife* (classes: *excellent, very good, good, fair, poor*) as the label attribute. After pre-processing, we obtain 6795 instances which we split into 5096 ($\sim$ 75%) and 1699 ($\sim$ 25%) for training and testing, respectively.

Adult. The adult dataset is extracted from the 1994 Census database. The purpose is to predict whether an individual has income is higher or lower than 50K in a year [17] from the individual's other features. The dataset has 48,842 instances and 14 attributes, including marital status, occupation, education, and race. After pre-processing, we obtain 45,222 instances which we split into 35,222 ($\sim$ 75%) and 10,000 ($\sim$ 25%) for training and testing, respectively.

FiveThirtyEight. FiveThirtyEight Datalab [19] surveyed 553 individuals to identify their steak preferences, given their habitual features and demographic data, e.g., smoking, drinking, age, and gender. This dataset has 15 attributes with $steak_type$ as the target label. After pre-processing, we obtain 331 instances that we use exclusively for training.

2) Experiment Setup: In Table II, we present the total instances in the training sets and the binary sensitive attributes we consider, along with their positive class counts in the training set. In Table IX, we present multi-class sensitive attributes that we consider. There is no positive class for multi-class; therefore, we present the average of all class estimation performances in our experiments. For each dataset, we train 3 different target models in the BigML [30] platform– decision tree (DT), logistic regression (LR), and deep neural network (DNN). We use BigML's 1-click supervised feature for training the target models with default parameters. We present performances of all 3 target models trained on Adult dataset, tested on training and test datasets in Tables III, IV, respectively. We observe that target models perform similarly on training and test datasets, indicating no significant overfitting on target models. Target model performances trained on other datasets are presented in Tables XI, XII in Appendix. After training the target model, we query the target model with API provided by the BigML and obtain the attack dataset DS_A (using Algorithm 1). For each target model, we train the attack model as a bootstrap decision-tree forest of 10 decision tree models trained on the attack dataset DS_A (i.e., bagging technique), denoted by the 1-click ensemble model feature in BigML [30].

TABLE III: Target model performances trained on Adult dataset (tested on *training* dataset)

Model	Precision	Recall	Accuracy	F1 score
DT	83.05%	78.04%	86.15%	80.00%
DNN	77.16%	80.68%	82.83%	79.00%
LR	79.95%	76.02%	84.31%	78.00%

We compare performances of our proposed SDMIA with baselines for both binary (*k=2*) and multi-class (*k>2*) sensitive

[1]Our experiments comply with data sharing and re-identification agreements.

TABLE IV: Target model performances trained on Adult dataset (tested on *test* dataset)

Model	Precision	Recall	Accuracy	F1 score
DT	81.59%	76.16%	85.29%	78.00%
DNN	75.96%	79.29%	82.11%	77.00%
LR	79.34%	75.2%	84.11%	77.00%

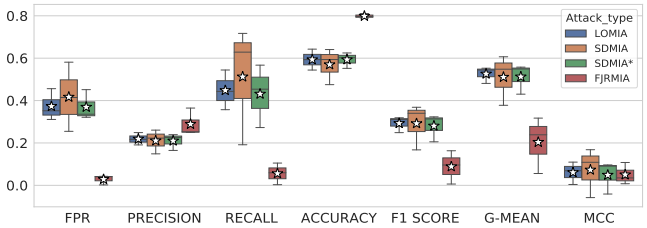


Fig. 2: Comparison of performance metrics distributions among SDMIA, SDMIA*, LOMIA, and FJRMIA; while inferring *drug_marijuana* (lower prior *dm_yes*=18.9% positive class) obtained from 3 target models trained on NLSY dataset.

attributes in different datasets, varying the target models. In binary sensitive attribute (*k=2*), we consider three different scenarios (depending on sensitive attribute's positive class marginal priors): (i) estimating *drug_marijuana* in NLSY dataset, where the positive class (i.e., 'dm_yes') has very low (18.9%) prior, (ii) estimating *alcohol* in FiveThirtyEight dataset, where the positive class (i.e., 'Yes') has very high (80.3%) prior, and (iii) estimating the *marital* in Adult dataset, where priors are balanced, i.e., positive class (i.e., 'married') has 47.96% marginal prior. For each scenario, we perform all attacks on three target models (DT, LR, DNN) trained on NLSY, FiveThirtyEight, and Adult datasets. We present results in Section IV-C4.

3) Evaluation Metrics: Since accuracy is not an effective evaluation metric for imbalanced class data, we also consider the F1 score, which balances precision and recall of the positive class only. This metric also does not capture the overall performance. We consider Mathews correlation coefficient (MCC) and Geometric-mean (G-Mean) [31], which account for all confusion matrix entries and provide more balanced measures. We also consider false-positive rates (FPR) to measure model's incorrectness in prediction. In different metrics, besides numerical comparison, we compare attacks in *attack stability* property, i.e., the resistance of the attack performance to target model variations (model agnostic).

4) SDMIA Performance Comparison:

(1) Estimating binary sensitive attributes (*k=2*): In Fig. 2, we present attack performance distributions (horizontal bars (−) and stars (⋆) in boxes indicate *'median'* and *'mean'*) from three different target models in scenario (i), as discussed in Section IV-C2. Since FJRMIA is impacted by positive class marginal priors, in scenario (i), we obtain the lowest performances, i.e., F1 score (8.85%) and G-mean (20.38%) for FJRMIA (Fig. 2). Mean FPR, F1 score, and accuracy for SDMIA* are similar to those of LOMIA, despite having the least adversary capabilities, and queries to the target model

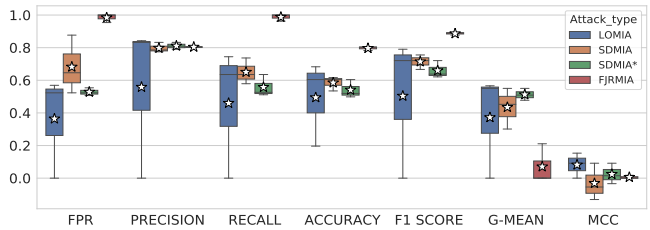


Fig. 3: Comparison of performance metrics distributions among SDMIA, SDMIA* and existing LOMIA, FJRMIA; while inferring *alcohol* (higher marginal prior *Yes*=80.3% positive class) obtained from 3 target models trained on FiveThirtyEight dataset.

are limited to half. For example, mean FPR and accuracy scores in LOMIA are 37.3% and 59.23%, whereas SDMIA* has 36.94% and 59.29% mean FPR and accuracy, respectively. Also, SDMIA performs similarly to LOMIA. In summary, all attacks, except FJRMIA, achieve similar performances. In Table V, we present the attack performances for DT target models (Tables XVI and XVII in Appendix for DNN, LR).

In Fig. 3, we present distributions of attack performances in scenario (ii). For higher marginal prior positive class, i.e., in scenario (ii), FJRMIA achieves the highest recall at 98.75% but results in an FPR of 98.46% (Fig. 3). In contrast, all other attacks achieve comparable and more consistent performance. Moreover, SDMIA and SDMIA* have more stable distributions compared to LOMIA across different models (Fig. 3). For example, LOMIA has a higher *interquartile range (IQR)* of accuracy (24.32), whereas SDMIA and SDMIA* have 4.07 and 5.28 IQRs, respectively. In some cases, our SDMIA and SDMIA* outperform LOMIA. For example, the mean values of precision and F1 score in SDMIA* are 81.08% and 65.98%, whereas SDMIA achieves 79.76% and 71.42%, and LOMIA has the lowest values at 55.84% and 50.37%, respectively. In Table VI, we present the attack performances for DT target models (Tables XVIII and XIX in Appendix for DNN, LR).

In scenario (iii), when the classes have more balanced priors, we find LOMIA, SDMIA, and SDMIA* to have similar performances, and all three outperform FJRMIA. We present the distribution in the Appendix in Fig. 17; FJRMIA has the lowest F1 score (35.30%) compared to ∼59% in other attacks. In Table VII, we present the attack performances for the DT target model (Tables XX and XXI in Appendix for DNN, LR).

(2) Estimating multi-class sensitive attributes (*k>2*): We experiment with multi-class sensitive attributes (*k=4*) *age*={*18-29, 30-44, 45-60, >60*} in FiveThirtyEight and *race*={*nonblhis, black, hispanic, mixed*} in NLSY dataset. We compute average class performances for each attack for each target model. In Fig. 4a and 4b, we present the mean and standard deviations (error bars) of average class performances across models. In both plots, observe that SDMIA and SDMIA* perform slightly better than LOMIA in precision and F1 scores, and do not perform significantly differently in accuracy and recall than LOMIA. FJRMIA has higher accuracy than all

TABLE V: Attack performance while inferring *drug_marijuana* sensitive attribute, against DT model trained on NLSY dataset

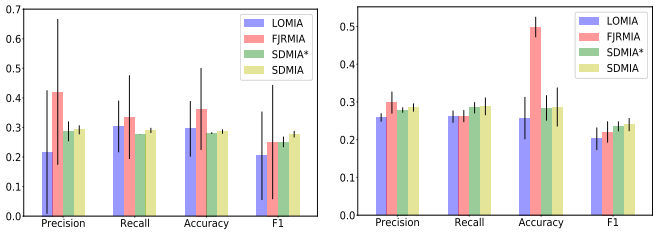
Attack Strategy	Query#	TP	TN	FP	FN	Precision	Recall	Accuracy	F1 score	G-mean	MCC
FJRMIA [3]	10192	101	3959	176	860	36.46%	10.51%	79.67%	16.32%	31.72%	10.79%
LOMIA [11]	10192	426	2849	1286	535	24.88%	44.33%	64.27%	31.87%	55.27%	10.96%
SDMIA	10192	689	1732	2403	272	22.28%	71.70%	47.51%	34.00%	54.80%	10.88%
SDMIA*	5096	436	2747	1388	525	23.90%	45.37%	62.46%	31.31%	54.90%	9.63%

TABLE VI: Attack performance while inferring *alcohol* sensitive attribute, against DT model trained on FiveThirtyEight dataset

Attack Strategy	Query #	TP	TN	FP	FN	Precision	Recall	Accuracy	F1 score	G-mean	MCC
FJRMIA [3]	662	266	0	65	0	80.36%	100.00%	80.36%	89.11%	0.00%	0.00%
LOMIA [11]	662	198	28	37	68	84.26%	74.44%	68.28%	79.04%	56.63%	15.33%
SDMIA	662	196	8	57	70	77.47%	73.68%	61.63%	75.53%	30.11%	−13.11%
SDMIA*	331	140	32	33	126	80.92%	52.63%	51.96%	63.78%	50.90%	1.48%

TABLE VII: Attack performance while inferring *marital* sensitive attribute, against DT model trained on Adult dataset

Attack Strategy	Query #	TP	TN	FP	FN	Precision	Recall	Accuracy	F1 score	G-mean	MCC
FJRMIA [3]	70444	3788	17818	511	13105	88.11%	22.42%	61.34%	35.75%	46.69%	29.97%
LOMIA [11]	70444	7574	17132	1197	9319	86.35%	44.84%	70.14%	59.02%	64.74%	44.25%
SDMIA	70444	7565	17121	1208	9328	86.23%	44.78%	70.09%	58.95%	64.68%	44.12%
SDMIA*	35222	7565	17121	1208	9328	86.23%	44.78%	70.09%	58.95%	64.68%	44.12%



(a) *age* (b) *race*

Fig. 4: Performances comparison among different attack strategies, while estimating multi-class (*k=4*) sensitive attribute *age* in *FiveThirtyEight* and *race* in *NLSY* dataset.

attacks due to its biases to class marginal priors, which highly impacts multi-class accuracy. SDMIA and SDMIA* achieve slightly better F1 scores than all attacks. Significantly higher error bars in FJRMIA and LOMIA in most metrics indicate significant performance variation across models.

Discussion. Target model architecture impacts the attack stability, i.e., causes performance variations (e.g., error bars in Fig. 4 or higher IQRs in Fig. 3). However, among all attacks, our proposed SDMIA is more resilient to this phenomenon due to its ability to capture sensitive attribute-label dependency effectively compared to the existing attacks. FJRMIA and LOMIA query with the training data instances (known non-sensitive attributes). Comparatively higher dissimilarity among these instances (many non-sensitive attributes differ) causes higher prediction variations across models, negatively impacting attack stability. In other words, non-sensitive attributes also have significant attribute importance in the attack. Whereas, in SDMIA, random record generation with limiting search space enables comparatively higher similar record generation (only d_{max} attributes differ). This contributes to lower prediction variations across target models, i.e., similar distributions in attack datasets (label has significantly higher importance in the attack). Therefore, SDMIA captures sensitive attribute-label dependency strongly, achieving better stability. *In summary*, existing attacks are less stable in both binary and multi-class sensitive attribute estimation, while SDMIA is more stable. We conclude that SDMIA effectively estimates both binary and multi-class sensitive attributes, given that it requires the least capabilities and 50% fewer queries in SDMIA*.

V. Disparate Vulnerability in MIAI

Disparate Vulnerability in the MIAI context is a great privacy concern. It captures uneven impacts of the attack on subgroups, i.e., attack performances vary across disjoint training instances of subgroups, and particular subgroup instances might be more vulnerable to MIAI attacks than other subgroups. For example, while inferring marital happiness or other personal sensitive information, *divorced* individuals might have higher vulnerability than *married* individuals. First, we formally define *disparity* in subgroup vulnerability and then analyze two probable solutions for mitigating MIAI disparity– *mutual information regularization* and *fairness constraints*.

A. Formal Definition of Disparity

In an MIAI attack, the performance of the adversary ($\mathcal{A}$) quantifies the term *'vulnerability'*. We define two types of *'vulnerability'* in MIAI– i) *average vulnerability*, when $\mathcal{A}$ has no specific target subgroup knowledge, we refer to this as $\mathcal{V}_a(\mathcal{A})$, and ii) *subgroup vulnerability*, when $\mathcal{A}$ has subgroup knowledge and targets a specific subgroup, we refer to this as $\mathcal{V}_s(\mathcal{A})$.

Average Vulnerability $\mathcal{V}_a(\mathcal{A})$: We mathematically define $\mathcal{V}_a(\mathcal{A})$ as follows:

$$\mathcal{V}_a(\mathcal{A}) = Pr[MIAI(f_{tar}, V(x_s, x_{ns}), d_{ta}) = x_s] \quad (2)$$

where $V(x_s, x_{ns})$ is the set of possible values of sensitive and non-sensitive attributes and d_{ta} is the targeted instance in the training dataset (the randomness is from d_{ta} selection). The vulnerability is determined by the correct estimation of sensitive attribute values (i.e., $MIAI(f_{tar}, V(x_s, x_{ns}), d_{ta}) = x_s$), where x_s is the actual value of the sensitive attribute, and

$MIAI(f_{tar}, V(x_s, x_{ns}), d_{ta})$ represents the estimated sensitive attribute value.

Subgroup Vulnerability $\mathcal{V}_s(\mathcal{A})$: Let the attribute of interest for subgroup vulnerability be x_b (e.g., gender), i.e., we are interested in understanding whether MIAI attacks pose significantly different vulnerability for different subgroups (e.g., male, female) based on this x_b attribute, where a subgroup $S = s_g$ is defined as the disjoint set of samples that belong to a particular subgroup. We mathematically define $\mathcal{V}_s(\mathcal{A})$ as follows:

$$\mathcal{V}_s(\mathcal{A}) = Pr[(MIAI(f_{tar}, V(x_s, s_g, x_{ns}), d_{ta}|S = s_g) = x_s] \tag{3}$$

where all notations are similar to $\mathcal{V}_a(\mathcal{A})$ with the additional capability of $\mathcal{A}$ to target a specific subgroup $S = s_g$ of subgroup attribute x_b (the randomness is from d_{ta} selection for $S = s_g$). Hence, $\mathcal{V}_s(\mathcal{A})$ in Eqn. 3 represents the vulnerability of subgroup s_g only.

Disparity: For different subgroups $S = s_1, ..., s_n$, the subgroup vulnerability $\mathcal{V}_s(\mathcal{A})$ can vary, i.e., $\mathcal{V}_{s1}(\mathcal{A}) \neq \mathcal{V}_{s2}(\mathcal{A}) \ldots \neq \mathcal{V}_{sn}(\mathcal{A})$. We define *disparity* in $\mathcal{V}_s(\mathcal{A})$ as follows:

$$\mathcal{V}_{ds}(\mathcal{A}) = gap(\mathcal{V}_{s1}(\mathcal{A}), ..., \mathcal{V}_{sn}(\mathcal{A})) \tag{4}$$

where the gap stands for the generic distance among subgroup vulnerabilities $\mathcal{V}_s(\mathcal{A})$ and can be computed using a suitable metric. We propose two metrics to compute this gap.

B. Proposed Metrics for Disparity $\mathcal{V}_{ds}(\mathcal{A})$ Measure

To measure disparity, i.e., gap among subgroup vulnerabilities, we introduce two metrics as defined below.

Absolute Maximum Disparity (AMD): We denote this metric by the absolute difference between the maximum and minimum subgroup vulnerabilities ($\mathcal{V}_s(\mathcal{A})$) in an attribute, expressed as follows:

$$\mathcal{V}_{ds}^{amd}(\mathcal{A}) = |V_{max} - V_{min}| \tag{5}$$

where V_{max} is the maximum subgroup vulnerability and V_{min} is the minimum subgroup vulnerability.

Maximal Mean Disparity Deviation (MMDD): We use this metric to capture the central tendency, i.e., maximal deviation of subgroup vulnerabilities from the mean value. We denote MMDD by the absolute difference between maximum subgroup vulnerability $\mathcal{V}_s(\mathcal{A})$ and average subgroup vulnerability $\mathcal{V}_a(\mathcal{A})$ defined in Section V-A. We express MMDD as below:

$$\mathcal{V}_{ds}^{mmdd}(\mathcal{A}) = |V_{max} - V_a| \tag{6}$$

C. Disparity in SDMIA

We perform experiments with subgroup vulnerabilities ($\mathcal{V}_s(\mathcal{A})$), and show that disparity exists in both existing and proposed MIAI attacks. In Fig. 5, we present the subgroup vulnerabilities for DT target model trained on Adult dataset where the adversary estimates *marital* sensitive attribute. As first demonstrated by Mehnaz et al. [11] in their LOMIA strategy, the attack accuracy against *male* and *female* subgroups are 62.5% and 85.8%, respectively. In our SDMIA and SDMIA*,

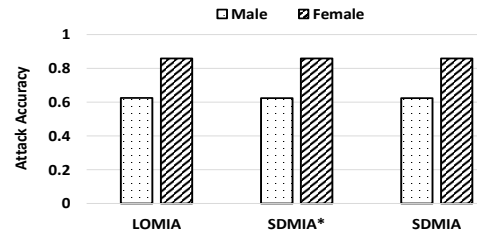


Fig. 5: Illustrating *disparity* in MIAI attacks– vulnerabilities in *sex* subgroups in Adult dataset, while estimating *marital*.

we also observe similar trends, i.e., a significant disparity with ∼62.4% and ∼85.9% attack accuracy against the two subgroups, respectively. This indicates that an adversary, even with the least capabilities, can perform SDMIA and achieve better performance on higher vulnerable subgroups than other subgroups due to the presence of disparity.

Therefore, we perform an in-depth study of MIAI disparity to investigate the impact of existing privacy defense techniques on disparity and potential factors contributing to disparity.

D. Impact of Existing Techniques in Disparity Mitigation

We empirically analyze the effectiveness of the existing privacy defense techniques to mitigate disparity, i.e., $\mathcal{V}_{ds}(\mathcal{A})$ among subgroups without increasing individual subgroup vulnerabilities, i.e., $\mathcal{V}_s(\mathcal{A})$ and without compromising target model utility significantly. We investigate the impact of mutual information regularization and fairness constraints on MIAI disparity mitigation.

1) Mutual Information Regularization: Wang et al. [16] proposed a *mutual information (MI) regularization* based approach to defend against model inversion attacks. The key idea is to reduce dependency between target model inputs and labels by applying a regularization penalty. We extend this in the context of subgroup vulnerability $\mathcal{V}_s(\mathcal{A})$. We aim to leverage attribute level dependency (i.e., between subgroup attribute x_b and label attribute y') in the form of *mutual information* (MI) and reduce that to investigate its impact on subgroup vulnerabilities and disparity in MIAI. In our work, we consider a similar approach as [16] to reduce attribute level MI by incorporating an MI-based regularizer in the training loss function. We apply the regularizer as an additional penalty term in the loss function. We consider the following overall loss function to train the target model:

$$\mathcal{L}_{mi} = \min_{f \in \mathcal{H}} \mathcal{L}_e(y, f(x)) + \lambda \mathcal{I}(x_b, y') \tag{7}$$

where $\mathcal{L}_{mi}$ is the mutual-information based regularization loss which is the sum of cross entropy loss ($\mathcal{L}_e(y, f(x))$) and a penalty term ($\lambda \mathcal{I}(x_b, y')$), where λ is the regularization weight coefficient (we consider $\lambda = 0.01$), and $\mathcal{I}(x_b, y')$ is the mutual information (Appendix B2).

2) Fairness Constraints: Since disparate vulnerability is attributed to the distributional generalization gap in the target model's property functions (e.g., loss function that computes distributional difference for models on input data and outputs

a numeric vector) among different subgroups [15], we aim to investigate the role of this distributional gap in the case of MIAI disparity. *Fairness* is commonly used to reduce this distributional generalization gap among different subgroups. For example, let ϕ be the target model's (f_{tar}) property function, and x be the input vector. For two subgroups s_1 and s_2, the distributional gap in the target model ($\mathcal{D}_{gap}$) can be formally defined as the δ deviations (generic distance) between subgroups in terms of property function ϕ:

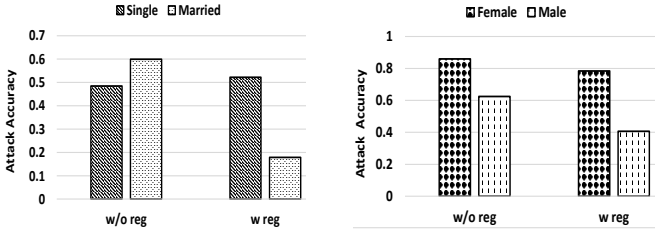
$$\mathcal{D}_{gap} = \delta(Pr[\phi(f_{tar}, x \in s_1)|s_1], Pr[\phi(f_{tar}, x \in s_2)|s_2]) \tag{8}$$

We consider two fairness constraints– i) demographic parity (DP), and ii) equalized odds (EO) [32]. We train the model with the commonly used Exponentiated Gradient reduction algorithm [33] for classification with fairness. For the experiment, we use the accuracy score metric as a measure of the gap. DP reduces the distributional gap among subgroups, ensuring subgroups have a similar percentage of instances with each label. In contrast, EO reduces the distributional gap by minimizing true positive and false positive rates' differences among subgroups [34].

3) Disparity Mitigation Experiment Setup: In the mutual information regularization experiment, we apply regularization between subgroup attribute x_b (e.g., marital) and label attribute y (e.g., income) considering the DNN target models trained on Adult and NLSY datasets. We train the target model with regularization and iteratively reduce the loss function defined in Section V-D1. In our implementation, we have modified the default loss function provided by the Scikit-learn ML library. We have computed (between x_b and y) another penalty term (as illustrated in Eqn. 7), and added it with the default cross-entropy loss function in Scikit-learn. After target model training with regularization, we perform SDMIA to compute subgroup vulnerabilities. We present the results in Section V-D4.

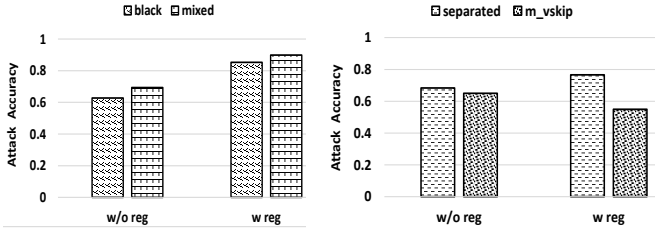
For the fairness experiment, we experiment with one subgroup as *control* (e.g., *white* in *race* attribute in Adult dataset) with a fixed number of instances, and change the number of other subgroup's (*target*) instances. For each subgroup size, we randomly select *target* (e.g., *black*) subgroup instances (and repeat the experiment three times). We train corresponding DT target models (three models) based on these subgroup sizes, perform SDMIA on each model, and compute the mean of subgroup vulnerabilities across these three models. For binary subgroups (e.g., *sex*), we calculate $\mathcal{V}_{ds}(\mathcal{A})$ from subgroup vulnerabilities using our proposed disparity metrics. For multi-valued subgroups (e.g., *race*), we use 1-way ANOVA with pairwise t-test to identify significant subgroups before calculating $\mathcal{V}_{ds}(\mathcal{A})$. Since we perform multiple comparisons, we also apply Benjamini-Hochberg *p-value* correction [35]. In Section V-D5, we present the results.

4) Disparity Mitigation via Mutual Information (MI) Regularization: In this section, we compare subgroup vulnerabilities, disparity, and target model utilities between two cases– target models trained (i) with and (ii) without MI regularization. We consider setup discussed in Section V-D3.



(a) x_b: *marital*, x_s: *sex* (b) x_b: *sex*, x_s: *marital*

Fig. 6: Comparison between *marital* and *sex* subgroup attack accuracies with and without MI regularization, while estimating *sex* and *marital* sensitive attributes, respectively, in Adult dataset.



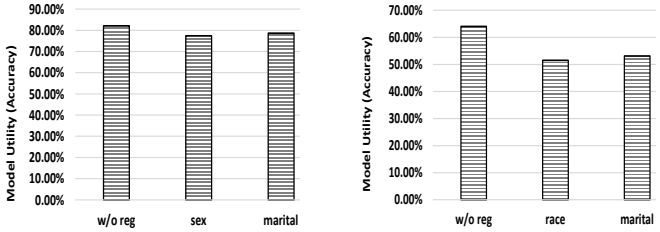
(a) x_b: *race*, x_s: *drug_marijuana* (b) x_b: *marital*, x_s: *drug_marijuana*

Fig. 7: Comparison between significant *race* and *marital* subgroup attack accuracies with and without MI regularization, while estimating *drug_marijuana* sensitive attribute in NLSY dataset.

Subgroup Vulnerabilities $\mathcal{V}_s(\mathcal{A})$. For experiments with binary subgroups, we consider *sex* and *marital* attributes in the Adult dataset. In Fig. 6a, we present the subgroup vulnerabilities of individuals with different marital status where the adversary estimates the *sex* attribute. After MI regularization, *single* subgroup's vulnerability is increased to 53.23% from 48.46%, whereas for *married* subgroup it is reduced to 46.56% from 59.94%. In contrast, as shown in Fig. 6b, *male* and *female* subgroups have 62.43% and 85.90% vulnerabilities without regularization whereas with regularization both are reduced to 40.68% and 78.43%, respectively.

For multi-valued subgroups, we consider *race* and *marital* attributes in the NLSY dataset. From ANOVA test for *race* attribute, we obtain *mixed* and *black* subgroups as the most significant pair (Table XIV). Similarly, for *marital* attribute, *separated* and *m_vskip* represent the most significant pair (Table XV). In Fig. 7a and 7b, we present the comparisons among significant *race* and *marital* subgroups, respectively. With MI regularization, both subgroups' vulnerabilities in *race* increase (Fig. 7a). In contrast, *marital* subgroups show different pattern. While the *separated* subgroup's vulnerability increases to 76% from 68%, it is reduced to 55% from 65% for *m_vskip*. We conclude that MI regularization does not consistently reduce subgroup vulnerabilities in MIAI attacks.

Disparity $\mathcal{V}_{ds}(\mathcal{A})$. We measure disparity using our proposed



(a) Adult target model utility (b) NLSY target model utility

Fig. 8: Comparison among target model utility with and without MI regularization in Adult and NLSY datasets.

AMD and MMDD metrics, as presented in Section V-B. Table VIII shows the computed disparity values. In the Adult dataset, for *marital*, both AMD and MMDD values increase with MI regularization. For example, AMD is increased to 34.33 from 11.48, and MMDD is increased to 16.46 from 5.97 after MI regularization, which we also observe in Fig. 6a. A similar pattern can be observed in *sex* subgroups in the Adult dataset. For multi-valued subgroups in NLSY dataset, i.e., both *marital* and *race* subgroups, AMD and MMDD values show mixed trend. Although, AMD in *marital* increases from 3.33 to 21.66, MMDD decreases from 4.73 to 1.12. In contrast, AMD in *race* decreases from 6.62 to 4.59 while MMDD increases from 5.79 to 7.89. Experiments from both binary and multi-valued subgroup attributes show that disparity in MIAI is not consistently reduced with MI regularization. As illustrated in [16], a highly accurate model is more vulnerable to MIAI attacks. While regularization reduces overall MIAI attack by marginally reducing target model accuracy, it does not ensure each subgroup's accuracy is reduced consistently, thereby causing subgroup vulnerabilities to change in different margins, impacting disparity.

TABLE VIII: Performance comparisons between models with and without MI regularization, using proposed *disparity* metrics (AMD, MMDD)

Dataset	Subgroup Attribute	AMD w/o reg	AMD w reg	MMDD w/o reg	MMDD w reg
Adult	*marital*	11.48	34.33	5.97	16.46
NLSY	*race*	6.62	4.59	5.79	7.89
Adult	*sex*	23.47	37.74	15.82	25.44
NLSY	*marital*	3.33	21.66	4.73	1.12

Target Model Utility. In Fig. 8a, we present the model utility with and without MI regularization on *sex* and *marital* attributes in the Adult dataset. With regularization, accuracy score is slightly reduced to 77.43% and 78.62% from 82.11% in the cases of *sex*, and *marital* subgroup attributes, respectively. In Fig. 8b, we present the model utility with and without regularization on *race* and *marital* attributes in the NLSY dataset. Again, with regularization, the target model accuracy score is slightly reduced. This indicates MI regularization does not significantly worsen the target model performance.

5) Disparity Mitigation via Fairness Constraints: We experiment with *sex* and *race* subgroup attributes, where the

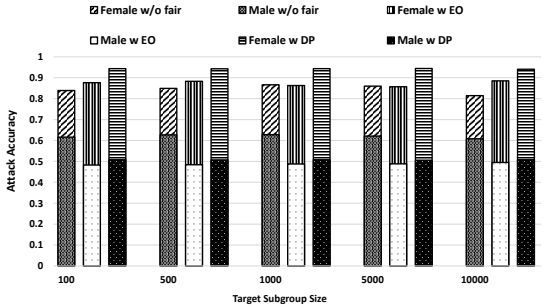


Fig. 9: Comparison between *sex* subgroups' vulnerabilities (*female* target) without fairness, with DP, and EO constraints, while estimating *marital* (Adult dataset). Lower and higher bars are two subgroup vulnerabilities, so the difference represents disparity.

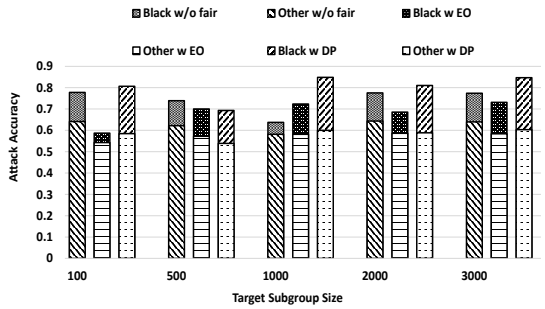


Fig. 10: Comparison between significant *race* subgroups' vulnerabilities without fairness, with DP, and EO constraints, while estimating *marital* (Adult dataset). Lower and higher bars are two subgroup vulnerabilities, so the difference represents disparity.

adversary estimates the *marital* attribute in the Adult dataset. We follow the setup in Section V-D3.

Subgroup Vulnerabilities $\mathcal{V}_s(\mathcal{A})$. First, we consider *female* as the *target* subgroup with sizes 100, 500, 1k, 5k, 10k and concatenate these with fixed 10k *male* instances representing the *control* subgroup. In Fig. 9, we present mean vulnerabilities from three models for each size of the target subgroup. We observe that *male* subgroup vulnerability is reduced with both fairness constraints. In contrast, *female* subgroup vulnerability increases slightly with EO while significantly with DP. This trend remains consistent across different target subgroup (female) sizes. For example, in the case of size 500, *female* subgroup has vulnerability ∼94% and ∼87% with DP and EO, respectively, compared to ∼85% without any fairness constraints. Note that there is only a slight change in disparity with sample size in a model without fairness since disparity depends on the holistic impact of other factors. We perform a similar set of experiments on *sex* subgroup, with *male* as *target* subgroup and observe similar trends (Fig. 15 in Appendix).

For multi-valued *race* subgroup, we consider *black* as the *target* and *white* as the control subgroup, keeping *other* subgroup instances fixed. From ANOVA test, we obtain *black* and *other* as the most significant pair (Table XIII). In Fig. 10,

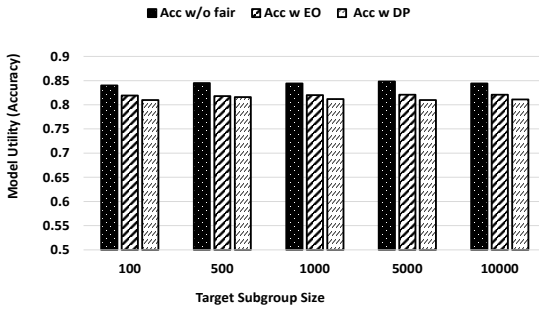


Fig. 11: Target model utility (accuracy) comparison without fairness, with DP, and with EO constraints in Adult dataset.

we present their vulnerabilities. Although, in most cases *other* subgroup's vulnerability is reduced with fairness, it is not consistent. In contrast, *black* subgroup's vulnerability increases with DP significantly. For example, in size 1000, with DP, the *black* subgroup vulnerability is increased to 85% with fairness compared to 63% without fairness. Also, with EO, the vulnerability increases in some subgroup sizes, e.g., at 1000. Hence, we conclude that fairness does not consistently reduce subgroup vulnerabilities in MIAI attacks.

Disparity $\mathcal{V}_{ds}(\mathcal{A})$. In Fig. 9, we observe that the disparity $\mathcal{V}_{ds}(\mathcal{A})$ increases with either of the fairness constraints compared to without fairness scenario. Also, from our experiments, another observation is that disparity with DP is higher than disparity with EO (Fig. 13 and Fig. 14 in Appendix show the disparity in separate plots). Fig. 10 shows a similar trend with DP, i.e., the disparity is increased compared to the model without fairness in most cases, except for some outliers. Also, in Fig. 15, in most cases, disparity also increases with either fairness constraints. In summary, fairness constraints do not consistently reduce disparity in MIAI. Note that fairness equalizes subgroups training samples by reducing the distributional gap. However, subgroup vulnerabilities in MIAI attacks are estimated on the attack model, where the training set contains other features than that one equalized by fairness constraints (i.e., label attribute). Therefore, unlike membership attack [15], fairness in MIAI does not guarantee consistent disparity mitigation.

Target Model Utility. We compare target model utility with and without fairness constraints, considering *female* as the *target* subgroup. We present the comparisons among model utilities (in accuracy metric) in Fig. 11. It shows that overall model utility is mostly consistent with varying subgroup sizes. Also, utility is slightly reduced in models trained with EO compared to model without fairness, which is further reduced with DP. Overall, we empirically show that fairness constraints do not compromise target model utility significantly.

VI. Disparity Mitigation

Our empirical evaluations show that MI regularization and fairness techniques are not consistently effective in reducing *disparity* in MIAI (Sections V-D4 and V-D5). While MI regularization aims to reduce mutual information, fairness reduces the distributional gap, i.e., overfitting. This indicates there exist other disparity factors that contribute toward MIAI disparity. Therefore, we extend our study to investigate other potential MIAI disparity factors and their contributions, i.e., importance/weights towards subgroup vulnerability and disparity in MIAI. Finally, we discuss possible future directions for disparity mitigation based on our findings.

A. Disparity Factors

To identify viable disparity factors, we consider two types of factors– (i) Training dataset-based factors (7): mutual information, correlation, marginal prior, skewness, kurtosis, covariance, and standard deviation, and (ii) Target model-based factors (1): overfitting. We first obtain disjoint training samples for a particular subgroup and then compute these factors using different methods or statistical formulations. For example, we use Shannon's entropy [36] to compute mutual information between subgroup and label. Statistical factors like skewness and kurtosis are computed on the training data label (attribute) distribution of disjoint subgroup samples, as the target model label has the highest importance in MIAI attack (Fig. 1b). Section B (Appendix) describes the details of computations of these factors.

B. Disparity Factors' Weight Analysis

We further experiment to identify the weights/importance of these disparity factors towards disparate vulnerability in MIAI. For this analysis, we compute disparity factors for all subgroups in a dataset (discussed in Section VI-A), and vulnerabilities of all subgroups (applying SDMIA) considering a target model (e.g., DT or DNN, or LR). We then fit the data in a linear regression model, where the disparity factors are inputs, and corresponding subgroup vulnerabilities are outputs. We obtain disparity factors' coefficients from the linear regression model. Disparity factors' weights are calculated from the coefficients of the factors in terms of factors' impact on the dependent variable (subgroup vulnerability $\mathcal{V}_s(\mathcal{A})$), i.e., odds ratio [37]. For example, let val_{coef} be the coefficient of a factor, then we capture its impact on the label (subgroup vulnerability) as follows:

$$\begin{aligned} logR_1 &= logR_0 + val_{coef} \\ \implies R_1 &= R_0 * e^{val_{coef}} \end{aligned} \tag{9}$$

where R_1 is the odds of label attribute $\mathcal{V}_s(\mathcal{A})$ with a unit change of the input factor value, and R_0 is the odds without a unit change of input factor value (initial). For each factor, we calculate this odds ratio to identify the impact of that factor on subgroup vulnerability with a unit change of its value. Finally, we compute the importance of each factor (weight) in terms of the normalized odds ratio.

C. Impact of Target Model on Disparity Factor Weight

We compute the disparity factors' weights varying the target models. In Fig. 12, we present the results on Texas dataset. We observe that the target model architecture significantly impacts disparity factor weight/importance. Our analysis shows that

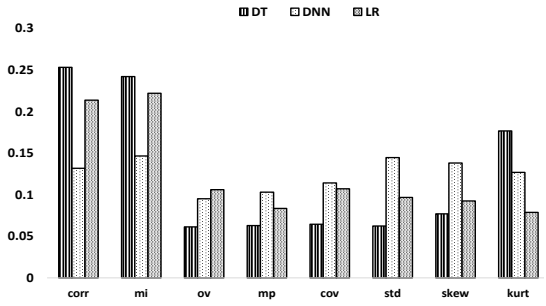


Fig. 12: Disparity factors' weights in Texas dataset, varying target models (DT or DNN or LR). *Notations: corr=correlation, mi=mutual information, ov=overfitting, mp=marginal prior, cov=covariance, std=standard deviation, skew=skewness, kurt=kurtosis.

the correlation has the highest weight for the DT target model. This can be explained by the fact that correlation between inputs and label determines optimal split criteria in DT, thus positively impacting subgroups' accuracy in the target model and hence the disparity in MIAI attack. Mutual information has a slightly higher weight than the correlation for both LR and DNN target models. This is because mutual information inherently captures layered model internal properties/parameters (invariant to parameterization) and can interpret the entire learning process, thereby better capturing subgroups' disparate behavior as well. We also observe similar patterns in Adult dataset, presented in Fig. 16.

D. Disparity Mitigation in MIAI Attacks

According to our experiments, no single factor controls disparity in MIAI. More specifically, correlation, and mutual information seems more important, although depending on data distribution other factors might have significant weights as well (Fig. 12, Fig. 16) and holistically impact disparity. Therefore, to mitigate disparity in MIAI, it is important to reduce multiple factors, i.e., adopting a multi-factor-based disparity mitigation technique. One possible direction is to train the target models with a weighted multi-factor regularization strategy. It involves first identifying possible disparity factors' weights in the training data distribution. Then apply regularization on each factor, and adjust the overall loss function with a weighted regularization (factors' weights) penalty for all factors (similar to Eqn. 7). A more generic approach might be just considering the top few disparity factors and training target models with regularization on them (e.g., mutual information and correlation regularization). This might reduce the target model performance gap among subgroups, contributing to attack model disparity mitigation. Another possible mitigation during training can be guided adversarial training, where the victim can craft adversarial examples to change training data distribution. Tuning the training data distribution can regulate disparity factors' weight (training dataset-based) and hence impact on disparity in the MIAI attack. However, this scenario might have a trade-off between target model performance and disparity.

VII. Discussions and Limitations

k vs. MIAI Performance. In general, for both $k = 2$ and $k > 2$, our proposed SDMIA with the least adversarial capabilities (even with 50% fewer queries in SDMIA*), performs comparably or even better in some metrics in some scenarios (e.g., Tables V-VII, Tables XVI-XXI) compared to the existing MIAI attacks. Also, we observe that existing attacks are less stable in performance across target models. As discussed in Section IV-B, we make a realistic assumption that $k <$ number of classes (label) and empirically evaluated SDMIA on 3 different real-life datasets with different k values (tested up to 4). Our evaluations show that all attack performances degrade with increasing k, as expected. However, existing attacks do not capture input output dependency as effective as SDMIA and as a result, suffer more (e.g., $\sim 56\%$ and $\sim 50\%$ accuracy drop in FJRMIA and SDMIA from $k = 2$ to $k = 4$).

Adaptive Algorithm. Algorithm 1 re-randomizes d_{max} attributes randomly in new record generation. Leveraging confidence scores returned by target models during the previous query to craft new records might make the algorithm more adaptive. However, this also widens assumptions on adversarial capabilities (i.e., confidence score) and might not be realistic. An alternative approach might be identifying crucial training attributes (based on prediction) and crafting records solely depending on those attributes, which also brings a trade-off between attack effectiveness and query numbers/computation overhead. Therefore, we want to investigate designing a more adaptive algorithm in future work.

Weak Correlation. MIAI attacks leverage the input-output dependency in the training dataset to estimate the sensitive attributes. If the correlation between the sensitive attribute and label is weak or no correlation exists, the corresponding sensitive attribute is less or not at all vulnerable to an MIAI attack. Therefore, our proposed algorithm generates fewer or no attack records in case of weak or no correlation.

VIII. Conclusions

This paper proposes a new black-box MIAI attack leveraging the least adversarial capabilities. We experimentally evaluate our proposed SDMIA with three target models trained on three datasets and show that they perform comparably to existing attacks for binary and multi-valued sensitive attribute estimation. We extend our study to investigate disparity in MIAI and show that two existing privacy defense techniques, *mutual information regularization* and *fairness constraints*, are not consistently effective in disparity mitigation. We also analyze potential disparity factors and their impacts on the disparity in MIAI. Finally, we discuss potential disparity mitigation techniques based on our experimental findings. Our work sheds light on the future of developing robust multi-factor-based defense to mitigate *disparity* in MIAI attacks.

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TABLE IX: Sensitive attributes (multi-class) in Training datasets.

Dataset	Training Instances	Sensitive attribute	Classes
NLSY	5096	race	4
Adult	35222	education	3
Adult	35222	race	5
Texas	67443	severity_illness	5
FiveThirtyEight	331	age	4

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Appendix

A. Synthetic Data Generation Algorithm for SDMIA

Algorithm presents the steps of the synthetic data generation.

B. Disparity Factors Computation

We compute all 8 disparity factors, either training data or target model related, contributing to the *MIAI disparity*.

Algorithm 1 Synthetic Data Generation Algorithm

Input: Sensitive attribute: $x_s \in \{x_1, ..., x_k\}$**, Non-sensitive attribute:** $x_2 \in \{x_{2,1}, ..., x_{2,ns}\}, ...x_d \in \{x_{d,1}, ..., x_{d,ns}\}$
Output: $Synthetic\ Dataset\ DS_A$

procedure $Data\ Synthesize(Sensitive : x_s)$
  $x^- \leftarrow RANDV(x_2...x_d)$ ▷ Initialize $d-1$ non-sensitive
  $j \leftarrow 0$ ▷ Counter
  $d_{max} \leftarrow c_{max}$ ▷ Max non-sensitive to change
  $d_{min} \leftarrow 1$ ▷ Min non-sensitive to change
  $r_{max} \leftarrow 2$ ▷ Max number of rejection
  for $iteration = 1\ to\ iter_{max}$ **do**
    $x_{\delta 1} \leftarrow x_1 \cup x^-$ ▷ Generate k records
    ⋮
    $x_{\delta k} \leftarrow x_k \cup x^-$
    $y'_1 \leftarrow f_{tar}(x_{\delta 1})$ ▷ Query target with k records
    ⋮
    $y'_k \leftarrow f_{tar}(x_{\delta k})$
    if $(y'_1 \neq null)$ & $...(y'_k \neq null)$ **then**
      if $y'_1 \neq y'_2 ... \neq y'_k$ **then**
        return $x_{\delta 1}, x_{\delta 2}, ...x_{\delta k}$ ▷ Sample Accepted
      else
        $j \leftarrow j + 1$ ▷ Sample Rejected, increment counter
        if $j \geq r_{max}$ **then** ▷ Update d_{max}
          $d_{max} \leftarrow max(d_{min}, \lceil d_{max}/2 \rceil)$
          $j \leftarrow 0$
        end if
      end if
    end if
    $x^- \leftarrow RANDV(x^-, d_{max})$ ▷ Re-randomize x^-
  end for
  return $null$
end procedure

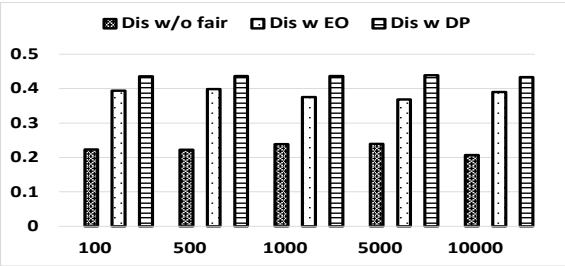

Fig. 13: Disparity in *sex* subgroups in Adult dataset (*female* target), while estimating *marital* sensitive attribute.

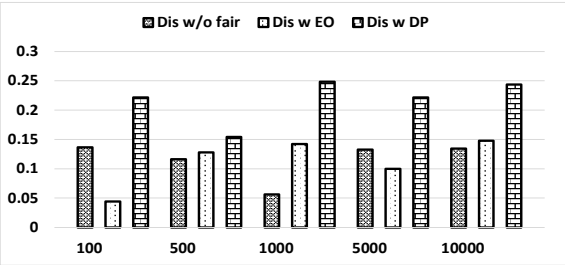

Fig. 14: Disparity in *race* subgroups in Adult dataset (*black* target), while estimating *marital* sensitive attribute.

1) Correlation: We calculate correlations of each subgroup with label attributes in the training data. We first test the following hypotheses by performing the Chi-square (χ^2) test [38]. H_0 (null hypothesis)= S_0 and O_0 are independent, and H_a (alternate hypothesis)= S_0 and O_0 are correlated, where S_0 is the subgroup attribute and O_0 is the label, all variables are categorical. We consider significance level $\alpha = 0.05$. We present the categories in label attribute (*m*) and subgroup attributes (*n*) in a *m* x *n* contingency matrix, where $m \geq 2$, $n \geq 2$ and degrees of freedom $d_f = (m-1)*(n-1)$. We calculate the p-value applying the χ^2 test. If p-value≥ 0.05, we fail to reject the null hypothesis H_0. Otherwise, we reject H_0 and accept the alternate hypothesis H_a, indicating a significant correlation. If the test accepts H_a, we compute the correlation in terms of Cramer's values, as follows:

$$C_v = \sqrt{\frac{\chi^2}{[n_total * (min(m,n) - 1)]}} \tag{10}$$

Where, *n_total* is the total instances, and C_v is Cramer's value. We define *correlation* of a subgroup by computing average Cramer's value with respect to other subgroups.

2) Mutual Information: Mutual Information (MI) captures the mutual dependency between two variables (i.e., subgroup and label attributes in our experiment). For each subgroup,

TABLE X: Abbreviation Table.

Abbreviation	Complete meaning
x_s	sensitive attribute
x_{ns}	non-sensitive attribute
d	total number of attributes
$\mathcal{I}mp_{AI}$	attribute Importance
$\mathcal{M}_A$	attribute Metric
$\mathcal{S}_{x_d}$	samples reaching to attribute node x_d
L_c	left Child
R_c	right Child
EO	equalized odds fairness constraint
DP	demographic parity fairness constraint
AMD	absolute maximum disparity
MMDD	maximal mean disparity deviation
DT	decision tree
LR	logistic regression
DNN	deep neural network
f_{tar}	target model
f_{adv}	attack model
DS_A	attack dataset
$\mathcal{V}_a(\mathcal{A})$	average vulnerability
$\mathcal{V}_s(\mathcal{A})$	subgroup vulnerability
$\mathcal{V}_{ds}(\mathcal{A})$	disparity
x_b	subgroup attribute
S_g	subgroup
$\mathcal{V}'_s(\mathcal{A})$	predicted subgroup vulnerability
d_{ta}	target instances
IQR	interquartile range
δ	generic distance
$\mathcal{H}$	Shannon's entropy
$\mathcal{I}$	mutual information
$\mathcal{L}_{mi}$	mutual inf regularization loss
val_{coef}	coefficient of a disparity factor
ϕ	property function
SDMIA	synthetic data-based MIAI attack

TABLE XI: Target model performances trained on NLSY dataset (tested on *training* dataset)

Model	Precision	Recall	Accuracy	F1 score
DT	43.41%	35.2%	44.72%	36.00%
DNN	32.01%	30.37%	33.48%	26.00%
LR	27.17%	26.03%	36.87%	24.00%

TABLE XII: Target model performances trained on FiveThirtyEight dataset (tested on *training* dataset)

Model	Precision	Recall	Accuracy	F1 score
DT	95.18%	96.86%	96.38%	96.00%
DNN	15.31%	18.77%	8.46%	1.00%
LR	28.51%	25.82%	46.53%	22.00%

we compute the mean of pairwise MI with respect to another subgroup, each time considering a different subgroup, and finally calculate the mean. We compute MI by calculating the difference between the entropy of label $\hat{Y}$, and conditional entropy of label $\hat{Y}$, given the subgroups attribute X, presented with Shannon's entropy [36] as below:

$$\mathcal{I}(X, \hat{Y}) = \mathcal{H}(\hat{Y}) - H(\hat{Y}|X) \tag{11}$$

Where, the conditional entropy $\mathcal{H}(\hat{Y}|X)$ can be formally defined as below from Shannon's entropy:

$$\mathcal{H}(\hat{Y}|X) = -\sum P(X, \hat{Y}) \log \frac{P(X, \hat{Y})}{P(X)} \tag{12}$$

where Shannon's entropy [36] is formally defined as:

$$\mathcal{H}(X) = -\sum_{i=1}^{n} P(x_i) \log P(x_i) \tag{13}$$

where there are n possible outcomes $x_1, ..., x_n$ of the random variable X with the probability of them occurring being $P(x_1), ..., P(x_n)$.

3) Marginal Prior: Marginal prior is the subgroup probability of an attribute in the training data, derived as the ratio of the number of instances of that particular subgroup and total instances, denoted as follows:

$$\mathcal{MP}_{class_1} = \frac{N_{class_1}}{N} \tag{14}$$

Where, $\mathcal{MP}_{class_1}$ is the marginal prior of a class $class_1$, N_{class_1} number of subgroup instances and N is total instances.

4) Distributional Overfitting: We consider the *overfitting* as a feature to identify the gap between model performance on training and test data (accuracy), defined as below:

$$\mathcal{OV}_{fit} = Acc_{tr} - Acc_{te} \tag{15}$$

where $\mathcal{OV}_{fit}$ is the overfitting of a subgroup, Acc_{tr} and Acc_{te} are prediction accuracy on training and test data.

5) Skewness: Skewness is a distributional property. It measures the deviation of the distribution from the symmetric normal distribution. We compute skewness as follows:

$$\mathcal{S}_y = \frac{\sum_{i=1}^{N}(y_i - \bar{y})^3/N}{\sigma^3} \tag{16}$$

where $\mathcal{S}_y$ is the skewness of label y and N is the total number of instances, and $\bar{y}$ is the mean.

6) Kurtosis: Like skewness, kurtosis is a property of the distribution. Kurtosis measures the distributional peak heights with respect to the center. We compute kurtosis as follows:

$$\mathcal{K}_y = \frac{\sum_{i=1}^{N}(y_i - \bar{y})^4/N}{\sigma^4} \tag{17}$$

where $\mathcal{K}_y$ denotes the kurtosis of label y. The higher the $\mathcal{K}_y$ means the distribution is highly tailed on the center.

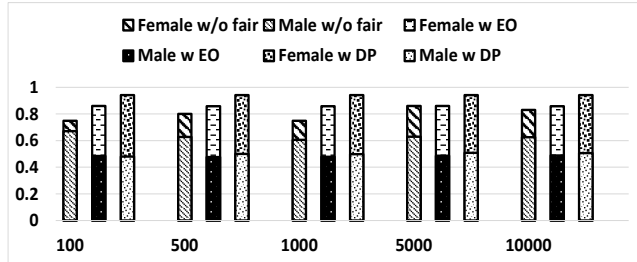

Fig. 15: Comparison between *sex* subgroups (*male* target) vulnerabilities without fairness, with DP, and EO constraints, while estimating *marital* (Adult dataset). lower and higher bars are two subgroup vulnerabilities, so the upper half of each bar is disparity.

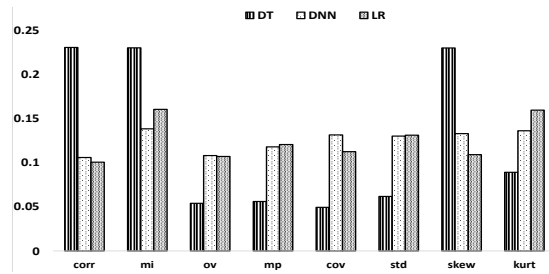

Fig. 16: Disparity factors' weights in Adult dataset, varying target models (DT or DNN or LR). *Notations: corr=correlation, mi=mutual information, ov=overfitting, mp=marginal prior, cov=covariance, std=standard deviation, skew=skewness, kurt=kurtosis.

7) Covariance: While *correlation* measures the strengths of association between two variables, *covariance* measures the direction of this association (positive if it moves in the same direction, otherwise, negative). We compute the *covariance* in our experiment between the subgroup and label attribute. We calculate the covariance using the following formula:

$$\mathcal{C}_{ov}(A, B) = \frac{\sum_{i=1}^{N}(A_i - \bar{A})(B_i - \bar{B})}{N} \tag{18}$$

Where $\mathcal{C}_{ov}(A, B)$ is the covariance, N is the total number of instances, A_i and B_i are instance values for the attributes, and their corresponding means are $\bar{A}$ and $\bar{B}$.

8) Standard Deviation: Standard deviation (σ) is the amount of variation of data samples from the expected value. We compute this on the label distribution of the subgroups. We calculate σ in terms of the mean μ, as follows:

$$\sigma_y = \frac{\sum_{i=1}^{N}(y_i - \mu)}{N} \tag{19}$$

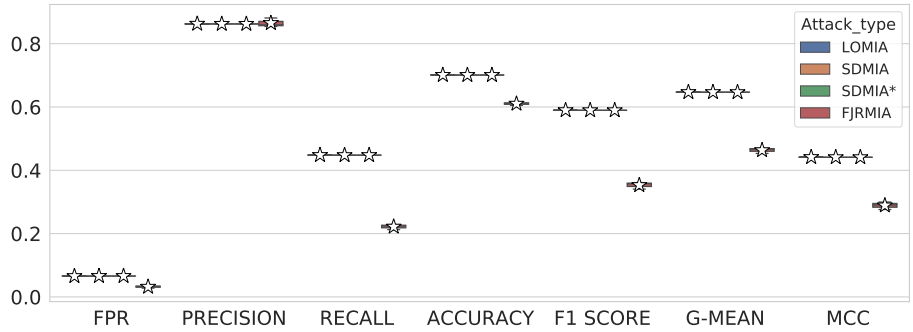

Fig. 17: Comparison of performance metrics distribution among the existing FJRMIA, LOMIA, and our proposed SDMIA obtained from 3 target models trained on Adult dataset estimating *marital* sensitive attribute (balanced marginal prior *married* positive class).

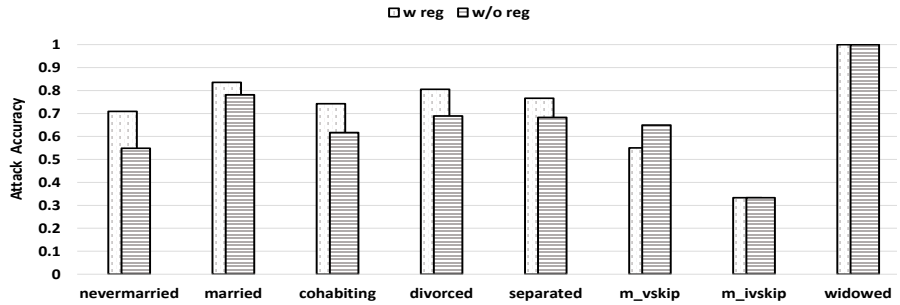

Fig. 18: Comparison among vulnerabilities of *marital* subgroups with and without MI regularization, while estimating *drug_marijuana* sensitive attribute in NLSY dataset.

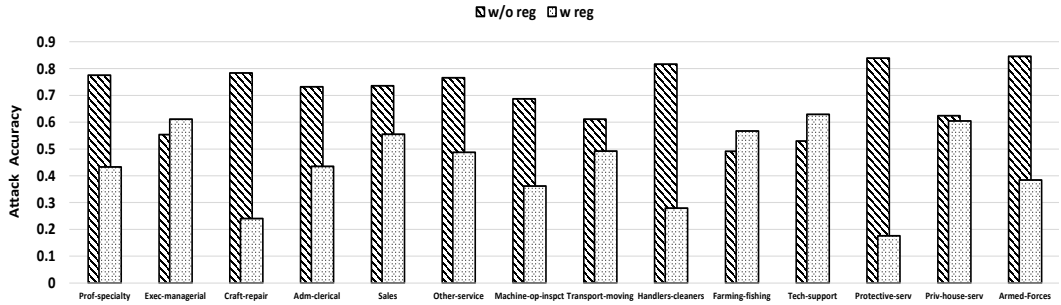

Fig. 19: Comparison between vulnerabilities of *occupation* subgroups with and without MI regularization, while estimating *marital* sensitive attribute in Adult dataset.

TABLE XIII: *p-value* on ANOVA test & pairwise t-test with correction for *race* subgroups in Adult dataset.

p-value	White	Asian-Pac-Islander	Amer-Indian-Eskimo	Other	Black
White	1.000000	1.000000	0.535602	0.044286	0.000837
Asian-Pac-Islander	1.000000	1.000000	0.187795	0.004859	0.000837
Amer-Indian-Eskimo	0.535602	0.187795	1.000000	1.000000	0.000246
Other	0.044286	0.004859	1.000000	1.000000	0.000037
Black	0.000837	0.000837	0.000246	0.000037	1.000000

TABLE XIV: *p-value* on ANOVA test & pairwise t-test with correction for *race* subgroups in NLSY dataset.

p-value	nonblhis	black	hispanic	mixed
nonblhis	1.000000	1.000000	0.035558	0.002349
black	1.000000	1.000000	0.020586	0.002349
hispanic	0.035558	0.020586	1.000000	0.259587
mixed	0.002349	0.002349	0.259587	1.000000

TABLE XV: *p-value* after ANOVA test and pairwise t-test with Benjamini-Hochberg correction on *marital* subgroups in NLSY dataset.

p-value	nevermarried	married	cohabiting	divorced	separated	m_vskip	m_ivskip	widowed
nevermarried	1.000000	1.000000	0.96816	1.000000	0.067627	0.461070	1.000000	1.00000
married	1.000000	1.000000	1.00000	1.00000	0.461070	11.000000	1.000000	1.000000
cohabiting	0.968160	1.00000	1.000000	1.000000	1.00000	0.104640	1.000000	0.96816
divorced	1.000000	1.000000	1.000000	1.000000	0.897037	0.461070	1.000000	1.000000
separated	0.067627	0.46107	1.00000	0.897037	1.000000	0.002724	0.150231	0.46107
m_vskip	0.461070	1.00000	0.10464	0.46107	0.002724	1.000000	0.461070	1.000000
m_ivskip	1.000000	1.000000	1.0000006	1.000000	0.150231	0.461070	1.000000	1.000000
widowed	1.000000	1.000000	0.96816	1.000000	0.461070	1.000000	1.000000	1.000000

TABLE XVI: Attack performance while inferring drug_marijuana sensitive attribute, against LR target model trained on NLSY dataset

Attack Strategy	Query #	TP	TN	FP	FN	Precision	Recall	Accuracy	F1 score	G-mean	MCC
FJRMIA [3]	10192	57	3966	169	904	25.22%	5.93%	78.94%	9.60%	23.85%	3.50%
LOMIA [11]	10192	523	2249	1886	438	21.71%	54.42%	54.40%	31.04%	54.41%	6.90%
SDMIA	10192	604	2421	1714	357	26.06%	62.85%	59.36%	36.84%	60.66%	16.81%
SDMIA*	5096	545	2268	1867	416	22.60%	56.71%	55.20%	32.32%	55.77%	9.06%

TABLE XVII: Attack performance while inferring drug_marijuana sensitive attribute, against DNN target model trained on NLSY dataset

Attack Strategy	Query #	TP	TN	FP	FN	Precision	Recall	Accuracy	F1 score	G-mean	MCC
FJRMIA [3]	10192	3	4126	9	958	25.00%	0.31%	81.02%	0.62%	5.58%	0.76%
LOMIA [11]	10192	343	2680	1455	618	19.08%	35.69%	59.32%	24.86%	48.10%	0.41%
SDMIA	10192	184	3081	1054	777	14.86%	19.15%	64.07%	16.73%	37.77%	−5.79%
SDMIA*	5096	262	2807	1328	699	16.48%	27.26%	60.22%	20.54%	43.02%	−4.10%

TABLE XVIII: Attack performance while inferring *alcohol* sensitive attribute, against LR target model trained on FiveThirtyEight dataset

Attack Strategy	Query #	TP	TN	FP	FN	Precision	Recall	Accuracy	F1 score	G-mean	MCC
FJRMIA [3]	662	266	0	65	0	80.36%	100.00%	80.36%	89.11%	0.00%	0.00%
LOMIA [11]	662	169	31	34	97	83.25%	63.53%	60.42%	72.07%	55.05%	9.16%
SDMIA	662	169	31	34	97	83.25%	63.53%	60.42%	72.07%	55.05%	9.16%
SDMIA*	331	169	31	34	97	83.25%	63.53%	60.42%	72.07%	55.05%	9.16%

TABLE XIX: Attack performance while inferring *alcohol* sensitive attribute, against DNN target model trained on FiveThirtyEight dataset

Attack Strategy	Query #	TP	TN	FP	FN	Precision	Recall	Accuracy	F1 score	G-mean	MCC
FJRMIA [3]	662	256	3	62	10	80.50%	96.24%	78.25%	87.67%	21.08%	1.75%
LOMIA [11]	662	0	65	0	266	0%	0%	19.64%	0%	0%	0%
SDMIA	662	154	23	42	112	78.57%	57.89%	53.47%	66.67%	45.26%	−5.43%
SDMIA*	331	136	29	36	130	79.07%	51.13%	49.85%	62.10%	47.76%	−3.38%

TABLE XX: Attack performance while inferring *marital* sensitive attribute, against LR target model trained on Adult dataset

Attack Strategy	Query #	TP	TN	FP	FN	Precision	Recall	Accuracy	F1 score	G-mean	MCC
FJRMIA [3]	70444	3861	17697	632	13032	85.93%	22.86%	61.21%	36.11%	46.98%	29.06%
LOMIA [11]	70444	7565	17121	1208	9328	86.23%	44.78%	70.09%	58.95%	64.68%	44.12%
SDMIA	70444	7565	17121	1208	9328	86.23%	44.78%	70.09%	58.95%	64.68%	44.12%
SDMIA*	35222	7565	17121	1208	9328	86.23%	44.78%	70.09%	58.95%	64.68%	44.12%

TABLE XXI: Attack performance while inferring *marital* sensitive attribute, against DNN target model trained on Adult dataset

Attack Strategy	Query #	TP	TN	FP	FN	Precision	Recall	Accuracy	F1 score	G-mean	MCC
FJRMIA [3]	70444	3592	17717	612	13301	85.44%	21.26%	60.50%	34.05%	45.34%	27.62%
LOMIA [11]	70444	7565	17121	1208	9328	86.23%	44.78%	70.09%	58.95%	64.68%	44.12%
SDMIA	70444	7565	17121	1208	9328	86.23%	44.78%	70.09%	58.95%	64.68%	44.12%
SDMIA*	35222	7565	17121	1208	9328	86.23%	44.78%	70.09%	58.95%	64.68%	44.12%

Summary of Changes: We thank the reviewers for their constructive comments on improving the manuscript. We have carefully reviewed and addressed the reviewers' comments in the revised manuscript. In this revised version, we have clarified different explanations and provided details of motivation and illustrations, where applicable. We also put effort into removing any inconsistencies and fixed key criticisms. Additionally, we provide better background studies following reviewer recommendations, significantly improve presentation, and illustrate the advantages of our work. According to the reviewer's suggestion, considering significant contributions to other parts, we have removed the disparity prediction model and focused on our attack along with explaining insights for future research direction. Finally, we have improved the write-up and proofread the paper to improve the overall quality of the manuscript.

****
This manuscript was last submitted to the 23rd Privacy Enhancing Technologies Symposium (PETS 2023). We have appended the reviewer comments along with how we have addressed them in the revised manuscript during this IEEE SaTML 2023 submission.
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Review #54A
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* Updated: 25 Jul 2022 9:55:15pm EDT

Overall merit
---
3. Major Revisions needed

Reviewer expertise
---
3. Knowledgeable

Reviewer confidence
---
2. Medium

Relevance to PETS
---
3. Directly related to PETs (scope is not an issue)

Ethical considerations
---
4. I don't see any ethical implications for this paper.

Paper summary

The paper's main contribution is a new model inversion attribute inference (MIAI) attack with minimal assumptions about the adversary's capabilities. The authors also study the disparate vulnerability to MIAI for specific MIAI attacks, including their own, and evaluate the effect of popular defenses on the disparities. The authors show, through empirical evaluations, that such countermeasures are ineffective in reducing the disparate impact and investigate the cause for their ineffectiveness by designing a disparity predictor that allows them to measure the importance of a range of "disparity factors." Their predictor evaluation shows that the cause of the disparities is multifactor and requires a defense that tackles multiple factors instead of focusing on just one as existing countermeasures do.

Comments for author

I agree with the meta-review of the previous submission in that the paper makes novel contributions to the field. The insights the authors obtain from the predictor into the defenses' ineffectiveness are interesting. Also, the study of the disparity of the impact of the attacks across demographics is an unexplored area. I think the authors have improved the presentation and structure of the paper since the previous submission. I still found many grammar mistakes (more specifically, the use of articles), but I would say this is no longer a reason for rejection.

Response: We have revised the manuscript and proofread it to improve the manuscript.

However, there are some issues with the current version of the paper that the authors should address. I hope the following comments will help the authors improve the paper.

- It is unclear how the three models are combined (Section 4.3.2). The authors mention an ensemble, but I am not sure why they do that and why they choose those models (DT, DNN, LR) as an ensemble, instead of bagging or boosting multiple instances of the same weak learner (random forest as an ensemble of decision trees).

Response: DT, DNN, and LR are the 3 different target models trained on the training datasets in BigML platform. Then, the corresponding attack dataset is generated with the API query to each target model (using the proposed algorithm in SDMIA). Finally, for each target model, we design an attack model as a bootstrap decision-tree forest of 10 decision tree models trained on the attack dataset (i.e., bagging technique denoted by the 1-click ensemble model feature in BigML).

In the revised manuscript, we have clarified this in Section IV-C2.

- Section 4.3.1 needs work. The authors do not mention what the sensitive attribute in each dataset is. I also do not understand why some datasets are multiclass (e.g., "ratelife" in NLSY), but the authors treat them as binary: what is the positive class in Table 2 in those datasets?

Response: We have revised the manuscript. Binary sensitive attributes are in Table II. For binary, we estimate positive class (Table II) using SDMIA. For multiclass, we present the average of all class estimation performances, and there is no positive class in multi-class. In the revised manuscript, for binary, we present sensitive attributes and corresponding positive classes in Table II. In Table IX in Appendix, we present multi-class sensitive attributes for different datasets that we consider in our experiments. We have also clarified this in text in Section IV-C2.

- Section 5.3.1 theoretically describes the regularization term, but it is unclear how the authors implement it. It would be helpful to provide more detail about how the authors implement the regularization (in particular, for the DT models). In addition, the authors should provide the source code (and ideally the models or model parameters) for all the experiments in the paper.

Response: In our implementation, we have modified the default loss function provided by the Scikit-learn ML library. We have computed and added another loss term ($\lambda I(x_b, y')$ in equation 7 on paper) with the default cross-entropy loss function in Scikit-learn. Our added loss term optimizes the mutual information between subgroup and label attributes.

We illustrate details implementation in Section V-D3 in the revised manuscript.
To ensure anonymity in the review process, we will provide all datasets, models, and source codes in the shared repository with the camera-ready version (once accepted) of the paper.

- The authors need to expand the explanation of some of the results. For example, the authors should explain the large error bars in Fig 4. They say they are "an indication for performance variations across different models" but can you offer at least a hypothesis for why these models perform so differently across runs?

Response: Target model architecture has an impact on the attack performances. However, among all attacks, our proposed SDMIA is more resistant to this phenomenon. This is due to the ability of our attack to capture the input-output dependency effectively compared to the existing attacks. FJRMIA and LOMIA query with the training data instances (known non-sensitive attributes). Since the training instances might have higher dissimilarity in non-sensitive attributes, this causes higher prediction variation across models. In other words, non-sensitive attributes also have significant importance in the attack. In SDMIA, random record generation with limiting search space enables higher similar record generation. This contributes to lower prediction variations across models (label has comparatively higher importance in the attack), thus causing less performance variations in the attack models.

We have added this explanation/clarification in Discussion in Section IV-C4.

- The authors mention that the fairness countermeasures do not impact model "utility." The authors should clarify the utility metric they use. In any case, I am surprised that ensuring fairness does not decrease utility, as it is well-known that ensuring fairness (except for some special cases) reduces model accuracy.

Response: We consider ‘accuracy’ as the utility metric (caption in Fig.11). Fairness slightly reduces target model accuracy in MIAI attack (Section V-C5, Fig.11), but not significantly. This is consistent with the findings in membership inference (ref.[15], page 472).

- The authors should give an estimation of the complexity of Algorithm 1. It seems the search space would be too big for large d's and continuous non-sensitive attributes.

Response: The complexity is $O(c_2 + c_1 * m)$, where m, c_1, and c_2, stand for loop counter (number of instances), array access time, and outside loop runtime. Therefore, algorithm1 has linear time complexity. We mention this in Section IV-B of the revised manuscript.

- The rationale for synthesizing the data is clear: it is more efficient for the attack to generate data that captures the correlation between the label and the sensitive attribute. However, can you comment on the attack's effectiveness when they are uncorrelated, or the correlation is weak?

Response: The MIAI attack aims to leverage the input-output dependency in the dataset to estimate the sensitive attribute. If the correlation (i.e., dependency) between sensitive attribute and label is weak or no correlation exists, the corresponding sensitive attribute is less or not at all vulnerable in MIAI. Therefore, in line with this principle, our proposed algorithm generates fewer or no attack records in case of weak or no correlation scenarios.

We have added this discussion in Section VII (Discussions and Limitations) of the revised manuscript.

- I am not sure why the authors say that having access to the confusion matrix is a strong assumption. Since they assume query access, the adversary can approximate the confusion matrix with the test dataset.

Response: SDMIA is more realistic with the least capabilities. Having access to ground truth/labels is a stronger assumption. Our assumption for the proposed attack is that adversary does not have access to the target model training data confusion matrix and individual training data instances. We also assume that the adversary does not have knowledge about label (ground truth) of training/test datasets. We assume it can only generate synthetic data (applying knowledge about possible values of the attributes), query the target model, and perform the attack. Since the adversary doesn’t have access to ground truth labels, therefore unable to compute the confusion matrix. In different real-life applications, it is not uncommon that there is no access to training data/confusion matrix or even ground truth labels (e.g., unsupervised learning scenarios with unlabeled data such as anomaly detection). Existing attacks with very stronger assumptions fail in those cases. Therefore, in our work, we consider a more realistic case with limited capabilities and show that still, MIAI attack is effective.

We have clarified our assumptions in Section I (Introduction).

- I don't understand why "ratelife" appears as a column in Fig. b. That is the label, so it is clearly important. In fact, I am surprised that it is not 100%.

Response: There are two ML models- target and attack model. In the target model, 'ratelife' is the label, and 'drug_marijuana' is the label in the attack model. Fig. 1(b) shows the attribute importance for the attack model, where 'ratelife' is an input attribute (target model label is input in attack model, as defined in MIAI definition), and therefore in the attack model, it appears as an input attribute column. This figure shows that the target model label attribute that has the highest attribute importance is the MIAI attack model.

- The authors should show the training accuracies of the target models to give a sense of whether they are overfitting.

Response: We present the performance of different target models trained on different datasets in Tables III, IV, XI, and XII in the revised manuscript. Note that Tables III, IV show performances of different target models trained on Adult dataset, tested on training and test sets, respectively. It shows the target model, either DT/DNN/LR performs similarly on both training and test datasets. Since there is no significant difference in target model performances between the training and test dataset, we conclude that target models do not significantly suffer from overfitting. We also illustrated this clarification in Section IV-C2 in the revised manuscript.

Minor comments

- It is unclear what "factors" mean in the introduction (I would add a few words to explain it).

Response: In this work, we have analyzed potential disparity contributing features/properties in the MIAI context (e.g., correlation, marginal priors, etc.) termed as 'factors.' These factors can be related to the model itself or depend on the training data distribution. We have clarified 'factors' in the introduction (Section I) of the revised manuscript.

- Some relevant concepts are not defined. For example, Section 4.3.3 requires a definition of "attack stability."

Response: We have explained "attack stability" in Section IV-C3 in the revised manuscript.

- Error bars in Figure 7 and onwards are missing.

Response: Figures 7, 8 are the plots considering a run for a single target model. Therefore, there are no standard deviation and error bars in these figures. Figures 9 and 10 have very insignificant standard deviations; therefore, we do not consider error bars for these figures.

- The font of the text in all the figures is too small; it's hard to read.

Response: We have redrawn all figures with increased font size to make them readable.

- Figure 13 is hard to interpret. The patterns are confusing.

Response: We have redrawn Figure 13, and split it into multiple figures to make it easier to interpret. They are represented in Figures 12, 13, and 19 in the revised manuscript.

- Unclear what "model name" means in Section 6.1.1. I guess this is the name of the underlying learning algorithm.

Response: Yes, that's the type of model used as the target model, for e.g., decision tree, logistic regression, etc.

Areas to address in response

I have sorted the bullet points with my comments by order of importance.

Response to authors' rebuttal

I thank the authors for their rebuttal. The authors have addressed some of my comments, but I am not satisfied with the following answers:

- I am still confused by the mention of "logistic regression" and "deep neural networks" in Section 4.3.2: are those the target models? And then you only use a random forest for the attack model? Please, clarify.

Response: Yes, that's correct. DT, DNN, and LR are the 3 different target models trained on the training datasets in BigML platform. Then with the API query to each target model (using the proposed algorithm in SDMIA), the corresponding attack dataset is generated. Finally, for each target model, we design an attack model as a bootstrap decision-tree forest of 10 decision tree models trained on the attack dataset (i.e., bagging technique denoted by the 1-click ensemble model feature in BigML).

In the revised manuscript, we have clarified this in Section IV-C2.

- I understand the idea behind your regularization; I was asking for details about the implementation: did you modify BigML's loss function? Did you use a different ML package? Or did you implement the optimization with the regularization term yourself?

Response: In our implementation, we have modified the default loss function provided by the Scikit-learn ML library. We have computed and added another loss term ($\lambda l(x_b, y')$ in equation 7

on paper) with the default cross-entropy loss function in Scikit-learn. Our added loss term optimizes the mutual information between subgroup and label attributes.

We illustrate details implementation in Section V-D3 in the revised manuscript.

- In the next revision of the paper, please, provide the source code and data for *all* the experiments, not only the regularization part.

Response: To ensure anonymity in the review process, we will provide all datasets, models, and source codes in the shared repository with the camera-ready version (once accepted) of the paper.

- Why can't the adversary collect or obtain a test dataset with the ground truth? I feel the authors are making an assumption about the scenario where the attack is applied that I'm missing.

Response: SDMIA is more realistic with the least capabilities. Having access to ground truth/labels is a stronger assumption. Our assumption for the proposed attack is that adversary does not have access to the target model training data confusion matrix and individual training data instances. We also assume that the adversary does not have knowledge about the label (ground truth) of training/test datasets. We assume it can only generate synthetic data (applying knowledge about possible values of the attributes), query target model and perform attack. Since the adversary doesn't have access to ground truth labels, therefore unable to compute the confusion matrix. In different real-life applications, it is not uncommon that there is no access to training data/confusion matrix or even ground truth labels (e.g., unsupervised learning scenarios with unlabeled data such as anomaly detection). Existing attacks with very stronger assumptions fail in those cases. Therefore, in our work, we consider a more realistic case with limited capabilities and show that still, MIAI attack is effective.

We have clarified our assumptions in Section I (Introduction).

- Table 9 does not tell me whether there is overfitting. You need to compare the target model performance between testing on the training and the test datasets.

Response: We present the performance of different target models trained on different datasets in Tables III, IV, XI, and XII in the revised manuscript. Note that Tables III, IV show performances of different target models trained on Adult dataset, tested on training and test sets, respectively. It shows the target model, either DT/DNN/LR performs similarly on both training and test datasets. Since there is no significant difference in target model performances between the training and test dataset, we conclude that target models do not significantly suffer from overfitting. We also illustrated this clarification in Section IV-C2 in the revised manuscript.

* *

Review #54B
==========
* Updated: 27 Jul 2022 5:59:10am EDT

Overall merit
---
2. Reject and Resubmit

Reviewer expertise
---
3. Knowledgeable

Reviewer confidence
---
3. High

Relevance to PETS
---
3. Directly related to PETs (scope is not an issue)

Ethical considerations
---
4. I don't see any ethical implications for this paper.

Paper summary

The paper studies Model Inversion Attribute Inference (MIAI) attacks against machine learning models, where the goal of the adversary is to infer a sensitive attribute of a given data sample from its remaining attributes by querying a target model.

The paper proposes a new attack, called SDMIA, that only requires black-box access to the target model and label-only leakage (the model returns the labels, and not confidence scores). Authors show the proposed attack provides similar performance to existing attacks that require additional leakage (scores), even when SDMIA requires half the queries to the model.

Furthermore, the paper studies the vulnerability of different subgroups of the training data to MIAI attacks, and shows that two existing defense techniques that aim at preventing disparate vulnerability in membership inference are not effective against MIAI attacks.

Finally, the paper proposes MIDP, a disparity prediction model that aims at predicting the vulnerability of different subgroups against MIAIs given different features computed from a dataset.

Comments for author

Authors have done significant changes in the document. The new document structure, where the core of the paper is separated into three big sections (SDMIA attack, disparate vulnerability study, and disparity prediction model), each with its own evaluation, is more intuitive and easier to follow than the previous version.

The authors have addressed most of the reviewers' concerns: the new structure is easier to follow, the paper explains the SDMIA algorithm and the MIDP training more clearly, the cases where $k>2$ are now explained, and the paper gives more intuition about why the fairness constraints seem to worsen disparity. The evaluation of disparity is also clearer and authors have included disparity plots in the appendices. The paper still has plenty of writing issues, incorrect statements, vague explanations, etc. I give details about these issues below, but I believe should be relatively easy to fix.

I think SDMIA and the vulnerability evaluation (Sections 4 and 5) are good contributions to the field. However, I am still not convinced by the vulnerability prediction model (MIDP, Section 6): even though the new version of the paper has improved the explanations of this part, the results still indicate that MIDP performance is not consistent (more on this below).

I think this could be a good paper without the MIDP contribution (the new attack plus the disparity analysis would perhaps be an enough contribution, even if we ignore Section 6).

Response: Thanks for the constructive feedback. We have fixed the writing issues and provided clarifications in the revised manuscript. According to the reviewer's recommendation, in the revised manuscript, we have removed the MIDP and rather focused on better clarifying our proposed attack and in-depth analysis of its disparate vulnerability property.

Below are more detailed comments:

C1) The paper states, in different places, that "our goal is to mitigate disparity in MIAI". This is not correct. This paper proposes a new attack, then measures how well existing techniques to reduce disparate vulnerability work against MIAI, and finally proposes a model to predict this disparity. It never tries to mitigate the disparity (e.g., by proposing a new defense technique). Please fix this in Section 3 (second paragraph), and in S5.3 (first paragraph).

Response: Yes, our goal is to perform an in-depth analysis of disparity in MIAI and provide insights (based on empirical findings) as a basis of possible direction for future disparity

mitigation defense design and deployment. We have fixed the inconsistencies in Section I, Section III, Section V-C, and Section VIII.

C2) SDMIA Training (S4.2.1)
The selection step for $k\geq 2$ is still somewhat confusing in the text. It is explained in two (contradictory) ways:
- Example 1) The text mentions that "the adversary includes the generated query instances to the attack model training dataset [...] if more than one sensitive attribute value do not generate the same prediction" (otherwise they're rejected).
- Example 2) In the same paragraph, the text explains that "k query instances set [...] is accepted to form DS_A if all the predictions [...] are different [...]. If more than one prediction is same, set of instances is rejected".

I think these are different sets of rules. If only two query instances generate different predictions (the others are repeated), the rule in Example 1 would accept them (two is "more than one"). However, Example 2 would reject it (it requires all of them are different). Please, fix the text so that it is consistent. The figure is consistent with Example 2, so I believe this is the correct way. Please stick to the phrasing in Example 2.

Response: Yes, all k-predictions need to be different to be accepted (as illustrated in Fig.1(a)), So, Example 2) is correct. We have fixed this in Section IV-B-1 in the revised manuscript.

At the end of S4.2.1, the paper explains that, in order to capture a strong dependency, "we only consider accepting the set of instances to form DS_A, when more than one sensitive attribute value does not yield the same prediction.". This is in line with the Example 1 above. Is this correct? Also, this text reads as if you were changing the rule that decides inclusing in DS_A. Is anything changing here compared to the previous text, or why is it phrased like that?

Response: No, we are not changing the rule here. Example 2) is the correct one that we use everywhere. We have fixed this in Section IV-B-1 in the revised manuscript.

Regarding the d_{max} updating: when there are many consecutive rejections, d_{max} is reduced. Is there an intuition for this? Why do you reduce it instead of increasing it? (if I can't find suitable features that lead to different predictions, maybe I would try to change more of the features, not less).

Response: We reduce d_max to control search diameter around accepted records while re-randomizing. This enhances search speed. Also, as accepted records vary in the least #of attributes, it better captures the correlation between the sensitive attribute and label. We do not update d_min (set to 1). We have clarified this in Section IV-B-1 in the revised manuscript.

C3) MIDP explanation.
While Section 6 is clearer now, I still can't follow how MIDP is trained:

- What makes an actual "row" of Training1 and Training2 datasets? Is it that one "subgroup" corresponds to one row? I do not understand why we have 216 and 210 "rows" for NLSY and Texas, respectively. How do we get that number of "subgroups"?
- Figure 12 depicts two datasets, D1 and D2, that are used to compute disparity features and subgroup vulnerabilities, which then are stacked together and used to train the MIDP. Why do we need two datasets? Are there any of the features computed using a difference between datasets? Is the process the same if we simply stack D1 and D2 (along rows), and then compute disparity features and vulnerabilities? (if we don't need two datasets, the figure should explain how MIDP training works in general, not tailored to the evaluation in this paper).
- S6.1.3 explains the input features (DF module) are concatenated with the vulnerabilities, and these are fit to a linear regression model. Are the vulnerabilities also inputs to the regression model, or are those the values the model is trying to predict? Also, is there one vulnerability value per row/feature set, or multiple values?
- S6.1.3 mentions that MIDP-T uses 7 features and MIDP-TM uses "all 9 features". However, the paper introduced a total of 11 features (including the 2 based on sensitive features). The paper should clarify here what happens with those 2 sensitive features. This is mentioned later in S6.2.1, but it should be earlier.
- The "mean" baseline vulnerability prediction "predicts the subgroups' vulnerabilities as the mean of the data for every subgroup instance". This is rather vague ("the mean of the data"). Does this take the vulnerability of every subgroup, compute the average vulnerability, and report that?

Response: As per the reviewer's recommendation, we have removed the MIDP in the revised manuscript and focused on better clarifying our proposed attack and in-depth analysis of its disparate vulnerability property.

C4) MIDP performance:
- The paper mentions that "MIDP outperforms state-of-the-art mean and random prediction models". Are these actual prediction models proposed in other works? How is choosing a vulnerability "at random" a state-of-the-art technique?
- The paper mentions, regarding Table 12 in Appendix, that "[the table] shows that MIDP performs significantly better than baselines" -> The "mean" baseline provides MAE, MSE and RMSE of 0.09, 0.01 and 0.1, respectively. MIDP-T provides 0.08, 0.01, and 0.1, respectively. They perform almost identically. MIDP is not "significantly" better.
- While MIDP prediction in Fig 15 seems nice, the cases in Figs 20, 22, and 23 are consistently bad (the actual vulnerabilities are very far from the predicted ones; this can be seen in the plots). The text mentions that MIDP finds "a consistent pattern between actual and predicted vulnerabilities", but I think the plots do not say that. The results indicate that MIDP is not consistent in predicting vulnerabilities and other techniques such as empirically evaluating MIAI attacks in the dataset, although more expensive, are safer approaches to predict vulnerability.

Response: According to the reviewer's recommendation, we have removed the MIDP in the revised manuscript and rather focused on better clarifying our proposed attack and in-depth analysis of its disparate vulnerability property.

C5) MINOR, general:
- "Importance" is still not defined formally.
Response: We have formally defined 'Attribute Importance' in Section II of the revised manuscript.

- Please add the number of classes for the Texas, FiveThirtyEight and GSS datasets in S4.3.1, since this is not in the description.

Response: We present the number of classes in Table IX in the revised manuscript.

- Table 9 reports accuracies by providing a link to a website hosting an image with the accuracy of each model. I think the paper should have the actual accuracy values in the table, since we can't guarantee those images are going to be hosted there forever. Why not just include an overall utility metric, like the accuracy, in the table, instead?

Response: In the revised manuscript, we have removed Table 9, which reported model utilities. Instead of Table 9 redirecting (link shared) to model performance images, we present actual values in the paper in Table III, Table IV, Table XI, and Table XII.

- S5.1: "where the gap (attack model)" -> I do not understand this "(attack model)". How is the gap related to the attack model? I thought it was simply a distance between vulnerabilities.

Response: Yes, it's a generic distance among subgroups' vulnerabilities computed in the attack model. In the revised manuscript, we have revised this.

- The same paragraph ends with "We propose two metrics to compute this gap.", but then the paper switches to something else, and the metrics are defined in S5.3.4. I think the metrics should be in S5.1 right at the end; they're small definitions, they would fit nicely here.

Response: We have updated accordingly in the revised manuscript.

- "the adversary in our least capability case can also leverage the disparity and target a specific subgroup" -> is the adversary "targeting" a subgroup, or simply performing better for samples in that particular subgroup? (I believe the adversary is not "targeting" the subgroup, e.g., tailoring the attack to perform better against the subgroup, it's just that it naturally performs better in that subgroup).

Response: Yes, we used 'targeting' to illustrate that if the adversary performs the attack for that particular subgroup (higher vulnerable), it naturally achieves better performance for that

subgroup. However, it does not tailor or manipulate to get better performance on that particular subgroup. We have rewritten this part.

- Some plots use "Subgroup Vulnerability" (Fig. 5) and others "Attack Accuracies" (Fig. 6) for the y-label, but I believe they represent the same (the attack accuracy is also the vulnerability). Please stick to one terminology so that it's easier to understand which plots are showing the same metric.

Response: We have fixed this. All Figures are redrawn with the "Attack Accuracies" y-label in the revised manuscript.

- S5.3.1: "label attribute y'" -> I believe this is not the actual label but the predicted label?
- Fig 8a and 8b have very different y-axis limits (one is zoomed in, the other one starts at 0). Please either start both at zero or zoom both in (and perhaps using the same limits for both plots would make them easier to compare).

Response: We have fixed this. Figures 8a, and 8b are redrawn in the revised manuscript.

- Figures 9 and 10 are stretched. Please generate figures of the same aspect ratio as the ones used in the paper, or use vector images.
Response: Figures 9, 10 are redrawn in the revised manuscript.

- In S6.1, the "(1) MIDP training process" and "(2) MIDP prediction process" are "\paragraph"'s, but they contain "subsubsections". It should be the other way around, since they are at a higher organization level.
Response: MIDP is removed in the revised manuscript based on reviewer feedback.

- Algorithm 1: Line 20: "argmax" -> should this be a "max", instead of "argmax"?
Response: Yes, it should be a “max.” We have addressed this in the revised manuscript.

- Algorithm 1: d_{max} is initialized to 2, and the update operation on line 20 will make it 1. These are hard-coded parameters. Thus, line 20 could just be $d_{max}<- 1$. If d_{max} can take other values, then change line 4 and make the algorithm more general.
Response: Yes, d_max can take other values. In the revised manuscript, we have updated line 4 and initialized d_max to some general value c_max, just to make this more generalized in the pseudocode.

- Algorithm 1: Line 25 is explained as "Re-randomize d_{max}". But this is re-randomizing x^-, not d_{max}.
Response: Yes, as explained in the SDMIA details in Section IV-B, we re-randomize non-sensitive attribute values (X^-) by changing d_max non-sensitive attribute values. In Algorithm 1, we have updated the comment in Line 25 to indicate re-randomizing X^-.

C6) MINOR/WRITING:
- p1: "[31], property inference [23]," -> add "[31], *and* property inference", to separate MIAI from the rest in this sentence.

Response: We have addressed this in the revised manuscript.

- p1: "knowledge of possible values of different attributes" -> this is too vague. What are "different attributes"? Different attributes chosen at random? All attributes? Or just the sensitive attribute that the adversary wants to predict?

Response: Our proposed SDMIA considers the least adversary capabilities. We assume the adversary can only API query to the black-box model and obtain predictions (no confidence score), and it has knowledge of possible values of all attributes (sensitive and non-sensitive) that it can consider applying to our algorithm to randomly choose values for attributes, generate random records, and obtain attack dataset based on query results. However, unlike existing attacks, we consider the adversary does not know any of the training instance's attribute values. Hence the attack is more realistic and challenging. We have clarified this in the revised manuscript.

- p2: "this notion captures serious privacy concern," -> concerns?
Response: We have addressed this in the revised manuscript.

- p2: "on a particular disjoint set of training instances or subgroups" -> I think the word "disjoint" makes the sentence more confusing here, since this is a high-level description.

Response: We have removed this in the revised manuscript.

- p2: "for same/similar distributions" -> "*the* same/similar"

Response: We have addressed this in the revised manuscript.

- p2: "the sensitive attribute, x_s, of the target model training data" -> this reads as if x_s was an attribute of the training data, not of a particular data sample in the model's training data.

Response: We have addressed this in the revised manuscript.

- p2: "ML-as-a-service(MLaaS)" -> add space before parenthesis

Response: We have addressed this in the revised manuscript.

- p3: "ML model either classification or regression predicts" -> this needs commas before "either" and after "regression", and either add an article if you keep it singular "An ML model," or "A ML model,", or "ML models," (if the latter, adjust sentence accordingly).

Response: We have addressed this in the revised manuscript.

- p3: "MIAI attacks on tabular data is" -> are

Response: We have addressed this in the revised manuscript.

- p3: "to defend MI attacks" -> *against* MI attacks

Response: We have addressed this in the revised manuscript.

- p3: "two parties are involved-- target individual and the adversary" -> it would be "a target individual", but also, I think the individual is not necessarily involved. It would be the model owner, and the adversary. (The adversary interacts with the model owner by issuing black-box queries, the individual's data might be part of the training data.)

Response: We have addressed this in S4.1 in the revised manuscript.

- p4: "consistent with baseline" -> *the* baseline

Response: We have addressed this in the revised manuscript.

- p4: "one sensitive attribute value [...] do not" -> *does* not

Response: We have addressed this in the revised manuscript.

- p4: "otherwise, we reject" -> reject *them*.
Response: We have addressed this in the revised manuscript.

- p4: "if more than one prediction is same, set of instances is rejected" -> *the* same, *the* set of instances.
Response: We have addressed this in the revised manuscript.

- p4: "we re-randomized" -> the whole explanation is in present tense; this should also be.
(There are many other writing issues, I stop describing them here for brevity. I recommend asking a native speaker to revise the document)

Response: We have addressed this in the revised manuscript. Thanks for the recommendation. We have reviewed and revised the manuscript by a native speaker.

Areas to address in response

- Regarding the rule to accept samples in DS_A: are the explanations I denote by "Example 1" and "Example 2" in my review contradictory? If so, which is the correct rule?

Response: Yes, all k-predictions need to be different to be accepted (as illustrated in Fig.1(a)), So, Example 2) is correct. We have fixed this in Section IV-B-1 in the revised manuscript.

- What makes one "training sample" (row) for MIDP? Does each subgroup defines one sample? How do we get 216 rows in NLSY dataset, for example?

Response: According to the reviewer's recommendation, we have removed the MIDP in the revised manuscript and focused on better clarifying our proposed attack (SDMIA) and in-depth analysis of its disparate vulnerability property.

Response to authors' rebuttal

Thanks for the revised manuscript and for the rebuttal. Although the paper has improved from the previous version, there are still many parts of the paper that need clarification, as pointed out by the reviewers. Some parts that should have been clear from the previous comments (e.g., clarify what happens with the rejection rule when $k>2$) are still unclear due to conflicting statements in the paper. Overall, I believe the paper should have been more clear and polished after one round of R&R; I am not confident that the paper will be above the acceptance bar after a Major Revisions round, so I recommend R&R.

Response: We have carefully reviewed the reviewers' comments and addressed them in our revised manuscript.

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Review #54C
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* Updated: 24 Jul 2022 9:43:53pm EDT

Overall merit
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3. Major Revisions needed

Reviewer expertise
---
2. Some familiarity

Reviewer confidence
---
3. High

Relevance to PETS
---
3. Directly related to PETs (scope is not an issue)

Ethical considerations
---
4. I don't see any ethical implications for this paper.

Paper summary

The authors study the attribute inference attacks. In MIAI, the adversary aims to infer the sensitive attribute of a data sample without access to sensitive attributes.

The paper proposes SDMIA, that assumes the adversary has only black-box
query access to the target model and only hard labels. The paper is the first to look at hard label attribute inference attack.

Comments for author

Strength:
- Strong attack under hard label scenario
- Effective against existing defenses

Weekness:
- Lack explanation on why SDMIA performs well under stronger assumptions
- Fail to cite and compare against prior works

While I wasn't a reviewer for the last round, I really enjoyed reading through this paper and it appears that the authors have carefully addressed revision requests.

My main concern is that the author did not explain the reason why the proposed SDMIA method perform well under a stronger threat model. For example, would existing approaches also work well under this hard label scenario if one adapts them? I would highly appreciate if the author can offer some more discussion on the benefit of SDMIA.

Response: Existing MIAI attacks depend on stronger adversarial capabilities. These capabilities are stronger assumptions and might not always prevail in the real world. This limitation is a crucial challenge to existing MIAI attacks in the literature and restricts the applicability of these attacks to a more practical scenario. Our proposed SDMIA renders the following benefits over

existing attacks: (i) novel back-box attack with the least capabilities, (ii) query-efficient attack (SDMIA* requires 50% less query), (iii) more realistic and broad applicability, (iv) performs similarly in most cases compared to existing attacks, and (v) achieves more-stable attack performances than state-of-the-art MIAI attacks varying target models.

In Section I (Introduction) in the revised manuscript, we have added this discussion and motivation.

Related, hard label MIA is not new. Several work [1][2] has looked at performing MI using only output labels. The authors should at least cite and discuss some of these works in related work section, despite that the paper is addressing attribute inferencing.

Response: Although our focus is MIAI, in the revised manuscript, we have cited and discussed the suggested membership papers in Section III (Related Work).

Lastly, it is unclear to me why attribute inferencing is more challenging than membership inferencing, and why can't an adversary uses membership inferencing techniques for attribute inference. Moreover, I would like to see some non-trivial effort of adapting existing approach and check whether the proposed approach performs better than existing attacks.

Response: MIAI and membership attacks have different goals. While the membership inference attack infers whether a sample is in the training set of the target model (i.e., binary classification), MIAI infers the sensitive attribute value of a training sample. Several research works have explored the membership inference attack with the least capabilities, i.e., based on the predicted label only. However, recent research shows that membership inference attack has quite different characteristics than MIAI attack. For example, dataset complexity positively impacts membership inference attack performance, whereas it has no such impact on the MIAI attack. Moreover, this work demonstrated that higher overfitting leads to better membership inference, whereas there is no explicit relationship between overfitting and MIAI attacks. Additionally, increasing training epochs positively affects membership performance, which is not the case for MIAI. All these distinct characteristics make an MIAI attack more challenging than membership inference and do not ensure a membership attack can be adapted to an MIAI attack. Therefore, instead of leveraging the membership attack in this work, we focus on designing a novel black-box MIAI attack.

In Section III, in the revised manuscript, we have provided this discussion.

[1] Zheng Li, Yang Zhang, "Membership Leakage in Label-Only Exposures", CCS'21

[2] Christopher A. Choquette-Choo, Florian Tramer, Nicholas Carlini, Nicolas Papernot"Label-Only Membership Inference Attacks", ICML'20

Response to authors' rebuttal

The authors' rebuttal addressed my questions. However, I am still not convinced why this is a harder problem than membership-inference. Being a binary classification or a multiclass classification has nothing to do with the hardness of a problem, especially they are classifying different tasks. One would assume the task of membership inference is harder because it requires high precision identification of a specific training example, whereas MIAI only consider a general attribute.

I would appreciate the authors providing more discussion on this in the paper and show reasons existing MI attacks cannot be leveraged.

Response: In Section III, in the revised manuscript, we have provided this discussion.

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Review #54D
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Overall merit
---
2. Reject and Resubmit

Reviewer expertise
---
2. Some familiarity

Reviewer confidence
---
3. High

Relevance to PETS
---
3. Directly related to PETs (scope is not an issue)

Ethical considerations
---
4. I don't see any ethical implications for this paper.

Paper summary

This paper proposes a new model inversion attack against the tabular data. The general idea is to generate a synthetic dataset that captures the correlation between the sensitive attributes and the non-sensitive attributes by iteratively querying the target model. The proposed SDMIA

method assumes the least adversary knowledge but the attack performance is worse than the state-of-the-art. The authors further explore the disparate vulnerability properties of the proposed model inversion attack.

Comments for author

Strengths:

- The research topic is interesting
- New model inversion attack
- Least adversary knowledge

Weaknesses:

- The writing needs significant improvement
- The attack performance is worse than the state-of-the-art, especially for multi-class sensitive attributes

Comments for the Authors:

- The presentation of the synthetic data generation step is unclear. Specifically, the authors should first highlight the general idea and intuition before introducing the detailed synthetic data generation steps. Further, the statement "If more than one sensitive attribute value (where k≥2) do not generate the same prediction, we accept the instances to form DSA" and "If more than one prediction is the same, set of instances is rejected" seems conflicting. Do you mean we accept when all the k predictions are different or when at least two predictions are different? Further, why is d_{max} updated in the proposed manner and how is d_{min} updated?

Response: The major intuition for synthetic data generation is to design an MIAI attack that is more realistic than existing attacks. Therefore, we consider our attack with the least adversarial capabilities and leverage the designed algorithm in the first phase of the proposed SDMIA attack.

In the revised manuscript, in Section I (introduction), we illustrated in-depth the motivation for this algorithm and proposed attack.

Yes, we accept the records when all the k predictions are different. We have updated this in the revised manuscript in Section IV-B1. We reduce d_max to control search diameter around accepted records while re-randomizing. This enhances search speed. Also, as accepted records vary in the least #of attributes, it better captures the correlation between sensitive attribute and label. We do not update d_min (set to 1). We have clarified this in Section IV-B-1 in the revised manuscript.

- Comparing the results of Figure 3 and Figure 4, it seems that the proposed SDMIA performs worse than the state-of-the-art in many cases. Then what is the advantage of the proposed algorithm?

Response: Please note that these box plots (Figure 2, 3, 17) indicate the performances across 3 runs (against 3 different target models) for binary attributes and Figure 4 for multi-class. In fact, in a single run (against a target model) our SDMIA performance might be better than existing attacks and the other way for another target model. Therefore, we also consider attack stability as a comparison measure (i.e., interquartile range and error bars) and show our attack is more stable than existing attacks. For a single run result, i.e., for one target model performance, please refer to Tables V-VII and XVI-XXI, which show that for a single run, in many cases, SDMIA performance is better. Also, for the multi-class case, Figure 4, our SDMIA performs better in the F1 score (comparatively balanced metric).

Figure 2, Figure 3, and Figure 17 represent the performance comparisons among existing attacks (average performance in 3 runs) and our proposed SDMIA for binary sensitive attribute inference. In Figure 17, when the class priors are balanced, our attack performs the same as existing attacks. In the other two cases (imbalanced priors), attack performance varies. Still, in Figure 2, in many performance metrics, our attack performs better than FJRMIA and is similar to LOMIA (e.g., F1 score, G-mean, recall, etc.). In Figure 3, SDMIA performs better than existing in some metrics (e.g., FPR, MCC, G-mean, etc.).

Our goal is not just designing an effective MIAI attack, but also our proposed SDMIA renders the following benefits over existing attacks: (i) novel back-box attack with the least capabilities, (ii) query-efficient attack (SDMIA* requires 50% less query), (iii) more realistic and broad applicability, (iv) performs similarly in most cases compared to existing attacks, and (v) achieves more-stable attack performances than state-of-the-art MIAI attacks varying target models.

- The authors claim that the proposed algorithm suffers when k>4, does FJRMIA and LOMIA also suffer from larger k? It seems that FJRMIA and LOMIA suffer less from larger k when comparing the current results of Figure 3 and Figure 4. The authors should evaluate on the situation when k is up to 10. If the proposed algorithm suffers a lot while the state-of-the-art does not, then this would be the main limitation.

Response: In our proposed attack, we assume k< number of classes (label), as discussed in Section IV, which is realistic and consistent with prior works. Since the publicly available datasets we experiment with have the max number of classes 5, we have evaluated our proposed attack for sensitive attribute values up to k=4. Our empirical evaluations demonstrate that all attacks suffer from k=2 to increasing k>2, i.e., from binary to multi-class, as expected. Observe that, with multi-class, existing FJRMIA and LOMIA suffer more from stability in all metrics compared to our SDMIA. In binary cases (Figure 2, 3), also existing attack performance varies largely with changing target model (higher interquartile range compared to SDMIA). It is important to note that, comparing from k=2 (Figure 3) to k=4 (Figure 4), we find that the

performance drop in FJRMIA is higher compared to LOMIA and our proposed SDMIA, e.g., in the accuracy metric, it drops from 0.8 to 0.35 (Fig. 4(a)) ~56% in FJRMIA, whereas it drops from 0.6 to 0.3 ~50% in SDMIA.

We have added this discussion in Section VII (Discussions and Limitations) of the revised manuscript.

- I am wondering what is the exact number of queries for different methods? Since SDMIA requires to reject sampling, the number of queries might be large if the non-sensitive attributes are not well-initialized and the queries are frequently rejected. I would suggest the authors explicitly compare the number of queries of different methods.

Response: In our attack, we bounded iterations to count queries (total number of queries either accept/reject decision), and then we remove rejected queries in our synthetic data generation algorithm. Similarly, we consider total query counts to the target model for other attacks. Therefore, the query numbers represented in Tables V-VII, and Tables XVI-XXI are the actual query numbers.

- The disparate vulnerability properties of model inversion are unclear. I would suggest the authors first give a high-level introduction before introducing the formal definition.

Response: MIAI disparity is a serious privacy concern since it impacts subgroups differently, i.e., subgroups are vulnerable to MIAI attacks on varying margins. For example, divorced individuals might be higher vulnerable compared to married individuals regarding marital happiness or personal sensitive information related attribute inferring.

In the revised manuscript, we have explained this property right before introducing the formal definition in Section V.

Minor Issues:
- The font size of Figure 1a is too small.
Response: We have increased the font size of Figure 1a in the revised manuscript.

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Meta Review #54E
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Overall merit
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2. Reject and Resubmit

Reviewer expertise
---
2. Some familiarity

Reviewer confidence
---
2. Medium

Relevance to PETS
---
3. Directly related to PETs (scope is not an issue)

Ethical considerations
---
4. I don't see any ethical implications for this paper.

Paper summary

This is the Meta Review

Comments for author

Thank you for your resubmission and your rebuttal response. The reviewers have carefully examined your submission and your response and agree that, while the paper has improved some, many of the key criticisms from the prior round remain unfixed. As such, they recommend that the paper again be rated as Reject and Resubmit.

Before any further resubmissions, please consider the remaining issues carefully.

Response: Thank you for your comments. We have carefully looked at the reviewers' comments and addressed them properly in the revised manuscript.

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