

# Credit Card Fraud Detection and Concept-Drift Adaptation with Delayed Supervised Information

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**Abstract**—Most fraud-detection systems (FDSs) monitor streams of credit card transactions by means of classifiers returning alerts for the riskiest payments. Fraud detection is notably a challenging problem because of concept drift (i.e. customers’ habits evolve) and class unbalance (i.e. genuine transactions far outnumber frauds). Also, FDSs differ from conventional classification because, in a first phase, only a small set of supervised samples is provided by human investigators who have time to assess only a reduced number of alerts. Labels of the vast majority of transactions are made available only several days later, when customers have possibly reported unauthorized transactions. The delay in obtaining accurate labels and the interaction between alerts and supervised information have to be carefully taken into consideration when learning in a concept-drifting environment.

In this paper we address a realistic fraud-detection setting and we show that investigator’s feedbacks and delayed labels have to be handled separately. We design two FDSs on the basis of an ensemble and a sliding-window approach and we show that the winning strategy consists in training two separate classifiers (on feedbacks and delayed labels, respectively), and then aggregating the outcomes. Experiments on large dataset of real-world transactions show that the alert precision, which is the primary concern of investigators, can be substantially improved by the proposed approach.

**Index Terms**—Fraud Detection, Concept Drift, Unbalanced Data, Data Streams, Anomaly Detection.

## I. INTRODUCTION

Everyday a huge and growing number of credit cards payments takes place while being targeted by fraudulent activities. Companies processing electronic transactions have to promptly detect any fraudulent behavior in order to preserve customers’ trust and the safety of their own business.

Most fraud-detection system (FDSs) employ machine-learning algorithms to learn frauds’ patterns and detect them as datastreams of transactions come [4]. In particular, we focus here on FDSs which aim to detect frauds by means of classifiers that label transactions as fraudulent or genuine. Fraud detection is particularly challenging for two reasons [5]: frauds represent a small fraction of all the daily transactions [3] and their distribution evolves over time because of seasonality and new attack strategies [29]. This

situation is typically referred to as *concept drift* [19] and is of extreme relevance for FDSs which have to be constantly updated either by exploiting the most recent supervised samples or by forgetting outdated information that might be no more useful whereas not misleading.

In a real-world setting, it is impossible to check all transactions. The cost of human labour seriously constrains the number of alerts, returned by the FDS, that can be validated by investigators. Investigators in fact check the alerts by calling the cardholders, and then provide the FDS with *feedbacks* indicating whether the alerts were related to fraudulent or genuine transactions. These feedbacks, which refer to a tiny fraction of the daily transactions amount, are the only real-time information that can be provided to train or update classifiers. The labels of the rest of transactions can be assumed to be known several days later, once a certain reaction-time for the customers have passed: all the transactions that customers do not report as frauds are considered genuine. In the paper we will distinguish between *immediate feedback samples* (i.e. transactions annotated with the investigator feedback) and *delayed samples*, whose labels is obtained only after some time. This distinction is crucial for the design of an accurate FDS, though most FDSs in the literature [25], [36], [16], [4] assume an immediate and accurate labeling after the processing of each transaction. This oversimplifying assumption ignores the alert-feedback interaction, which makes the few recent supervised couples dependent from the performance of the FDS itself.

Another substantial difference between the real-world settings and the ideal ones considered in literature is that the primary concern of any FDS should be to return a small number of very precise alerts, then reducing the number of genuine transactions (false positives) that have to be controlled by investigators. In practice, the optimal FDS should be the one maximizing the number of frauds detected within the budget of alerts that can be reported. Notwithstanding, classical performance metrics considered in the literature are the area under the curve (AUC), the cost (namely, financial losses arising from misclassification), and metrics based on the confusion matrix [23] (e.g the F-measure), which are not necessarily meaningful for the alert precision.

In this work we show that, in a real-world fraud-detection scenario, it is convenient to handle immediate feedbacks separately from delayed supervised samples. The former, in fact, are *selected* as the most risky transactions according to the FDS itself, while the latter refer to all the occurred transactions. Our claim is better illustrated in Section IV, where

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we investigate two traditional learning approaches for FDSs, namely, i) a sliding-window approach where a classifier is re-trained everyday on the most recent supervised samples and ii) an ensemble approach where, everyday, a new component replaces the oldest one in the ensemble. We designed and assessed two different solutions for each approach: in the first, feedbacks and delayed supervised samples are pooled together while in the second we train two distinct classifiers, based on feedbacks and delayed samples respectively, and then aggregate the outputs. Experiments shown in Section V on two real-world credit card datasets indicate that handling feedbacks separately from delayed training samples can substantially improve the alert precision. We motivate this result as the fact that this solution guarantees a prompt reaction to concept drift: additional experiments on datasets that have been manipulated to introduce concept drift in specific days, confirm our intuition.

To the best of our knowledge, this is also the first work addressing the problem of fraud detection when supervised pairs are provided according to the alert-feedback interaction, as formulated in Section III.

## II. RELATED WORKS

FDSs are confronted with two major challenges: i) handling *non-stationary* streams of transactions, namely a stream where the statistical properties of both frauds and genuine transactions change overtime; ii) handling the class *unbalance*, since legitimate transactions generally far outnumber the fraudulent ones. In what follows we provide an overview of state-of-the-art FDSs with a specific focus on solutions for evolving and unbalanced data streams.

In the fraud-detection literature both supervised [7], [10], [4] and unsupervised [6], [34] solutions have been proposed. Unsupervised methods do not rely on transactions labels (i.e. genuine or fraudulent) and associate fraudulent behaviours [6] to transactions that do not conform with the majority. Unsupervised methods exploit clustering algorithms [31], [36] to group customers into different profiles and identify frauds as transactions departing from customer profile (see also the recent survey by Phua [30]).

In this paper we will focus on supervised methods. Supervised methods exploit labels that investigators assign to transactions for training a classifier and, during operation, detect frauds by classifying each transaction in the incoming stream [5]. Fraud detection has been often considered as an application scenario for several classification algorithms, e.g. Neural networks [22], [1], [16], [7], Support Vector Machines [37], Decision Trees [13] and Random Forest [12]).

Learning on the stream of transactions is a challenging issue because transactions evolve and change over time, e.g. customers' behaviour change in holiday seasons and new fraud activities may appear. This problem is known as concept drift [19] and learning algorithms operating in non-stationary environments typically rely only on the supervised information that is up-to-date (thus relevant), and remove any obsolete training sample [2]. Most often, concept-drift adaptation is achieved by training a classifier

over a sliding window of the recent supervised samples (e.g. STAGGER [32] and FLORA [38]) or by ensemble of classifiers where recent supervised data are used to train a new classifier while obsolete ones are discarded (e.g. SEA [33] and DWM [26]).

Streams of credit card transactions present an additional challenge: the classes are extremely unbalanced since frauds are typically less than 1% of genuine transactions [13]. Class unbalance is typically addressed by resampling methods [24], which balance the training set by removing samples of the majority class (undersampling) or by replicating the minority class (oversampling). In practice, concept-drift adaptation in an unbalanced environment is often achieved by combining ensemble methods and resampling techniques. The class unbalance problem is addressed in [20], [21] by propagating minority class training samples and undersampling the majority class. Chen and He proposed REA [11] where they recommend to propagate only examples from the minority class that belong to the same concept using a  $k$ -nearest neighbors algorithm. Learn++.NIE [15] creates multiple balanced training sets from a batch using undersampling, then it learns a classifier on each balanced subset and combines all classifier's predictions. Lichtenwalter and Chawla [28] suggest to propagate not only positives, but also observations from the negative class that are misclassified in the previous batch to increase the boundary definition between the two classes.

All the aforementioned learning frameworks demand a training set of recent instances with their own ground-truth class label. However, in a real-world FDS, this is often not possible because only few recent supervised couples are provided according to the alert-feedback interaction described in Section I. The only FDS explicitly handling concept drift in the transaction streams is [35] which nevertheless, like other FDS presented in the literature [6], [7], [10], ignores the alert-feedback interaction.

It is worth to remark that this alert-feedback interaction could remind an active-learning scenario where the learner is allowed to query an oracle for requiring informative supervised couples from a large set of unlabelled observations. Unfortunately in a FDS scenario, this solution is not feasible since an exploration phase, where investigators should check a large number of (possibly uninteresting) transactions, would not be considered as acceptable.

## III. PROBLEM FORMULATION

We formulate here the fraud detection problem as a binary classification task where each transaction is associated to a feature vector  $\mathbf{x}$  and a label  $y$ . Features in  $\mathbf{x}$  could be the transaction amount, the shop id, the card id, the timestamp or the country, as well as features extracted from the customer profile. Because of the time-varying nature of the transactions' stream, typically, FDSs train (or update) a classifier  $\mathcal{K}_t$  every day ( $t$ ). The classifier  $\mathcal{K}_t : \mathbb{R}^n \rightarrow \{+, -\}$  associates to each feature vector  $\mathbf{x} \in \mathbb{R}^n$ , a label  $\mathcal{K}_t(\mathbf{x}) \in \{+, -\}$ , where  $+$  denotes a fraud and  $-$  a genuine transaction. Since frauds represent a negligible fractions of the total number

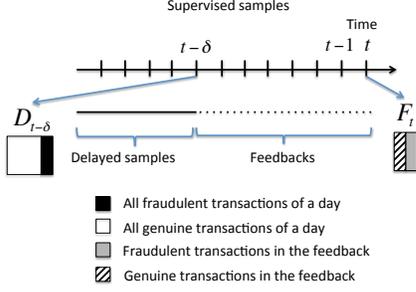


Fig. 1. The supervised samples available at day  $t$  include: i) feedbacks of the first  $\delta$  days and ii) delayed couples occurred before the  $\delta^{th}$  day.

of transactions, the positive class is also called the minority class and the negative one the majority class.

In general, FDSs operate on a continuous stream of transactions because frauds have to be detected online, however, the classifier is updated once a day, to gather a sufficient amount of supervised transactions. Transactions arriving at day  $t$ , namely  $T_t$ , are processed by the classifier  $\mathcal{K}_{t-1}$  trained in the previous day ( $t-1$ ). The  $k$  riskiest transactions of  $T_t$  are reported to the investigators, where  $k > 0$  represents the number of alerts the investigators are able to validate. The reported alerts  $A_t$  are determined by ranking the transactions of  $T_t$  according to the posterior probability  $P_{\mathcal{K}_{t-1}}(+|\mathbf{x})$ , which is the estimate, returned by  $\mathcal{K}_{t-1}$ , of the probability for  $\mathbf{x}$  to be a fraud. The set of reported alerts at day  $t$  is defined as

$$A_t = \{\mathbf{x} \text{ s.t. } r(\mathbf{x}) \leq k\} \quad (1)$$

where  $r(\mathbf{x}) \in \{1, \dots, \#T_t\}$  is the rank of the transaction  $\mathbf{x}$  according to  $P_{\mathcal{K}_{t-1}}(+|\mathbf{x})$ , and  $\#(\cdot)$  denotes the cardinality of a set. In other terms, the transaction with the highest probability ranks first ( $r(\mathbf{x}) = 1$ ) and the one with the lowest probability ranks last ( $r(\mathbf{x}) = \#T_t$ ).

Investigators will then provide feedbacks  $F_t$  about the alerts in  $A_t$ , defining a set of  $k$  supervised couples  $(\mathbf{x}, y)$

$$F_t = \{(\mathbf{x}, y), \mathbf{x} \in A_t\}, \quad (2)$$

which represents the only immediate information that the FDS receives. At day  $t$ , we also receive the labels of all the transactions processed at day  $t-\delta$ , providing a set of delayed supervised couples  $D_{t-\delta} = \{(\mathbf{x}, y), \mathbf{x} \in T_{t-\delta}\}$ , see Figure 1. Though these transactions have not been personally checked by investigators, they are by default assumed to be genuine after  $\delta$  days, as far as customers do not report frauds.<sup>1</sup> As a result, the labels of all the transactions older than  $\delta$  days are provided at day  $t$ . The problem of receiving delayed labels is also referred to as *verification latency* [27].

It is worth to remark that this is still a simplified description of the processes regulating companies analyzing credit cards transactions. For instance, it is typically not possible

<sup>1</sup>Investigators typically assume that frauds missed by the FDS are reported by customers themselves (e.g. after having checked their credit card balance), within a maximum time-interval of  $\delta$  days.

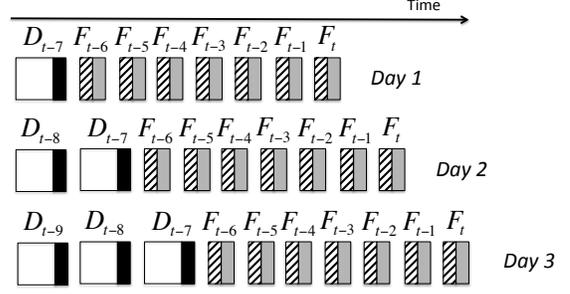


Fig. 2. Everyday we have a new set of feedbacks  $(F_t, F_{t-1}, \dots, F_{t-(\delta-1)})$  from the first  $\delta$  days and a new set of delayed transactions occurred on the  $\delta^{th}$  day ( $D_{t-\delta}$ ). In this Figure we assume  $\delta = 7$  and the colours refer to the notation in Figure 1.

to extract the alerts  $A_t$  by ranking the whole set  $T_t$ , since transactions have to be immediately passed to investigators; similarly, delayed supervised couples  $D_{t-\delta}$  do not come all at once, but are provided over time. Notwithstanding, we deem that the most important aspects of the problem (i.e. the alert-feedback interaction and the time-varying nature of the stream) are already contained in our formulation and that further details would unnecessarily make the problem setting complex.

Feedbacks  $F_t$  can either refer to frauds (correct alerts) or genuine transactions (false alerts): correct alerts are the true positives (TP), while false alerts are the false positives (FP). Similarly,  $D_{t-\delta}$  contains both fraud (false negative) and genuine transactions (true negatives), although the vast majority of transactions belong to the genuine class. Figure 2 illustrates the two types of supervised pairs that are provided everyday.

The goal of a FDS is to return accurate alerts: when too many FPs are reported, investigators might decide to ignore forthcoming alerts. Thus, what actually matters is to achieve the highest precision in  $A_t$ . This precision can be measured by the quantity

$$p_k(t) = \frac{\#\{(\mathbf{x}, y) \in F_t \text{ s.t. } y = +\}}{k} \quad (3)$$

where  $p_k(t)$  is the proportion of frauds in the top  $k$  transactions with the highest likelihood of being frauds ([4]).

#### IV. LEARNING STRATEGY

The fraud-detection scenario described in Section III suggests that learning from feedbacks  $F_t$  is a different problem than learning from delayed samples in  $D_{t-\delta}$ . The first difference is evident:  $F_t$  provides recent, up-to-date, information while  $D_{t-\delta}$  might be already obsolete once it comes. The second difference concerns the percentage of frauds in  $F_t$  and  $D_{t-\delta}$ . While it is clear that the class distribution in  $D_{t-\delta}$  is always skewed towards the genuine class (see Figure 2), the number of frauds in  $F_t$  actually depends on the performance of classifier  $\mathcal{K}_{t-1}$ : values of  $p_k(t) \sim 50\%$  provide feedbacks  $F_t$  where frauds and genuine transactions are balanced, while high precision values might even result in  $F_t$  skewed towards

frauds. The third, and probably the most subtle, difference is that supervised couples in  $F_t$  are not independently drawn, but are instead selected by  $\mathcal{K}_{t-1}$  among those transaction that are more likely to be frauds. As such, a classifier trained on  $F_t$  learns how to label transactions that are most likely to be fraudulent, and might be in principle not precise on the vast majority of genuine transactions. Therefore, beside the fact that  $F_t$  and  $D_{t-\delta}$  might require different resampling methods,  $F_t$  and  $D_{t-\delta}$  are also representative of two different classification problems and, as such, they have to be separately handled. In the following, two traditional fraud-detection approaches are presented (Section IV-A), and further developed to handle separately feedbacks and delayed supervised couples (Section IV-B). Experiments in Section V show that this is a valuable strategy, which substantially improves the alert precision.

### A. Conventional Classification Approaches in FDS

During operation, feedbacks  $F_t$  and delayed supervised samples  $D_{t-\delta}$  can be exploited for training or updating the classifier  $\mathcal{K}_t$ . In particular, we train the FDS considering the feedbacks from the last  $\delta$  days (i.e.  $\{F_t, F_{t-1}, \dots, F_{t-(\delta-1)}\}$ ) and the delayed supervised pairs from the last  $\alpha$  days before the feedbacks, i.e.  $\{D_{t-\delta}, \dots, D_{t-(\delta+\alpha-1)}\}$  (see Figure 2).<sup>2</sup>

In the following we present two conventional solutions for concept-drift adaptation [34], [20] built upon a classification algorithm proving an estimate of the probability  $P(+|\mathbf{x})$ .

- $\mathcal{W}_t$ : a *sliding window* classifier that is daily updated over the supervised samples received in the last  $\delta + \alpha$  days, i.e.  $\{F_t, \dots, F_{t-(\delta-1)}, D_{t-\delta}, \dots, D_{t-(\delta+\alpha-1)}\}$  (see Figure 3).
- $\mathcal{E}_t$ : an *ensemble* of classifiers  $\{\mathcal{M}_1, \mathcal{M}_2, \dots, \mathcal{M}_\alpha, \mathcal{F}\}$ , where  $\mathcal{M}_i$  is trained on  $D_{t-(\delta+i-1)}$  and  $\mathcal{F}_t$  is trained on all the feedbacks of the last  $\delta$  days  $\{F_t, \dots, F_{t-(\delta-1)}\}$ . The estimate of posterior probability  $P_{\mathcal{E}_t}(+|\mathbf{x})$  is estimated by averaging the posterior probabilities of the individual classifiers,  $P_{\mathcal{M}_i}(+|\mathbf{x}), i = 1, \dots, \alpha$  and  $P_{\mathcal{F}_t}(+|\mathbf{x})$ . Note that we use a single classifier to learn from the set of feedbacks since their size is typically small. Everyday,  $\mathcal{F}_t$  is re-trained considering the new feedbacks, while a new classifier is trained on the new delayed supervised couples provided ( $D_{t-\delta}$ ) and included in the ensemble. At the same time, the most obsolete classifier is removed from the ensemble.

These solutions implement two basic approaches for handling concept drift that can be further improved by adopting dynamic sliding windows or adaptive ensemble sizes [17].

### B. Separating delayed Supervised Samples from Feedbacks

Our intuition is that feedbacks and delayed transactions have to be treated separately because, beside requiring different tools for handling class unbalance, they refer to different classification problems. Therefore, at day  $t$  we

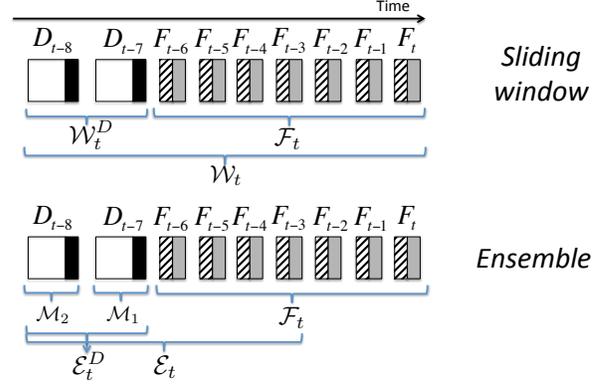


Fig. 3. Supervised information used by different classifiers in the ensemble and sliding window approach. The Figure assume that feedbacks are provided for the first 7 days ( $\delta = 7$ ) and delayed samples of two days before the feedbacks are available ( $\alpha = 2$ ).

train a specific classifier  $\mathcal{F}_t$  on the feedbacks of the last  $\delta$  days  $\{F_t, \dots, F_{t-(\delta-1)}\}$  and denote by  $P_{\mathcal{F}_t}(+|\mathbf{x})$  its posterior probability. We then train a second classifier on the delayed samples by means either of a sliding-window or an ensemble mechanism (see Figure 3): Let us denote by  $\mathcal{W}_t^D$  the classifier trained on a sliding window of delayed samples  $\{D_{t-\delta}, \dots, D_{t-(\delta+\alpha-1)}\}$  and by  $P_{\mathcal{W}_t^D}(+|\mathbf{x})$  its posterior probabilities, while  $\mathcal{E}_t^D$  denotes the ensemble of  $\alpha$  classifiers  $\{\mathcal{M}_1, \mathcal{M}_2, \dots, \mathcal{M}_\alpha\}$  where each individual classifier  $\mathcal{M}_i$  is trained on  $D_{t-\delta-i}, i = 1, \dots, \alpha$ . Then, the posterior probability  $P_{\mathcal{E}_t^D}(+|\mathbf{x})$  is obtained by averaging the posterior probabilities of the individual classifiers.

Each of these two classifiers has to be aggregated with  $\mathcal{F}_t$  to exploit information provided by feedbacks. However, to raise alerts, we are not interested in aggregation methods at the label level but rather at the posterior probability level. For the sake of simplicity we adopt the most straightforward combination approach based on averaging the posterior probabilities of the two classifiers ( $\mathcal{F}_t$  and one among  $\mathcal{W}_t^D$  and  $\mathcal{E}_t^D$ ). Let us denote by  $\mathcal{A}_t^E$  the aggregation of  $\mathcal{F}_t$  and  $\mathcal{E}_t^D$  where  $P_{\mathcal{A}_t^E}(+|\mathbf{x})$  is defined as:

$$P_{\mathcal{A}_t^E}(+|\mathbf{x}) = \frac{P_{\mathcal{F}_t}(+|\mathbf{x}) + P_{\mathcal{E}_t^D}(+|\mathbf{x})}{2} \quad (4)$$

Similar definition holds for the aggregation of  $\mathcal{F}_t$  and  $\mathcal{W}_t^D$  ( $\mathcal{A}_t^W$ ). Note that  $\mathcal{F}_t$  and  $\mathcal{W}_t^D$  jointly use the training set of  $\mathcal{W}_t$  and, similarly, the two classifiers  $\mathcal{F}_t$  and  $\mathcal{E}_t^D$  jointly use the same training samples of  $\mathcal{E}_t$  (see Figure 3).

However, in  $\mathcal{W}_t$  feedbacks represent a small portion of the supervised samples used for training, hence they have little influence on  $P_{\mathcal{W}_t}(+|\mathbf{x})$ , while in the aggregation  $\mathcal{A}_t^W$  their contribution becomes more prominent. Similarly,  $\mathcal{F}_t$  represents one of the classifiers of the ensemble  $\mathcal{E}_t$ , hence it has in principle the same influence as all the other  $\alpha$  classifiers trained on delayed samples to determine  $P_{\mathcal{E}_t}(+|\mathbf{x})$ .<sup>3</sup>

<sup>2</sup>There is no point of storing feedbacks from  $F_{t-\delta}$  (or before), as these supervised couples are provided in  $D_{t-\delta}$  (or before).

<sup>3</sup>In the specific case of the ensemble and of posterior probabilities computed by averaging (4), the aggregation of  $\mathcal{F}_t$  and  $\mathcal{E}_t^D$  ( $\mathcal{A}_t^E$ ) corresponds to assigning a larger weight to  $\mathcal{F}_t$  in  $\mathcal{E}_t$ .

TABLE I  
DATASETS

Id	Start day	End day	# Days	# Instances	# Features	% Fraud
2013	2013-09-05	2014-01-18	136	21,830,330	51	0.19%
2014	2014-08-05	2014-10-09	44	7,619,452	51	0.22%

Experiments in Section V show that handling feedbacks separately from delayed supervised samples provides much more precise alerts, and that FDSs relying on classifiers trained exclusively on feedbacks and delayed supervised samples (like  $\mathcal{A}_t^W$  and  $\mathcal{A}_t^E$ ) substantially outperform FDSs trained on feedbacks and delayed supervised samples pooled together (like  $\mathcal{W}_t$  and  $\mathcal{E}_t$ ). In what follows, as practical example of the separation of feedbacks from delayed supervised couples, we detail the specific solutions based on Random Forests that were used in our experiments.

### C. Two Specific FDSs based on Random Forest

As a base algorithm the FDSs presented in the previous section we used a Random Forest [9] with 100 trees. In particular, for  $\mathcal{W}_t^D$ ,  $\mathcal{W}_t$  and for all  $\mathcal{M}_i, i = 1, \dots, \alpha$ , we used a Balanced Random Forest (BRF) where each tree is trained on a balanced bootstrap sample, obtained by randomly undersampling the majority class while preserving all the minority class samples in the corresponding training set. Each tree of BRF receives a different random sample of the genuine transactions and the same samples from the fraud class in the training set, yielding a balanced training set. This undersampling strategy allows one to learn trees with balanced distribution and to exploit many subsets of the majority class. At the same time, this resampling method reduces training sizes and improve detection speed. A drawback of undersampling is that we are potentially removing relevant training samples from the dataset, however this problem is mitigated by the fact that we learn 100 different trees. Using undersampling allows us to rebalance the batches without propagating minority class observations along the streams as in [20]. Propagating frauds between batches should be avoided whenever possible, since it requires access to previous batches that we might not be able to store when data arrives in streams. In contrast, for  $\mathcal{F}_t$  that is trained on feedbacks we adopted a standard Random Forest (RF) where no resampling is performed.

## V. EXPERIMENTS

We considered two datasets of credit card transactions of European cardholders: the first one (referred to as 2013) is composed of daily transactions from the 5<sup>th</sup> of September 2013 to the 18<sup>th</sup> of January 2014, the second one (referred to as 2014) contains transactions from the 5<sup>th</sup> of August to the 9<sup>th</sup> of September 2014. In the 2013 dataset there is an average of 160k transactions per day and about 304 frauds per day, while in the 2014 dataset there is on average 173k transactions and 380 frauds everyday. Table I reports few additional details about these datasets and shows that they are also heavily unbalanced.

In the first experiments we process both datasets to assess the importance of separating feedbacks from delayed supervised samples. Though we expect these streams to be affected by concept drift (CD), since they span a quite long time range, we do not have any ground truth to investigate the reaction to concept drift of the proposed FDS. To this purpose, we design the second experiment where we juxtapose batches of transactions acquired in different times of the year to artificially introduce CD in a specific day in the transaction stream.

In both experiments we test FDSs built on random forests presented in Section IV-C. We considered both the sliding window and ensemble approaches and compared the accuracy of pooling feedbacks and delayed supervised samples together ( $\mathcal{W}_t$  and  $\mathcal{E}_t$ ) against learning separate classifiers ( $\mathcal{F}_t$ ,  $\mathcal{W}_t^D$  and  $\mathcal{E}_t^D$ ) that are then aggregated ( $\mathcal{A}_t^W$  and  $\mathcal{A}_t^E$ ). Let us recall that alerts are raised by each tested classifier. This means that also the feedbacks returned to the classifiers might be different. This has to be considered when comparing different classifiers, for instance, when comparing  $\mathcal{W}_t$  and  $\mathcal{W}_t^D$ , the supervised information provided is not the same because, in the first case alerts are raised by  $\mathcal{W}_t$  while in the second by  $\mathcal{W}_t^D$ .

We assume that after  $\delta = 7$  days all the transactions labels are provided (delayed supervised information) and that we have a budget of  $k = 100$  alerts that can be checked by the investigators: thus,  $\mathcal{F}_t$  is trained on a window of 700 feedbacks. We set  $\alpha = 16$  so that  $\mathcal{W}_t^D$  is trained on a window of 16 days and  $\mathcal{E}_t^D$  (resp.  $\mathcal{E}_t$ ) is an ensemble of 16 (resp. 17) classifiers.<sup>4</sup>

Each experiments is repeated 10 times to reduce the results' variability due to bootstrapping of the training sets in the random forests. The FDS performance is assessed by means of the average  $p_k$  over all the batches (the higher the better) and use a paired t-test to assess whether the performance gaps between each pair of tested classifiers is significant or not. We compute the paired t-test on the ranks resulting from the Friedman test [18] as recommended by Demsar [14]. In practice, for each batch, we rank the strategies from the least to the best performing and then compare each strategy against the others by means of a paired t-test based on the ranks. Then we sum the ranks over all batches. More formally, let  $r_{s,j} \in \{1, \dots, S\}$  be the rank of strategy  $s$  on day  $j$  and  $S$  be the number of strategies to compare. The strategy with the highest accuracy in  $j$  has  $r_{s,j} = S$  and the one with the lowest has  $r_{s,j} = 1$ . The paired t-test compares ranks of strategy  $a$  against  $b$  by means of  $r_{a,j} - r_{b,j}, j \in \{1, \dots, J\}$ , where  $J$  is the total number of batches. Then the sum of ranks for strategy  $s$  is defined as  $\sum_{j=1}^J r_{j,s}$ . The higher the sum, the higher is the number of times that one strategy is superior to the others.

<sup>4</sup>We ran several experiments with  $\alpha = 1, 8, 16, 24$  and found  $\alpha = 16$  as a good trade-off between performance, computational load, and the number of days that can be used for testing in each stream.

### A. Experiments on 2013 and 2014 Datasets

In order to evaluate the benefit of learning on feedbacks and delayed samples separately, we first compare the performance of classifier  $\mathcal{W}_t$  against  $\mathcal{F}_t$ ,  $\mathcal{W}_t^D$  and the aggregation  $\mathcal{A}_t^W$ . Table II shows the average  $p_k$  over all the batches for the two datasets separately. In both 2013 and

TABLE II  
AVERAGE  $p_k$  BETWEEN ALL THE BATCHES

classifier	Dataset 2013		Dataset 2014	
	mean	sd	mean	sd
$\mathcal{F}$	0.609	0.250	0.596	0.249
$\mathcal{W}^D$	0.540	0.227	0.549	0.253
$\mathcal{W}$	0.563	0.233	0.559	0.256
$\mathcal{A}^W$	0.697	0.212	0.657	0.236

2014 datasets,  $\mathcal{A}_t^W$  outperforms the other FDSs in terms of  $p_k$ . The barplots of Figure 5 show the sum of ranks for each classifier and the results of the paired t-tests. Figure 5 indicates that in both datasets (Figures 5(a) and 5(b))  $\mathcal{A}_t^W$  is significantly better than all the other classifiers.  $\mathcal{F}_t$  achieves higher average  $p_k$  and higher sum of ranks than  $\mathcal{W}_t^D$  and  $\mathcal{W}_t$ : this confirms that feedbacks are very important to increase  $p_k$ . Figure 4(a) displays the value of  $p_k$  for  $\mathcal{A}_t^W$  and  $\mathcal{W}_t$  in each day, averaged in a neighborhood of 15 days. During December there is a substantial performance drop, that can be seen as a Concept Drift (CD) due to a change in cardholder behaviour before Christmas. However,  $\mathcal{A}_t^W$  dominates  $\mathcal{W}_t$  along the whole 2013 dataset, which confirms that a classifier  $\mathcal{A}_t^W$  that learns on feedbacks and delayed transactions separately outperforms a classifier  $\mathcal{W}_t$  trained on all the supervised information pooled together (feedbacks and delayed transactions).

Figures 5(c), 5(d) and Tables III confirm this claim also when the FDSs implements an ensemble of classifiers.<sup>5</sup> In particular, Figure 4(b) displays the smoothed average  $p_k$  of classifiers  $\mathcal{A}_t^E$  and  $\mathcal{E}_t$ . For the whole dataset  $\mathcal{A}_t^E$  has better  $p_k$  than  $\mathcal{E}_t$ .

TABLE III  
AVERAGE  $p_k$  BETWEEN ALL THE BATCHES

classifier	Dataset 2013		Dataset 2014	
	mean	sd	mean	sd
$\mathcal{F}$	0.603	0.258	0.596	0.271
$\mathcal{E}^D$	0.459	0.237	0.443	0.242
$\mathcal{E}$	0.555	0.239	0.516	0.252
$\mathcal{A}^E$	0.683	0.220	0.634	0.239

### B. Experiments on artificial dataset with CD

In this section we artificially introduce an abrupt CD in specific days by juxtaposing transactions acquired in different times of the year. Table IV reports the three datasets that have been generated by concatenating batches of the dataset 2013 with batches from 2014. The number of days after concept

<sup>5</sup>Please note that classifier  $\mathcal{F}_t$  returns different results between Table II and Table III because of the stochastic nature of RF.

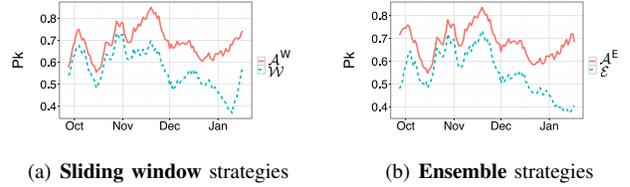


Fig. 4. Average  $p_k$  per day (the higher the better) for classifiers on dataset 2013 smoothed using moving average of 15 days. In the sliding window approach classifier  $\mathcal{A}_t^W$  has higher  $p_k$  than  $\mathcal{W}_t$ , and in the ensemble approach  $\mathcal{A}_t^E$  is superior than  $\mathcal{E}_t$ .

drift is set such that the FDS has the time to forget the information from the previous concept.

TABLE IV  
DATASETS WITH ARTIFICIALLY INTRODUCED CD

Id	Start 2013	End 2013	Start 2014	End 2014
CD1	2013-09-05	2013-09-30	2014-08-05	2014-08-31
CD2	2013-10-01	2013-10-31	2014-09-01	2014-09-30
CD3	2013-11-01	2013-11-30	2014-08-05	2014-08-31

Table V(a) shows the values of  $p_k$  averaged over all the batches in the month before the change for the sliding window approach, while Table V(b) shows  $p_k$  in the month after the CD.  $\mathcal{A}_t^W$  reports the highest  $p_k$  before and after CD. Similar results are obtained with the ensemble approach

TABLE V  
AVERAGE  $p_k$  IN THE MONTH BEFORE AND AFTER CD FOR THE SLIDING WINDOW APPROACH

classifier	(a) Before CD					
	CD1		CD2		CD3	
	mean	sd	mean	sd	mean	sd
$\mathcal{F}$	0.411	0.142	0.754	0.270	0.690	0.252
$\mathcal{W}^D$	0.291	0.129	0.757	0.265	0.622	0.228
$\mathcal{W}$	0.332	0.215	0.758	0.261	0.640	0.227
$\mathcal{A}^W$	0.598	0.192	0.788	0.261	0.768	0.221

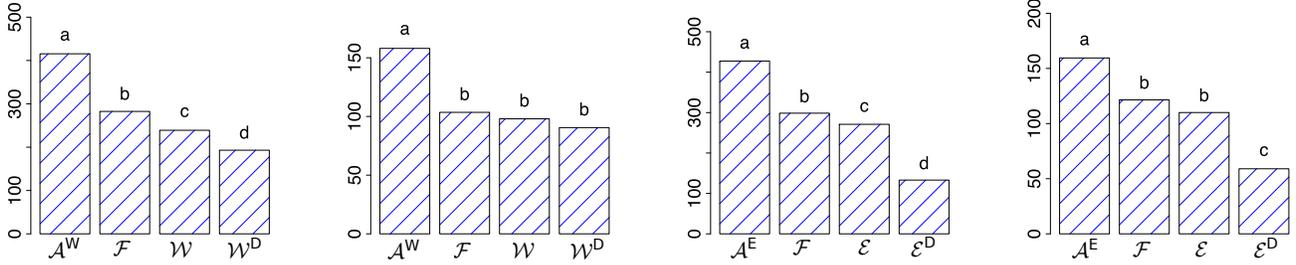
  

classifier	(b) After CD					
	CD1		CD2		CD3	
	mean	sd	mean	sd	mean	sd
$\mathcal{F}$	0.635	0.279	0.511	0.224	0.599	0.271
$\mathcal{W}^D$	0.536	0.335	0.374	0.218	0.515	0.331
$\mathcal{W}$	0.570	0.309	0.391	0.213	0.546	0.319
$\mathcal{A}^W$	0.714	0.250	0.594	0.210	0.675	0.244

(Tables VI(a), VI(b)). In all these experiments,  $\mathcal{A}_t^E$  is also faster than standard classifiers  $\mathcal{E}_t$  and  $\mathcal{W}_t$  to react in the presence of a CD (see Figure 6). The large variation of  $p_k$  over the time reflect the non-stationarity of the data stream. Except for dataset CD1, we have on average lower  $p_k$  after concept drift.

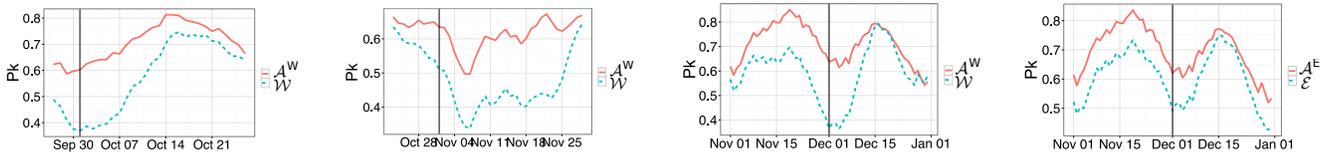
### C. Discussion

In this section we analyze the accuracy improvements achieved by classifiers  $\mathcal{A}_t^W$  and  $\mathcal{A}_t^E$  proposed in Section IV-B. First of all, we notice that the classifier learned on recent feedbacks is more accurate than the one learned on delayed samples. This is made explicit by Tables II and III showing that  $\mathcal{F}_t$  often outperforms  $\mathcal{W}_t^D$  (and  $\mathcal{E}_t^D$ ), and  $\mathcal{W}_t$  (and  $\mathcal{E}_t$ ).



(a) Sliding window strategies on dataset 2013 (b) Sliding window strategies on dataset 2014 (c) Ensemble strategies on dataset 2013 (d) Ensemble strategies on dataset 2014

Fig. 5. Comparison of classification strategies using sum of ranks in all batches and paired t-test based upon on the ranks of each batch (classifiers having the same letter on their bar are not significantly different with a confidence level of 0.95). In both datasets (2013 and 2014), classifiers  $\mathcal{A}_t^W$  and  $\mathcal{A}_t^E$  are significantly better than the others.



(a) Sliding window strategies on dataset CD1 (b) Sliding window strategies on dataset CD2 (c) Sliding window strategies on dataset CD3 (d) Ensemble strategies on dataset CD3

Fig. 6. Average  $p_k$  per day (the higher the better) for classifiers on datasets with artificial concept drift (CD1, CD2 and CD3) smoothed using moving average of 15 days. In all datasets  $\mathcal{A}_t^W$  has higher  $p_k$  than  $\mathcal{W}_t$ . For the ensemble approach we show only dataset CD3, where  $\mathcal{A}_t^E$  dominates  $\mathcal{E}_t$  for the whole dataset (similar results are obtained on CD1 and CD2, but they are not included for compactness). The vertical bar denotes the date of the concept drift.

TABLE VI  
AVERAGE  $p_k$  IN THE MONTH BEFORE AND AFTER CD FOR THE  
ENSEMBLE APPROACH

(a) Before CD						
classifier	CD1		CD2		CD3	
	mean	sd	mean	sd	mean	sd
$\mathcal{F}$	0.585	0.183	0.731	0.267	0.706	0.245
$\mathcal{E}^D$	0.555	0.318	0.563	0.217	0.562	0.223
$\mathcal{E}$	0.618	0.313	0.696	0.276	0.648	0.245
$\mathcal{A}^E$	0.666	0.222	0.772	0.272	0.751	0.221

(b) After CD						
classifier	CD1		CD2		CD3	
	mean	sd	mean	sd	mean	sd
$\mathcal{F}$	0.696	0.270	0.477	0.235	0.610	0.270
$\mathcal{E}^D$	0.551	0.298	0.286	0.182	0.486	0.265
$\mathcal{E}$	0.654	0.266	0.373	0.235	0.581	0.268
$\mathcal{A}^E$	0.740	0.232	0.575	0.227	0.659	0.245

We deem that  $\mathcal{F}_t$  outperforms  $\mathcal{W}_t^D$  (resp.  $\mathcal{E}_t^D$ ) since  $\mathcal{W}_t^D$  (resp.  $\mathcal{E}_t^D$ ) are trained on less recent supervised couples. As far as the improvement with respect to  $\mathcal{W}_t$  (and  $\mathcal{E}_t$ ) is concerned, our interpretation is that this is due to the fact that  $\mathcal{W}_t$  (and  $\mathcal{E}_t$ ) are trained on the entire supervised dataset, then weakening the specific contribution of feedbacks.

Our results instead show that aggregation prevents the large amount of delayed supervised samples to dominate the small set of immediate feedbacks. This boils down to assign larger weights to the most recent than to the old samples, which is a golden rule when learning in non-stationary environments. The aggregation  $\mathcal{A}_t^W$  is indeed an effective way

to attribute higher importance to the information included in the feedbacks. At the same time  $\mathcal{A}_t^E$  is a way to balance the contribution of  $\mathcal{F}_t$  and the remaining  $\alpha$  models of  $\mathcal{E}_t$ .

Another motivation of the accuracy improvement is that classifiers trained on feedbacks and delayed samples address two different classification tasks (Section IV). For this reason too, it is not convenient to pool the two types of supervised samples together.

Finally, the aggregation presented in equation 4 provides equal weights to the two posterior probabilities  $P_{\mathcal{F}_t}$  and  $P_{\mathcal{W}_t^D}$  ( $P_{\mathcal{E}_t^D}$ ). However, more sophisticated and eventually adaptive aggregation schemes (e.g. non-linear or stacking [8]) could be used to react to concept drift. In fact, in a rapidly drifting environment, the relative weight of  $P_{\mathcal{F}_t}$  should eventually increase, because  $\mathcal{W}_t^D$  (or  $\mathcal{E}_t^D$ ) might be obsolete and prone to false alarms.

## VI. CONCLUSION

In this paper we formalise a framework that reproduces the working conditions of real-world FDSs. In a real-world fraud-detection scenario, the only recent supervised-information is provided on the basis of the alerts generated by the FDS and feedbacks provided by investigators. All the other supervised samples are provided with a much larger delay.

Our intuition is that the alert-feedback interaction has to be explicitly considered to improve alert precision and that feedbacks and delayed samples have to be separately

handled when training a realistic FDS. To this purpose, we have considered two general approaches for fraud detection: a sliding window and an ensemble of classifiers. We have then compared FDSs that separately learn on feedbacks and delayed samples against FDSs that pool all the available supervised information together. Experiments run on real-world streams of transactions show that the former strategy provides much more precise alerts than the latter, and that it also adapts more promptly in concept-drifting environments.

Future work will focus on investigating adaptive mechanisms to aggregate the classifier trained on feedbacks and the one trained on delayed samples, to further improve the alert precision in non-stationary streams.

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