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User Authentication Through Biometric Sensors and Decision Fusion

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Abstract—The interaction between humans and most desktop and laptop computers is often performed through two input devices: the keyboard and the mouse. Continuous tracking of these devices provides an opportunity to verify the identity of a user, based on a profile of behavioral biometrics from the user’s previous interaction with these devices. We propose a bank of sensors, each feeding a binary detector (trying to distinguish the authentic user from all others). In this study the detectors use features derived from the keyboard and the mouse, and their decisions are fused to develop a global authentication decision. The binary classification of the individual features is developed using Naive Bayes Classifiers which play the role of local detectors in a parallel binary decision fusion architecture. The conclusion of each classifier (‘authentic user’ or ‘other’) is sent to a Decision Fusion Center (DFC) where we use the Neyman-Pearson criterion to maximize the probability of detection under an upper bound on the probability of false alarms. We compute the receiver operating characteristic (ROC) of the resulting detection scheme, and use the ROC to assess the contribution of each individual sensor to the quality of the global decision on user authenticity. In this manner we identify the characteristics (and local detectors) that are most significant to the development of correct user authentication. While the false accept rate (FAR) and false reject rate (FRR) are fixed for the local sensors, the fusion center provides trade-off between the two global error rates, and allows the designer to fix an operating point based on his/her tolerance level of false alarms. We test our approach on a real-world dataset collected from 10 office workers, who worked for a week in an office environment as we tracked their keyboard dynamics and mouse movements during interaction with laptops and desktop computers.

Keywords—Decision Fusion, Behavioral Biometrics, Active Authentication, Binary Classification.

I. INTRODUCTION

The tracking of behavioral biometrics for continuous verification of a user’s identity has received considerable attention in recent years [1]. By monitoring actively metrics such as keyboard dynamics and mouse movements, classification of user as authentic or non-authentic has achieved accuracy on par with more traditional non-continuous approaches [2]. One popular non-continuous approach is for the user to verify his/her identity by typing a password or a common fixed phrase. The authentication system then estimates whether the user is who s/he claims to be by analyzing the biometric parameters associated with the typing of the password/phrase. Continuous “active authentication”, on the other hand performs verification of the user steadily, based on a set of metrics

collected during previous interaction with the computer, or updated based on known-user behavior. Due to the unconstrained nature of human-computer interaction, a single biometric is usually not sufficiently robust to determine the user’s identity. For that reason, many active authentication systems are (a) multi-modality, namely they monitor multiple features of a single type of biometric [3], and (b) multi-biometric, namely they consider more than one type of biometric [4]. In this study we consider multi-modality multi-biometric model for interaction with a computer through a mouse and keyboard.

We evaluated our algorithms using a dataset collected from office workers in a real-world office environment. Each user is represented through features collected from the user’s keyboard dynamics and mouse movements. We fuse these features using established algorithms for parallel binary decision fusion [5], [6]. The Receiver Operating Characteristic (ROC) helps quantify the relative importance of each biometric and each feature.

In §II, we discuss work on active authentication, multi-biometric system, and the tracking of mouse movement and keyboard dynamics. In §III, we describe the biometric dataset used in this study and the classifiers that mapped the data from feature space to decision space. In §IV, we discuss the decision fusion approach that combines the decisions of local sensors. In §V, we present the global performance provided by the Decision Fusion Center. We also estimate the contribution of each feature to the quality of the final decision.

II. USER AUTHENTICATION VIA BIOMETRICS

A. Mouse and Keyboard Dynamics

The movement dynamics of the mouse and the keyboard of a personal computer have been studied for over two decades [7], [8] as the primary human computer interface input devices. Keystroke dynamics have received most of the attention in behavioral biometrics studies [9]. The two basic tracked features of inter-key-press interval [10] and key-press dwell [11] were used as the basis for more complex features such as digraph latency [12], trigraph latency [13], or keyword latency [14]. These features provide timing information about a specific configuration of key-press and key-release events.

Mouse movement in the authentication domain has received considerably less attention until recently [15]. Mouse

movement signals are relatively noisy, requiring large testing windows for authentication [16]. Zheng et al. [17] were the first to show meaningful results based on testing windows as small as 20 mouse clicks. Jorgensen and Yu [18] studied short-time window continuous authentication and used touch-based mouse devices.

Most single-modality classifiers considered for mouse and keyboard use statistical methods [19] such as Naive Bayes, decision trees, linear discrimination analysis and support vector machines [21]. Some classifiers use trained neural networks [20]. In this paper our local detectors are Naive Bayes classifiers [22] due to their robustness to the relatively small amount of training data needed and the ease of design and implementation.

B. Multi-Biometric Systems

In the context of continuous authentication, multi-modality biometrics use multiple asynchronous streams of features to form a sequence of fused verification decisions. There are several approaches to categorize multi-biometric systems [23]. Most relevant to the approach in this paper is division of continuous fusion by Sanderson and Paliwal into: (1) pre-mapping, (2) midst-mapping, and (3) post-mapping [24]. Here "mapping" refers to the transformation from data into information (e.g, from the feature space to the decision space). While pre-mapping fusion has been extensively studied in other applications [25], in the authentication domain, the feature space is so varied (and often restricted by privacy concerns) that midst-mapping or post-mapping fusion have been preferred. We use the post-mapping (or decision fusion) approach in this study.

III. EXPERIMENTAL SETUP

A. Dataset

The dataset used in our study comes from 10 users in a simulated work environment. The users were tracked throughout a working week (5 sequential days) in their use of the mouse and

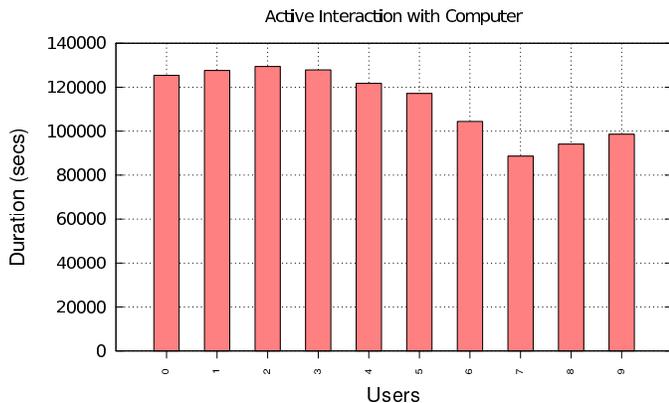


Fig. 1: The duration (in seconds) of each user’s interaction with the computer throughout the 5-day week with idle periods removed. An idle period is defined as a continuous period of time without any mouse or keyboard interaction with the computer.

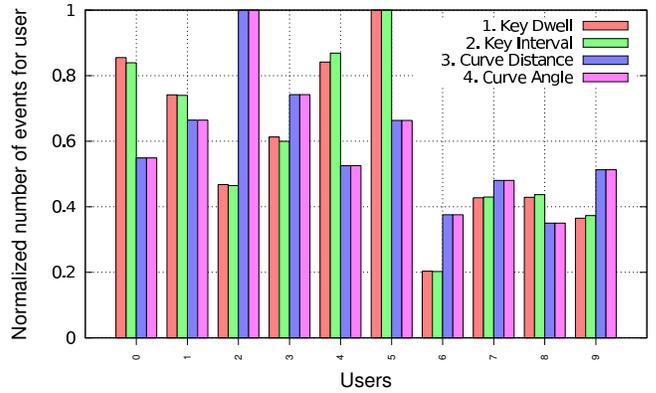


Fig. 2: The relative amount of biometric data per-type per-user extracted from the interaction of each user with their computer throughout the 5-day week. The variability between the users is noticeable.

keyboard as they sought to accomplish various writing tasks such as summarizing online opinion articles. The productivity, task-selection, and mouse/keyboard use ratio varied from user to user as shown in Fig. 1 and Fig. 2.

A tracking application logged two types of behavioral biometrics on the granularity of 5 milliseconds:

- Mouse movement, mouse click, and mouse scroll wheel events.
- Keystroke dynamics (include press, hold, release durations) for all keyboard keys including special keys.

Table I shows statistics on the biometric data in the dataset. The table contains data aggregated over all 10 users and all of the available user-days. The keystroke events include both the alpha-numeric keys and special keys such as shift, backspace, ctrl and alt.

TABLE I: Statistics on the 10-user dataset.

Metric	Total
Sensor 1: Keystroke Dwell Time	915,624
Sensor 2: Keystroke Interval Time	750,253
Sensor 3: Mouse Curvature Distance	3,462,912
Sensor 4: Mouse Curvature Angle	3,462,912

TABLE II: The total quantity of features extracted from the raw data for each of the four sensors. The number of keystroke intervals is significantly less than keystroke dwell time because only intervals that were part of bursts of continuous typing were collected.

B. Feature Classification

Data from each user were broken down into three segments relative to the duration of each user’s non-idle periods of activity (see Fig. 1):

- 1) *Training Segment*: for the construction of the empirical feature distribution;

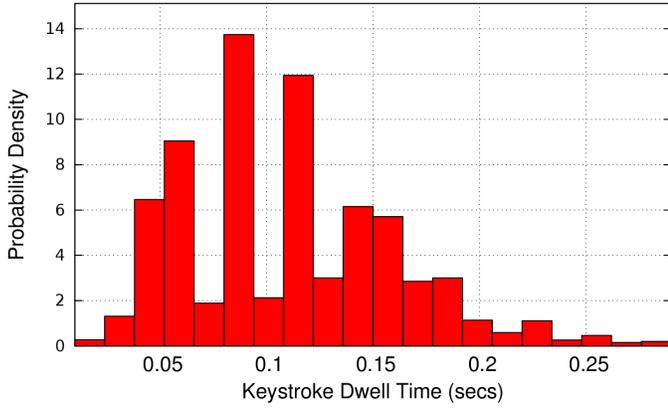


Fig. 3: An example of a histogram constructed from the training set for the empirical probability distribution of user 0 for the “Keystroke Dwell Time” feature (sensor 1).

- 2) *Characterization Segment*: for the estimation of the FAR and FRR rates of the sensor for the use by the Decision Fusion Center (DFC); and
- 3) *Testing Segment*: for the estimation of the local sensor performance compared to the fused sensor performance.

For each user we trained the classifier on the first 60% of the data, characterized the error rates of the trained classifier on the following 20%, and tested the local and the fused sensors on the remaining 20%.

For each local sensor, we use the Naive Bayes Classifier [26] for mapping from the feature space to the decision space. This classifier is constructed during the training phase and used for binary classification in the characterization and testing phases.

In the training phase, the empirical distribution for feature probabilities are constructed from the frequency of each feature in the training segment of each user’s data. An example histogram-based distribution for the “keystroke dwell time” metric for the first user is shown in Fig. 3. It shows the estimated probability of dwell time (in seconds). Two such histograms are constructed for each user j . The first histogram was constructed from the training segment of the data of that user. The second histogram was constructed from all the training segments of the other users. This latter set of training segments is meant to represent all other computer users. These two histograms are the empirical feature distributions associated with each user.

In the characterization and testing phases, for each user and each metric, the Naive Bayes Classifier considers a collection of ω (set to 10 in this paper) most recent events $\{x_1, x_2, \dots, x_\omega\}$ associated with that metric (e.g, keystroke dwell time). It then uses the maximum a posteriori (MAP) rule to pick the most likely hypothesis:

$$H^* = \operatorname{argmax}_{i \in \{0,1\}} P(H_i) \prod_t P(x_t | H_i), \quad (1)$$

where H_1 is the “authentic” class, H_0 is the “non-authentic” class, discussed further in §IV, and H^* is the most likely class associated with the observed biometric data. Given the open-world model considered in this paper, for the local sensor classifiers, we considered $P(H_0) = P(H_1) = 0.5$. The feature probability $P(x_t | H_i)$ is estimated by a non-parametric distribution (like the one in Fig. 3).

IV. DECISION FUSION

We employ a decentralized parallel binary decision fusion [5], [6] scheme to integrate a set of “local” binary decisions to a global binary decision. The local detectors are designed as binary Naive Bayes Classifiers each attached to a single feature of the mouse or the keyboard. The i^{th} local detector is characterized by its probability of correct detection ($P_{D_i} = 1 - P_{M_i}$; accepting hypothesis H_1 when hypothesis H_1 is true) and its probability of false alarm (P_{F_i} ; accepting H_1 when H_0 is true). Here we selected to design a Decision Fusion Center (DFC) that integrates the local decisions in the Neyman-Pearson sense [6]: for an upper bound on the global probability of false alarm, the DFC maximizes the global probability of detection. The distributed decision fusion scheme is depicted in Fig. 4. It involves 4 different sensors (2 Mouse and 2 Keyboard) shown in Table I, each connected to a local detector that announces whether or not the user is authentic. The experimental setup involved collecting data from 10 users and creating 10 schemes (local detectors and a Decision Fusion Center), each one designed to identify one of the 10 users and reject all others. The j^{th} DFC, ($j = 1, \dots, 10$) distinguishes the hypothesis ($H_1 = \text{User } j \text{ is present}$; against $H_0 = \text{User } j \text{ is not present}$).

Each sensor, designed as a Naive Bayes Classifier uses its own observations to decide on the hypothesis for the corresponding user. The local decisions are of the form

$$u_i = \begin{cases} 1, & \text{if } H_1 \text{ is accepted (user is authentic)} \\ -1, & \text{if } H_0 \text{ is accepted (user is non-authentic)} \end{cases} \quad (2)$$

The DFC performs a Neyman-Pearson test [27] for fusion and for each user it functions the same way; the DFC for the j^{th} user takes in the four local decisions and calculates the likelihood ratio for n sensors (in this study, $n = 4$);

$$\Lambda(u^j) = \frac{P(u_1^j, \dots, u_n^j | H_1)}{P(u_1^j, \dots, u_n^j | H_0)} \underset{H_0}{\overset{H_1}{\gtrless}} t_j^*. \quad (3)$$

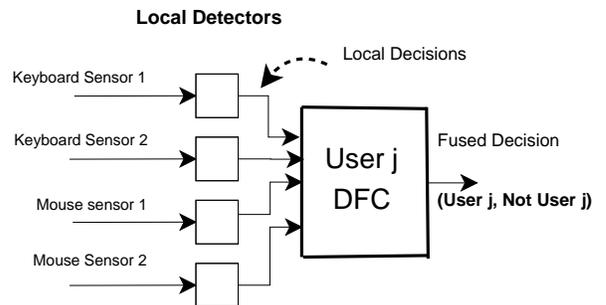


Fig. 4: Behavioral Sensor Fusion Scheme

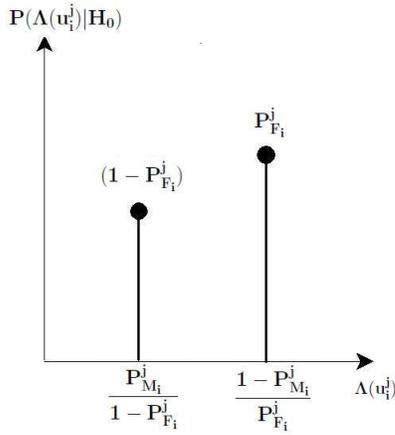


Fig. 5: Local Likelihood distribution under H_0

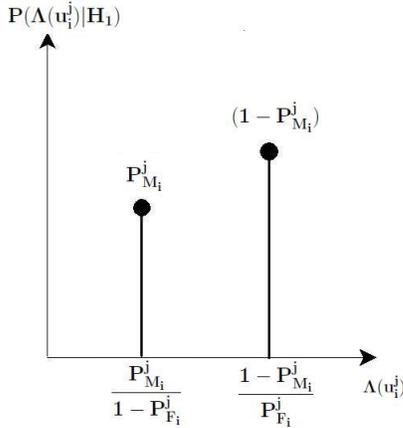


Fig. 6: Local Likelihood distribution under H_1

Assuming that the local decisions are independent (conditioned on the hypothesis), we have

$$\Lambda(u^j) = \prod_{j=1}^n \frac{P(u_n^j|H_1)}{P(u_n^j|H_0)} \times \dots \times \frac{P(u_1^j|H_1)}{P(u_1^j|H_0)} \underset{H_0}{\underset{H_1}{\gtrless}} t_j^* \quad (4)$$

where the threshold t_j^* is computed such that the global false alarm at the DFC for the j^{th} user (P_{FA}^G) is α_j . In other words, t_j^* is obtained such that

$$\sum_{\Lambda(u^j) \geq t_j^*} P(\Lambda(u^j)|H_0) = \alpha_j \quad (5)$$

Once the threshold t_j^* is determined, the global probability of detection (P_D^{Gj}) at the DFC for the j^{th} user becomes

$$P_D^{Gj} = \sum_{\Lambda(u^j) \geq t_j^*} P(\Lambda(u^j)|H_1) \quad (6)$$

Since the local decisions are binary in nature, the probability distributions of individual sensor likelihoods are discrete. The conditional distributions for the i^{th} sensor in the fusion system for the j^{th} user as represented by $P(\Lambda(u_i^j)|H_0)$ and $P(\Lambda(u_i^j)|H_1)$ are shown in Fig. 5 and Fig. 6 where $P_{M_i}^j$, $P_{F_i}^j$ are the *False Rejection* or *Mis-detection Rate* (MD) and *False*

Acceptance or *False Alarm Rate* (FA) of the i^{th} sensor respectively in the j^{th} user fusion system. The global conditional distributions $P(\Lambda(u^j)|H_0)$ and $P(\Lambda(u^j)|H_1)$ can therefore be obtained by multiplying the abscissae and ordinates of the individual distributions (4). As the global conditional distributions are discrete, only certain global false alarm values would be possible which would make the ROC contain a collection of disjoint points. To allow realization of an intermediate False Alarm rate, the DFC employs a randomized Neyman-Pearson test and computes the probability of using (one of the two) thresholds accordingly.

As the specified global False Alarm Rate P_{FA} varies from 0 to 1, the global Detection Rate ($P_D = 1 - P_M$) is calculated to create the Receiver Operating Characteristic (ROC).

V. RESULTS

The fusion setup used for generating the ROC curves is shown in Fig. 4. The 4 sensors are assumed to be fixed Naive Bayes Classifiers and the DFC performs a Neyman-Pearson test to fuse the local detector decisions. A total of 10 users and 10 systems were tested. To compare the contributions of each sensor towards the fused result, each sensor was removed (one at a time) and the ROC curve of the resultant system generated.

Fig. 7 shows the ROC for user 1. Fig. 8 shows a zoomed-in version of same plot. It is noticeable that fusion is profitable and produces the highest possible global detection rates for given false alarm rates. All the sensors are very similar in performance and therefore have comparable marginal contribution to the global performance. Similar results were obtained for the Decision Fusion Centers designed for the remaining 9 users. In general this approach of using ROC curves for sensor analysis can help in creating a hierarchy of sensor importance such that for a known tolerable global false alarm, the appropriate groups of sensors could be identified and used (and some sensors of only marginal contribution can be dropped).

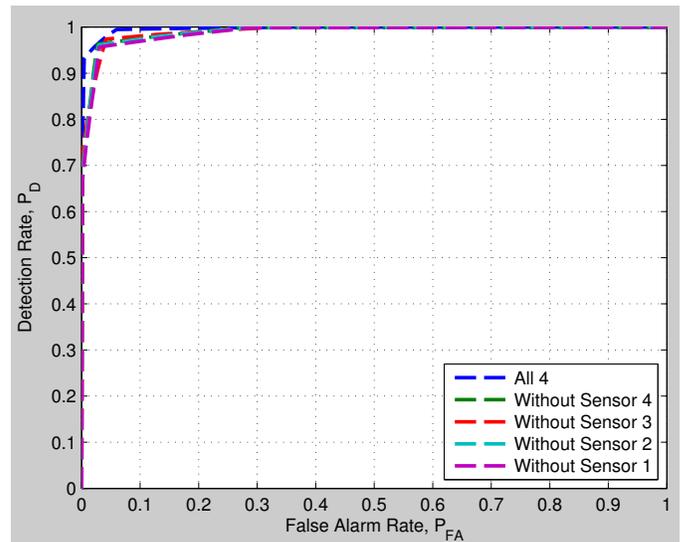


Fig. 7: ROC curves for incremental and global sensor fusion with one sensor taken out at a time

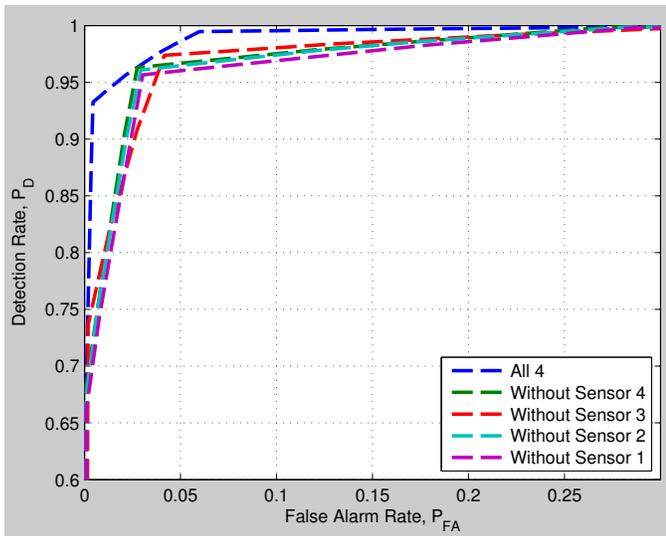


Fig. 8: Zoomed in version of Figure. 7

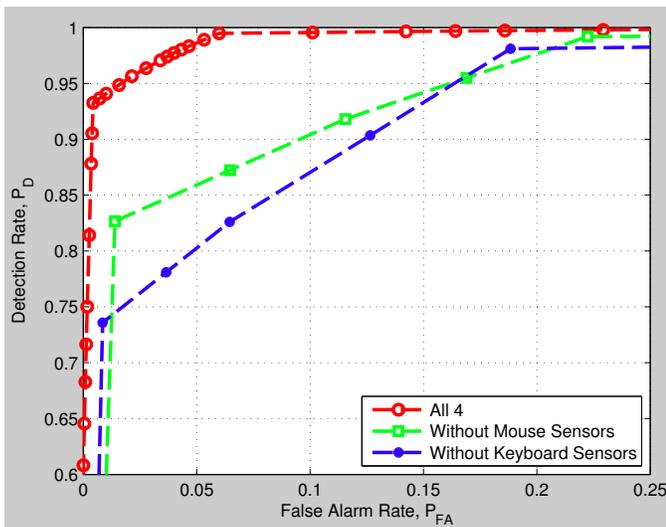


Fig. 9: ROC curves for incremental sensor fusion with mouse and keyboard sensors removed at a time

Fig. 9 shows the resultant ROC curves when either the two mouse sensors or the two keyboard sensors were removed incrementally. For small values of global false alarm rates, it is observable that removing the keyboard sensors and combining just the mouse sensors degrades the global performance more than removing the mouse sensors and combining only the keyboard sensors.

A. Multilevel Fusion

We may ask, how much would performance be affected when decisions associated with the same kind of sensors are combined first and then the results of such intermediate fusions are fused by the main DFC. In the fusion scheme shown in Fig. 10 all the mouse and keyboard sensors, were combined first, separately, using Neyman-Pearson criterion; the outputs were then fused at the main DFC. The false alarm at the

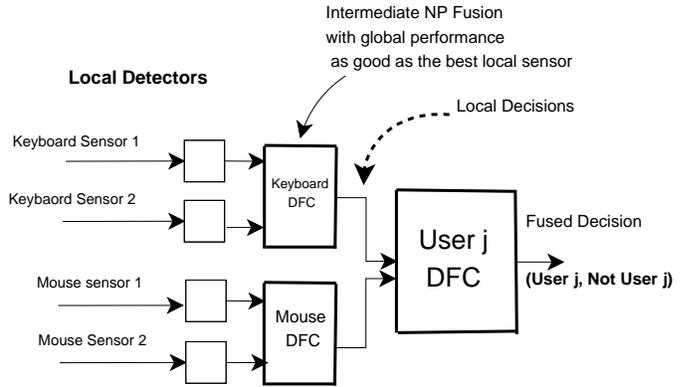


Fig. 10: Multilevel Decision Fusion

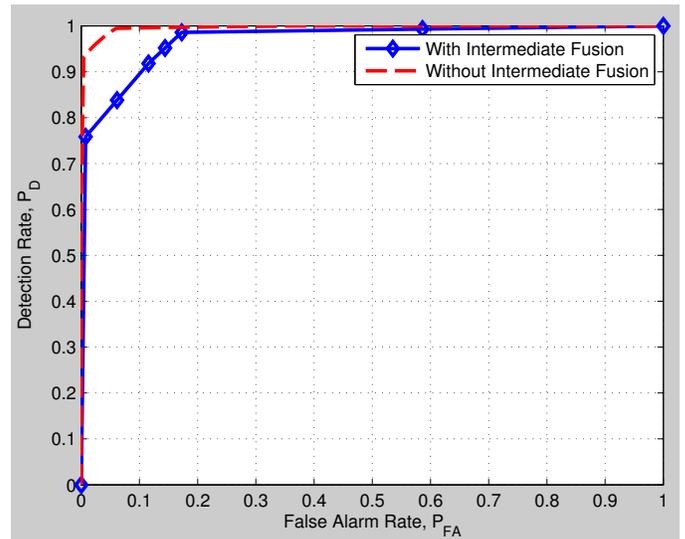


Fig. 11: ROC for 2 step fusion

intermediate fusion centers were chosen the same as the false alarm of best individual sensor of that class. For user 1, Fig. 11 shows the resultant ROC curves at the User DFC.

Not surprisingly, performing intermediate fusion degrades the overall system performance for low values of False Alarm rate.

VI. CONCLUSION

We illustrated the use of behavioral sensors towards active authentication of users of computer systems. Four (4) behavioral features based on mouse and keyboard usage were used to train 4 classifiers which then became part of a distributed fusion scheme. Each classifier ("local detector") generated decisions on the hypothesis set, authenticating (or refusing to authenticate) a particular user, and the DFC then performed a Neyman-Pearson test for a final authenticate/non-authenticate decision. ROC curves for the various DFCs were generated, which revealed a hierarchy of sensor importance and would be helpful in identifying economical groups of sensors to be used in user authentication. In future work, a wider variety of features would be included and an attempt will be made to tune

the local detectors better toward improving the performance of the DFC.

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