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Cloud based malicious PDF Detection using Machine Learning

– Diploma thesis –

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Abstract

PDF documents are one of the most popular file formats used for information exchange. People trust this format and open the files as soon as they come into their possession. Few know the risks to which they expose the integrity of their computers. For already many years PDF files became a frequently used attack vector for compromising the security of entire networks. This paper will introduce you into some of the currently known PDF attack techniques. Our work is aimed to research if the Machine Learning algorithms can successfully reinforce the classical antiviruses at analyzing malicious PDF documents. We provide an alternative security solution, which could take the responsibility of the hard task of malware analysis to an isolated, high-performant environment in the Cloud. Detected harmful PDF documents will be immediately removed from the computer and users should not worry about their data privacy nor computer performance.

Keywords—Cybersecurity, Machine Learning, malicious PDF, Cloud Application

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Chapter 1

Introduction

1.1 Context

The informational technology progress, that is in continuous growth, brings a lot of benefits along with new responsibilities. There are plenty of applications that we use everyday across the entire World Wide Web. We don't even realize how much of our personal information is transferred to the virtual environment. That being said, it's important to be prepared for cybersecurity threats that can misuse our sensitive data. The problem is that the cyber attackers develop a lot of *hacking*¹ techniques, which are becoming increasingly difficult to detect. The popular software applications are the best target to inject malicious behavior. This happened with the Adobe PDF format. PDF documents are well known, trustworthy files and they are a global solution for sharing information. There are a lot of PDF readers and even browsers and email applications have support to open these files for viewing. It became so convenient to work with this format, that users interact with PDF documents without noticing any possible danger. However, PDF is a often used attack vector. The large number of discovered PDF vulnerabilities and also the support of embedding Javascript code into documents are just some of the most exploited methods.

1.2 Motivation

Under the guise of seeming harmless, PDF documents are used on a daily basis across numerous public institutions, private companies and for personal purposes. Most of the people don't consider that these files could be dangerous and just copy the documents to their computers and access them. It is enough for one PDF to be malicious and the entire network affiliated to an institution can become compromised. The cyber attackers succeed in achieving their goals,

¹attempt to gain unauthorized access to data in a system

but the victim institution requires huge resources, both financially and time wise, to restore the integrity and security of their infrastructure. A measure to combat the described situation is having a real time protection installed on the computer. The most common solution, antivirus applications, work by signature matching, which is effective for detecting previously identified malware². This means that all the antivirus applications require permanent updates in order to keep their malware databases up to date. Many users opt out of security solutions because of the multitude of hardware requirements they need. In this thesis we will go through a new approach that implies transferring complex detection algorithms from user's computers to a remote service, whose only task is analyzing suspicious uploaded PDF documents. Consequently, the computers that will use this solution get rid of additional workload while still maintaining the system secure.

1.3 Paper structure and original contributions

The main contribution of this thesis is the research, design and implementation of alternative security solution oriented on multiplatform use and performance efficiency. For achieving this, the work was split into three important parts:

1. **Real time monitoring system on Windows**, whose goal is to notify the user when a specific file type, in our case PDF, is downloaded. The main focus when designing this software was to keep its functionality basic, so that it would require minimal computer's resources. As soon as it detects a new such file, it submits it to the Cloud for further analysis.
2. **Development of an intelligent algorithm for PDF classification** implies studying the PDF format skeleton, researching popular attack vectors using PDFs, extracting the most relevant features from a document and feeding them to the most fit Machine Learning classification algorithm. A part of this effort was also spent for searching the dataset, based on which, the classification model was trained to correctly detect malicious PDF files.
3. **Cloud based application for remote scanning**, which is a generic application that can integrate models such as the developed one for PDF classification and can use them for analyzing the uploaded files. It offers a user friendly dashboard for visualizing the scanned files and also provides the possibility of submitting an URL containing a PDF file. The application will care about downloading and analyzing the file, showing the user the scanning results. This is a perfect option for users that require the Cloud features from a smartphone.

²any software intentionally designed to cause damage to a computer, server, client, or computer network

The remaining parts of this thesis are structured in the following manner: Chapter 2 contains the research made in the past years on malicious PDFs and Cloud Computing as an antimalware solution. Chapter 3 introduces the reader into fundamental mechanisms used for implementing the final application, as well as a brief history of malware in PDF. In Chapter 4 we present a Proof of Concept for developed classification model based on recreating a pseudo attack using malicious PDF. The 5th Chapter is putting each component together and presents the overall design of the application. Chapter 6 is meant for our final conclusions and we also show some of the future ideas for improving the application.

Chapter 2

Related work

Beginning with the first reported occurrences of malware, the security researchers have made a huge effort to prevent its harmful behavior. Over the years malware has evolved in different forms and, of course, the antivirus industry has developed more complex detection solutions. Since PDF documents became a good target for cybercriminals, more and more specialists pay attention to the analysis of dangerous PDFs. Integration of so many analysis tools in a single antivirus software has a negative impact on computers performance. For this reason, the cybersecurity field attaches importance to Cloud Computing. In the following sections we will analyze other academic and industrial approaches for transferring antimalware engines to the Cloud and some documented detection techniques of malicious PDFs.

2.1 Cloud based malware detection

In the field of Cloud solutions for malware detection, there is a sparse amount of shared academic works. As compensation, in the antivirus industry there is a fast growing interest for Cloud Computing, which has higher computational power and could therefore run more advanced and complex detection algorithms.

An important example is **VirusTotal** [3], a popular Cloud application developed by Hispasec Sistemas, that aggregates more than 50 antivirus engines and makes them publicly available for scanning uploaded files. From the user perspective, this is an excellent application, that can extract metadata of the submitted file and can identify any dubious signal. The provided result represents a comparison between analysis verdicts of cybersecurity market leaders. Of course this is an advantage in terms of the scanning result precision and respectively a gain regarding spent computational time. On average it takes approx. 55 seconds to upload and analyze a 400KB file. VirusTotal is also helping to maintain the global cybersecurity at a high level, by sharing all the submitted suspicious files with the security researchers. Thereby the antivirus engines will be permanently improved.

Sandbox Analyzer is another antimalware Cloud solution developed by Bitdefender [5]. Its approach is a bit different, because it ensures the security on a private network, where the Bitdefender product is installed, thus not being available for public access. Its operating principle is also specific, by preventing the execution of threats on an endpoint and automatically sending of harmful files to the Cloud. After extra analysis in the Cloud, the Sandbox Analyzer can take remediation action based on the verdict. In that way, malicious files get disinfected, quarantined or deleted. One of the benefits for this solution is in-depth analysis of malicious files in an isolated environment, rather than on user's machine. Thereby the risk for performance implication, as well as the risk of accidental run of malware on an endpoint machine are eliminated. At the core of the Sandbox Analyzer there are Machine Learning algorithms and dynamic behavior analysis techniques that are constantly improved to detect fresh threats.

2.2 Detection of malicious PDF

PJScan, presented in the paper of Laskov and Srndic [10], is a Machine Learning approach that trains One-Class Support Vector Machine (*OCSVM*) to classify PDF files. This approach is focused on static analysis of embedded Javascript code, as it is known for the ability of integrating malicious behavior in PDF documents. The authors used *n-gram* analysis to extract lexical features. The obtained sequence of tokens served later as input for the machine learning algorithm. The trained model can correctly classify malicious samples containing Javascript code. However PJScan has a lower accuracy, because it is not able to detect obfuscated parts and there are also some samples containing other types of malicious payload, such as SWF¹.

Another example of static analysis of PDF Structure is **PDF Tools** by Didier Stevens [16]. It represents a suite of tools for scanning, parsing and dumping PDF files. This approach focuses on identifying the fundamental elements of the format, such as Streams, Cross Reference Tables etc. The advantage of PDF Tools is their ability of name obfuscation handling and their simplicity. Because of their high speed performance, PDF Tools are largely used in cybersecurity research.

A completely new approach mentioned in the research paper of Fettaya et al. [7] describes an algorithm that uses a Convolutional Neural Network (*CNN*) to detect malicious PDF files. The trained model, based on a single convolutional layer with a global max pool and a linear layer doesn't require any data preprocessing. Instead of this, the model is trained using as input the binary representations of the files. It is worth noting that the described algorithm could be efficiently used for distinguishing various families of malware. The rate of correct detections achieves 94%, the algorithm being also capable to classify approx. 80% of the malware into different categories.

¹Adobe Flash file format used for multimedia

Chapter 3

Scientific Problem

3.1 Problem definition

The purpose of the research in this thesis consists of studying some alternative methods to replace classic file scanning techniques. Particularly, our target is to demonstrate that Machine Learning algorithms can be used as an efficient mechanism for malicious PDF files detection. Additionally, we want to implement a framework that could remotely analyze suspicious PDF files by applying earlier mentioned performant algorithms. This framework should have several advantages:

- Take on the complicated task of applying classification model for uploaded files and give the analysis result to the users.
- Designed to be deployed as a Cloud Application on a powerful server that can handle multiple requests at the same time, freeing users from caring about having high specifications for their computers.
- Guarantee the privacy of the scanned documents. The algorithm shouldn't require the documents content in order to decide whether they are malicious or benign. Also, after the analysis process, none of the documents should be stored on the Cloud.
- Keep the detection algorithms up to date. It won't be the users responsibility anymore to regularly update the software antivirus installed on their computers.
- Provide a generic implementation for analyzing uploaded files. The support for a new file extension to be scanned, could be effortlessly added by adding a Machine Learning classifier model for the wanted file format.

Integrating both Machine Learning and Cloud Computing into Cybersecurity should provide a significant progress to this field.

In order to fully automate the process of detecting malicious PDF files, our application provides a tool (currently has support only for Microsoft Windows) that independently uploads detected files to the Cloud Service, waits for analysis results and takes appropriate protective measures. In the following we will introduce some operating system concepts that helped us achieve the expected behavior for our application.

3.2 Background processes in Microsoft Windows

In computing, a background process is a process¹ that runs independently and doesn't require any user involvement. Usually it has the task of system monitoring and sending any types of notifications to the user. Each operating system has its own principle of implementation for background processes. We will have an in-depth look at background processes in Microsoft Windows, which are called **Windows Services**. According to [18] these services are started by a central utility - *Services Control Manager* at the boot-time² of the computer and they don't have any graphical interface. For security and safety reasons, specifically to prevent user applications from accessing Windows Services that could run with high privileges, Windows OS creates a new session for each logged in user, reserving *Session 0* for non-interactive services. The mentioned features make Windows Services suitable for long-running functionality, whose operation doesn't intersect with other users who work on the same computer. The support for creating a service is provided by the **.NET Framework**, its features being possible to access by using one of Microsoft's high-level programming languages - C#.

3.3 File System monitoring

In the field of operating systems, a file system is aimed to store data in form of files in a long-term storage. Before being stored on physical devices, data that is created and saved by applications in User-Mode, goes through a chain of drivers from Kernel-Mode. This principle is adopted in many operating systems, inclusively in Microsoft Windows (see Figure 3.1). In order to track every change on the computer's file system, we need a monitoring mechanism. Throughout the development of Windows, several technologies have been implemented for integration by software engineers, including: File System Filter Drivers, Update Sequence Number Journal (*USN Journal*), Event Tracing for Windows (*ETW*), *FileSystemWatcher* Class from .NET. In this section we are focusing on two of the most popular Windows file system monitoring mechanisms: Minifilter drivers managed by *Filter Manager* and *FileSystemWatcher*.

¹a container for a set of resources used when executing the instance of the program

²the period when a computer is starting

Windows Filter Manager is a Kernel-Mode driver that intercepts every file system I/O operation and can extend the functionality of the requested operation through each minifilter driver that is registered to it (see Figure 3.1). The order of attachment of each minifilter is identified by an altitude³, thus avoiding interleaving the functionality of callback routines of each minifilter. Windows Driver Kit (*WDK*) provides the necessary SDK⁴ for developing minifilter drivers, which are most suitable for Backup agents, Encryption managers and antivirus filters. For more details consult [14].



Figure 3.1: Simplified I/O stack from Windows [14]

Compared to the previous described technology, which is complex for development and maintaining, **FileSystemWatcher** is a class from .NET that makes file system monitoring straightforward to implement. According to [4], this class represents a wrapper over Win32 SDK *ReadDirectoryChangesW* function, which is also used by Windows Explorer to monitor folder changes. By being provided by .NET, it is clear that **FileSystemWatcher** can be used in User-Mode for development (see Figure 3.2).

³unique identifier assigned by Microsoft that determines when a minifilter is loaded

⁴collection of software development tools



Figure 3.2: Relationship between .NET and Windows OS [18]

To configure a working instance of this class, we need to specify a couple of properties, such as *Path* (for indicating the folder to monitor), *NotifyFilters* (for specifying what kind of file changes to monitor) and *EnableRaisingEvents* (to start/stop monitoring process). Also we need to attach the corresponding events that we want to receive (see Table 3.1).

Table 3.1: Events supported by FileSystemWatcher

Event	Occurring time
Created	When a new file is created or is moved into monitored folder
Changed	When a file has its content or file attributes modified
Deleted	When a file is removed or is moved out of monitored folder
Renamed	When the name of the file gets changed

Earlier we mentioned that minifilter drivers live in Kernel-Mode, while FileSystemWatcher provided by .NET lives in User-Mode. One more argument in favor of FileSystemWatcher, besides the high level object-oriented programming language C# that we have at our disposal over unmanaged⁵ C language, is that it's safer to run applications in User-Mode. Each application runs in isolation in User-Mode and in case of a crash, it won't affect other applications or even worse the OS itself, what can happen with a Kernel-Mode driver. Even the smallest error that occurs in a driver can cause BSOD⁶.

⁵code executed directly by OS; does not provide any security to the application

⁶"Blue Screen of Death", error screen displayed by Windows in case of fatal system crash

3.4 Analyzing PDF File Structure

In this section we are going to understand PDF structure which is a foundation stone of identifying backdoors⁷ in this file format.

PDF was first developed by Adobe in the 90s with many versions being released afterwards. Its initial purpose was to allow to present various types of data, including text, images, webpage links etc. regardless of the environments it was opened in. As explained in [9], PDF files consist of objects, which are of eight types: Boolean values, Numbers (integer and real), Strings, Names, Arrays, Dictionaries, Streams and the Null object. Each PDF document should begin with a header that identifies it as a *PDF* and includes the version number `%PDF-1.7`. The document should also end in a certain way - with the signature `%%EOF` (see Figure 3.3). After header the objects are declared, that can contain necessary information for rendering the document. One of the most important objects is the stream, that can store an unlimited size sequence of bytes. Usually streams are used for storing text, but they can also store executable code, i.e., checkbox for agreement of *Terms and Conditions*. Streams can contain the optional entry `/Filter`, which is aimed for compression and encryption of data inside streams. Next comes the Cross-Reference Table (*Xref*), which determines the location of existing objects in PDF. The last section of the file is *Trailer*, that contains the metadata of the file, e.g., size of the file, number of objects, the id of the root object, etc. Hence it becomes clear that PDF documents are parsed from the end to the start.

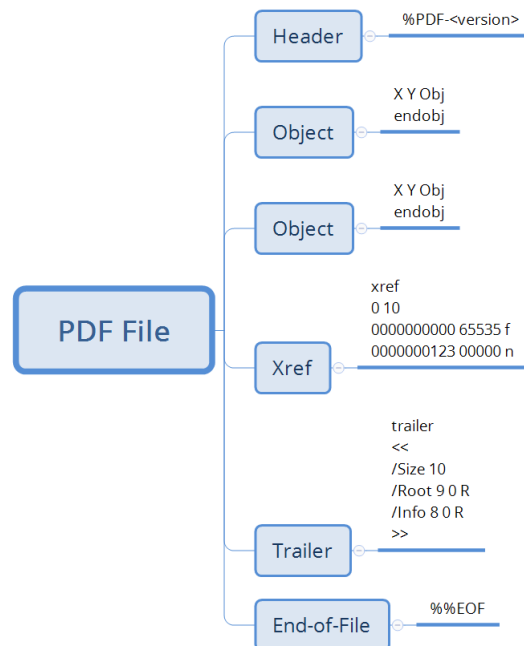


Figure 3.3: Structure of PDF Format [11]

⁷a malicious method by which a system bypass is hidden

3.5 Malware in PDF

Over the years PDF format has evolved and now it has support not just for text and images, but also for editable forms, animations and even 3D graphics. All of these features made PDF a great solution for information sharing. Meanwhile it also became a good target for cybercriminals, malware being easily embedded into PDF documents and widespread through different types of communication, e.g., HTTP, emails, etc. (see Figure 3.4)



Figure 3.4: Top malicious file types - H1 2019 [15]

Malicious PDF can be classified into three categories: *reader exploitation*, *feature abuse*, *phishing attacks*. Every year numerous vulnerabilities related to most used PDF readers, e.g., Adobe Reader, Acrobat Reader, Chrome, are reported. Before these weaknesses are patched⁸, attackers create exploits to execute arbitrary code, when a PDF file is opened with one of the vulnerable applications. Phishing attacks are more difficult to detect, because in the context of PDF documents, they aren't infected, instead social engineering is used in order to psychologically enforce someone to click on malicious links written in the documents. Another frequently used attack vector involves misusing the PDF extra-functionalities, such as running malicious code when file is opened, stealing sensitive information and sending to remote addresses, downloading infected executables and so on. Pursuant to [12], it's usually the fault of embedded Javascript code, whose intentions could be wrong, but as seen in Table 3.2 there are also several standard PDF entries, which seem to be interesting in terms of malware hunting. However, when searching for them we should not forget about the possibility of obfuscation using hex code, in which, for example, `/Launch` can turn into `/L0x61unc0x68`. Encrypting the streams and strings is another often applied "trick" to complicate the analysis work for both antiviruses and researchers. A PDF document from which it is impossible to copy text, or which cannot be printed, is such an obfuscated sample.

⁸applying changes to fix bugs or errors in a software program

Table 3.2: Standard PDF Entries whose functionality can be abused

Entry	Functionality
/JavaScript	Sets JavaScript code to be executed
/OpenAction, /Names, /AcroForm, /Action, /AA	Defines a script or an action to be automatically run
/Launch	Runs a program or opens a document
/URI	Accesses a resource by its URL
/SubmitForm, /GoToR	Can send data to indicated URL
/ObjStm	Hides objects inside Streams

3.6 Machine Learning for Malware Detection

Machine Learning (*ML*) algorithms are increasingly used in various fields of science due to their fast adaptability to the new arising problems. Cybersecurity is one of these areas, where the complexity and the assortment of attacks are raising daily. It becomes convenient to put ML into practice because of the large amount of collected data (application logs, network traffic scans, etc.), which can be processed using statistics techniques and can be transformed into models for making future predictions based on the new incoming inputs. This solution reduces the costs for continuous analysis, leaving the hard work on powerful computers, whose high performance don't require huge investments nowadays. Also it helps businesses to more efficiently prevent potential threats and automate routine tasks, allowing security teams to focus on implementing new detection techniques to advance ML algorithms.

As presented in [6], Machine Learning's use cases in security can be split into two types: *anomaly detection* and *pattern recognition*, thus these solutions are used to solve following specific security issues: spam detection (filters are applied on emails, webpages in order to detect patterns of usual phishing attacks), malware catching (polymorphic malwares such as Trojan⁹, Spyware¹⁰, Ransomware¹¹ etc. are recognized based on their behavior), account takeover spot (such kind of anomaly is detected, because of multiple tries when gaining access to someone's account) and many others. For more detailed information about Machine Learning techniques used in Cybersecurity consult Table 3.3.

⁹malware that is disguised as benign software to avoid detection

¹⁰malware that is aimed to collect information without permission of the user

¹¹malware that restricts access to personal data

Table 3.3: Application of Machine Learning to Cybersecurity problems

Technique	Explanation	Algorithm	Cybersecurity problem
Classification	Separation into different categories	K-Nearest Neighbors (KNN), Support Vector Machine(SVM), Random Forest	Spam filtering
Regression	Prediction of future values based on previous ones	Linear Regression (LR)	Fraud detection
Association Rule Learning	Recommendation based on past experience	Equivalence Class Clustering and bottom-up Lattice Traversal (ECLAT)	Incident response (suggest a policy to apply in case of a particular incident)
Clustering	Grouping into unknown categories based on similar features	K-Means	Detection of polymorphic malwares
Generative Model	Generation based on known distribution	Markov Chains	Vulnerability scanning

Many of the popular tech giants already apply Machine Learning solutions into their security departments. According to [8], Google is using ML to analyze threats against Android smartphones. Monthly new malicious applications are detected and removed from Google Play (Android application market). Microsoft integrates ML algorithms into Windows Defender Advanced Threat Protection (Microsoft cybersecurity cloud platform) in order to spot malware. Of course, a lot of companies are determined to use Machine Learning to combat cybersecurity attacks, however artificial intelligence should be just a tool to supplement human efforts, rather than replacing them.

Chapter 4

Proposed approach

For solving the problem of detecting malicious PDF documents, we came with a Machine Learning based approach. We took into account the importance of keeping the documents content confidentiality, as well as the need for ensuring the speed of analysis process. This solution will be next integrated into a Cloud framework responsible for remote documents scanning.

4.1 Dataset

The first step in building the optimal *ML* model was to create a dataset which would train the classifier. Our target was to collect malicious and benign PDF samples used in real life scenarios. Circa 80% of the clean and malicious documents were downloaded from the online malware repository *Contagio* [13], which provides samples collected from various open sources. Nevertheless, for more recent malicious PDFs we used VirusTotal [3], Hybrid Analysis [1] and VirSCAN [2], that allow searching files by their hash (*MD5*, *SHA1*, *SHA256*). Some of them provide access to the entire file collection so that we can order them by upload date and search for the most recent uploaded harmful files. Many clean samples were collected from public sources using Google Search Operators, i.e., `filetype:pdf`, for restricting search results of PDF files. Additionally, we completed the dataset with more than 100 clean interactive PDF files, that contain embedded 3D Widgets, incorporated JavaScript games etc. These clean samples should train the ML model, to correctly classify files even in corner cases.

Table 4.1: Dataset of PDF samples

Category	Source	Count
benign	Contagio, Google Queries, Tetra4D, PdfScripting	9.153
malicious	Contagio, VirusTotal, Hybrid Analysis, VirSCAN	10.982

4.2 Proof of Concept

In the following subsections we will touch upon algorithms and techniques we have used to achieve the purpose of this thesis, namely detecting malicious PDF documents using a Machine Learning based solution. Figure 4.1 represents the entire process which was followed while developing the *ML* model. Each process phase will be fathomed in the following.

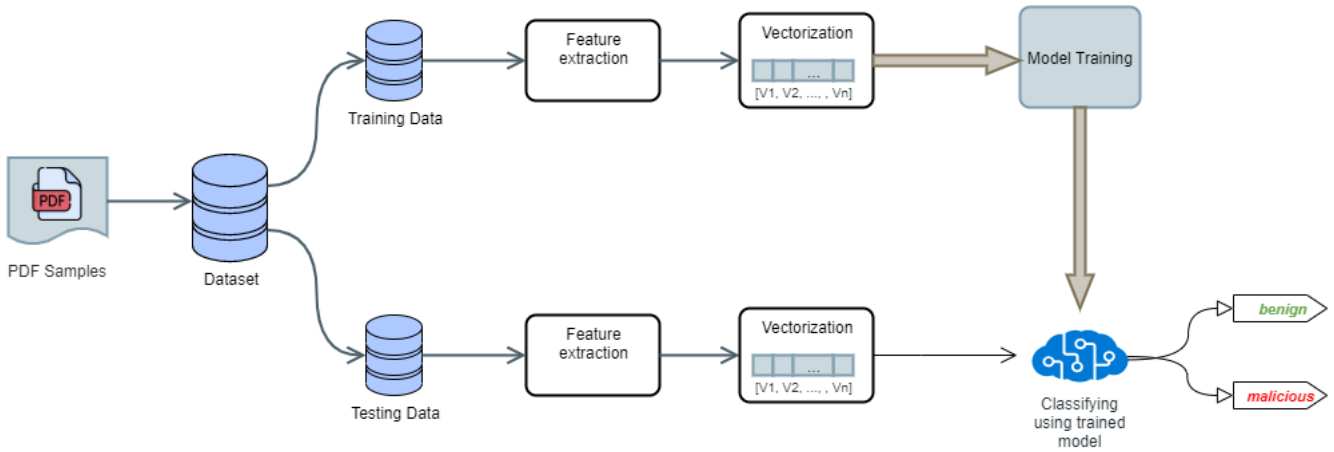


Figure 4.1: Machine Learning model creation

4.2.1 Feature Selection

As we already know, Machine Learning is based on mathematical concepts, hence the algorithms consist of performing mathematical operations to identify patterns in data. In order to use our dataset as input for ML algorithms, first of all we need to bring the data in an appropriate form. Therefore, the most relevant data from a PDF document should be extracted and transformed into a vectorized form. As already seen in Table 3.2, there are several standard PDF entries which can be used for malicious intentions. For featurizing PDF documents we have used *PDFiD* from *PDF Tools* suite [16], which is a Python script that selects 22 features from a PDF file, including keywords commonly found in malicious documents, name obfuscations etc. The output of the script is a list of PDF entries and their occurrences (see Figure 4.2). Before turning this featurized form of the PDF file into input for ML algorithms, the data should be normalized to $[0, 1]$ range. This is an important step in order to avoid ML issues when features are on drastically different scales (see [17]). The vectorized form of the PDF document is built by applying the *Min-Max Normalization* (4.1) strategy on the array of features extracted by *PDFiD*.

$$z = \frac{x - \min(x)}{\max(x) - \min(x)} \quad (4.1)$$

<pre> root@bt:/pentest/forensics/pdfid# python pdfid.py testpdf/apple1.pdf PDFiD 0.0.11 testpdf/apple1.pdf PDF Header: %PDF-1.4 obj 49 endobj 49 stream 15 endstream 15 xref 1 trailer 1 startxref 1 /Page 1 /Encrypt 0 /ObjStm 0 /JS 0 /JavaScript 0 /AA 0 /OpenAction 0 /AcroForm 0 /JBIG2Decode 0 /RichMedia 0 /Launch 0 /Colors &gt; 2^24 0 </pre>	<pre> root@bt:/pentest/forensics/pdfid# python pdfid.py testpdf/evil_apple1.pdf PDFiD 0.0.11 testpdf/evil_apple1.pdf PDF Header: %PDF-1.4 obj 57 endobj 57 stream 16 endstream 16 xref 2 trailer 2 startxref 2 /Page 2 /Encrypt 0 /ObjStm 0 /JS 1 /JavaScript 1 /AA 1 /OpenAction 1 /AcroForm 0 /JBIG2Decode 0 /RichMedia 0 /Launch 1 /Colors &gt; 2^24 0 </pre>
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Figure 4.2: Example of results of *PDFiD* applied on a benign PDF file (left) and on a malicious one (right)

4.2.2 Classification Technique

As we have successfully created the dataset by vectorizing each PDF from our collection and setting a label for each one (everything saved as a CSV file), the next steps would be feeding the dataset to a ML classifier and training a model. According to our application's requirements, a PDF file should pass through a binary classification, so the analyzed files can be only **malicious** or **benign**, respectively a supervised strategy was chosen. The model, that we will obtain when applying Machine Learning, is able to perform tasks that it has not been explicitly implemented to execute. First of all we split the dataset: 70% were used as training data and 30% were allocated as testing data. The training data is used to fit the model, so that the resulting trained model could be used to predict the correct verdict on previously unseen metadata.

Above all existing classification algorithms, **Random Forest** was selected because of its effective classification capability and the ease of use. Under the hood, this algorithm gives the classification result based on assembling the results from multiple decision trees. First a random subset from training data is selected. At each split point, m features from n available are randomly selected ($m \leq n$) and the optimal split point from m features is picked ($m = \sqrt{n}$ is recommended). This step is repeated until an individual tree is trained and each result represents the vote of a decision tree. These votes are combined to give an unified final classification result of the Random Forest technique.

Even if the training process is computationally expensive, once the classification model is constructed, categorizing is quickly executed. In order to make our API that integrates this model more efficient, we used the Python module - `pickle` to dump the virtual model into a file saved to disk. The process of refitting the model before using it to predict is much more time consuming than just loading the already fitted model from the disk.

4.2.3 Experiment

Before putting the chosen classification algorithm into work, we definitely had to take several aspects into consideration. The most important of them is the environment where the model is trained. When working with malicious samples it is crucial to ensure that the personal computer's integrity will not be affected. The instructions defined in Lenny Zeltser's articles [19] helped us to set up an isolated laboratory environment for our *experiment*. First of all we used VMware to create a virtual machine (VM), where we installed a Linux distribution. In this way no physical machine could be damaged and the lightweight OS keeps the performance unimpacted. For further performance evaluations (see Table 4.2), the allocated hardware specifications for the VM should be taken into consideration: $RAM = 3GB$, $CPU = 4$ processor cores. The communication with the development computer is through a shared folder, where the collection of PDFs, as well as the source code for training the model were dropped. After configuring all the required libraries, the network adapter of the VM was completely removed, so that it could not establish any connection to external sources in case of any malicious behavior. Also, a snapshot of the set up environment was taken. This is another huge advantage of a virtual machine: in case of accidental opening of a malicious file, we could easily revert to a safe snapshot.

Table 4.2: Run times on training the model on described dataset

Operation	Time
<i>Feature Extraction</i>	29 min
<i>Classifier Training</i>	0.405 sec
<i>Classification</i>	0.07 sec

After the classification model was successfully created, we decided to simulate a cyberattack using a malicious PDF file, in order to test the model prediction in a pseudo-real-life scenario. Metasploit¹ was used for injecting a malicious payload into an innocent looking file. After uploading the file to our analyzer, the classification result was as expected - **malicious**.

4.2.4 Performance Evaluation

As performance estimators for evaluating the strengths of the obtained classification model we have selected the following metrics, where TP stands for True Positives, FP - False Positives, FN - False Negatives and TN - True Negatives:

¹a penetration testing framework

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (4.2)$$

$$Recall = \frac{TP}{TP + FN} \quad (4.3)$$

$$Precision = \frac{TP}{TP + FP} \quad (4.4)$$

$$F1 - Score = \frac{2 \cdot Precision \cdot Recall}{Precision + Recall} \quad (4.5)$$

		Predicted	
		benign	malicious
Actual	benign	TP = 2708	FP = 1
	malicious	FN = 2	TN = 3329

Additionally, we generated a confusion matrix to observe the presence of FP and FN. The results of testing on 6640 samples (30% of the dataset) show an accuracy of **99,95%** for the trained model using *Random Forest Classifier* with 100 estimators. Of course there are some minor corner cases, when the detection fails: 2 files were detected as benign while they were malicious and 1 benign file was predicted as malicious. However, the overall results (see Table 4.3) demonstrate that the obtained model can be efficiently applied for malicious PDF files detection.

Table 4.3: Random Forest Classifier performance results

Accuracy	Recall	F1-Score
0.995	0.9992	0.9994

4.3 Used technologies

4.3.1 Microsoft .NET Framework

As previously mentioned in sections 3.2 and 3.3, our application is going to have a help tool for Windows based computers that will automatically detect new downloaded PDF documents, upload them to our Cloud Analyzer and take action (keep/delete) on that files corresponding to their category (benign/malicious). This tool will take the form of a Windows Service which will start running at the boot-time of the computer in the Session 0 (see section 3.2) and will communicate with an application responsible for notifying users through Windows notifications (see Figure 4.3).

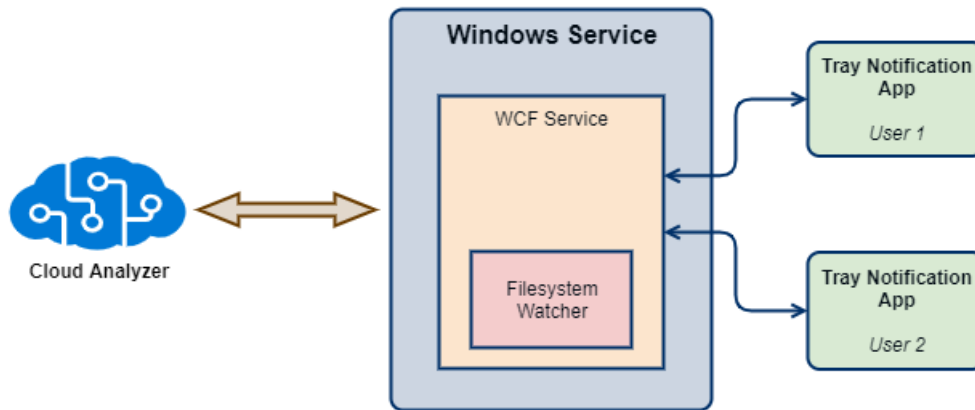


Figure 4.3: Architecture's outline of the help tool for Windows

Microsoft **.NET Framework** provides all the necessary classes for creating the described tool. This framework represents a solution for standardization of application development on Windows operating system. Prior to the introduction of .NET Framework, the developers mostly used COMs² as a solution for code reuse. However, COM requires developers to write boilerplate code in order to turn their business logic into a reusable component, including memory clean up, reference counting etc., whence result a lot of errors. The .NET Framework allows developers to focus on writing the business logic, while it is dealing with the memory management and is providing consistent exception-handling mechanisms. For example, in our application we implemented several .NET interfaces to achieve the expected behavior without having to manage a lot of low-level details. To create a Windows Service, we derived our class from `System.ServiceProcess.ServiceBase` and we had to override it's `OnStart` and `OnStop` methods. Because a service runs in Session 0, it means that it does not have support for user interface. Yet the application is intended to push Windows notifications and to ensure this functionality we had to treat our tool as a client-server application. The Windows service establishes

²Component Object Model (COM) is a model of reusable software introduced by Microsoft in 1993

an interprocess communication with the client *Tray Notification App* when a user logs in. For this mechanism the WCF³ framework is integrated, which allows sending data as asynchronous messages from one endpoint to another. WCF was chosen as communication layer because it provides the *duplex* message exchanging pattern, where two processes establish a secure TCP connection and can send data in both directions. To make this work, it is necessary to just define used entities for communication as *Data Contracts*, that will later serialize the metadata by the WCF serialization engine. Another important component that lies at the core of the WCF service is the monitor class that inherits from `.NET System.IO.FileSystemWatcher`. It's behavior was described in section 3.3 and we basically use it to monitor user's specified folders and to send events to the users via the WCF communication. At the top level, in order to catch sent events from the Windows Service, a hidden WPF⁴ application starts communication with the service at the user's login. When a PDF document is downloaded into the monitored folder the Windows Service throws an event that is displayed to the user in form of a Windows System Tray Notification.

4.3.2 Scikit-learn Machine Learning Library

It would be extremely inefficient to always reimplement each Machine Learning algorithm that is required for solving a specific problem. **Scikit-learn** is one of the well known and largely used ML libraries, that came across as a solution for code reusability and performance optimization. This open-source library was created above the already prepared "ecosystem" for Data Science - *Python*. Even though Python is just a programming language, there are a plenty of libraries created using Python, that are used on a daily basis by scientists. In terms of efficiency there are no doubts that Scikit-learn would not give way to other ML libraries. And all this because of its underlying technologies. At the core it integrates:

- *Cython* - a compiled language that can bind compiled libraries, reaching high performance of the CPU;
- *Numpy* - optimized Python module for working with large multidimensional arrays;
- *Scipy* - a large collection of efficient algorithms for linear algebra, interpolation etc.

Till now, the Scikit-learn developers have supplied the library with various supervised and unsupervised algorithms, such as: regression, clustering, classification algorithms, as well as: Random Forest, Support Vector Machine etc. It is a perfect solution for both academic and

³Windows Communication Foundation (WCF) is an API in the .NET Framework for building connected, service-oriented applications

⁴Windows Presentation Foundation (WPF) is a UI framework for desktop applications from .NET Framework

commercial projects, because of the simple API that it provides, thus the generic implementation of the ML algorithms can be adapted to personal purposes. Also, Scikit-learn integrates well with other Python libraries, that consistently simplify the data analysis process. Some of these libraries are:

- *Pandas* - offers optimized data structures (*DataFrames*) for manipulation of large datasets. We could simply apply *Min-Max Normalization* (see 4.2.1) on entire loaded dataset from a raw CSV file.
- *Matplotlib* - used for data visualization and plotting. Learning Curves of the classifier can be better analyzed from a visual representation.

4.3.3 Python Flask

As soon as the heart of our application came to life - the ML model for detecting malicious PDFs, we needed a way to make it publicly accessible. **Flask** is a microframework for web applications that helped us to make it possible. Comparing to other web frameworks, Flask is focused more on simplicity and extensibility, making the development much more oriented on solving own business case. This lightweight framework has no built-in database abstraction layer or object-relational mapping and neither any form of validation or authentication, instead it supports third-party libraries that provide all enumerated functionalities and even more. Flask core includes basic functionality required by all web applications and gives an abstraction for creating a request-response mechanism based on *Werkzeug* library, which provides a collection of utilities for WSGI⁵ applications. Other implementation details can be easily integrated based on personal preferences. For example, we used a NoSQL database in our application, having the possibility to choose from a large variety of available mechanisms for data storage.

The created web service respects the requirements of a RESTful architectural design, the Flask framework providing a simple mechanism for specifying routing and HTTP methods. For demonstration purposes we have listed below a minimalistic example of a REST HTTP Method (processes a file sent over a POST request and returns a JSON result) showing the Flask simplicity. One of the major advantages of this framework is the compatibility supported by nowadays giants of Cloud Computing. Our created web framework that exposes methods for uploading PDF files and analyzing them, as well as visualizing the history of scanned files, can be later deployed to Cloud services such as: Google Cloud Platform, IBM Bluemix, Microsoft Azure etc.

⁵Web Server Gateway Interface (WSGI) is a specification that describes the communication pattern between a web server and web applications

```
from flask import Flask, jsonify, request
app = Flask(__name__)

@app.route('/api/file-upload', methods=['POST'])
def upload_file():
    file = request.files['file']
    file_status = file_controller.upload(file)
    response = jsonify({'message': file_status})
    response.status_code = 200
    return response

if __name__ == "__main__":
    app.run()
```

4.3.4 ReactJS Framework

In order to use the web service in a user friendly way, a modern graphical user interface (*GUI*) is needed. The contemporary approach for developing a web GUI is to use a frontend JavaScript Framework. The range of choice is extremely large, e.g. *Angular*, *Vue.js*, *Ember.js* etc., but finally we decided for **ReactJS**. Being developed and maintained by Facebook, ReactJS has a fast-growing community and is one of the trending JavaScript Frameworks in 2020. The need of using a framework for web GUI arises because of necessity for time-efficient development experience, standardized methods of programming, faster performance and robust memory management. As well as other frameworks, ReactJS is aimed to render data to the *DOM*⁶ and to eliminate the subsequent page refreshes in a complex web application that constantly updates its data. This mechanism is provided by the concept of *Virtual DOM* used in React, which involves constructing the representation of a web page in a virtual memory, where it uses the *Reconciliation Algorithm*⁷ to perform only the necessary updates before rendering the page into the browser.

The extensibility of React code is assured by *Components*, that are rendered to specific elements in the DOM. These can be declared in two ways: functional and class-based, the main difference being in the "state" which can be hold only by a class-based component. The performance is influenced positively by the lifecycle methods in React Components. There are multiple lifecycle methods for controlling the state of a web page, but two of them that should be definitely took into consideration are `componentDidMount`, that is called once the data is

⁶Document Object Model (DOM) is the representation of a web page that can be manipulated using JavaScript

⁷is a diffing algorithm that compares the types of root elements and decides which element should be rerendered

fully loaded from a remote source, and **render** which is called every time the component's state gets updated.

Usually React requires the use of additional libraries for common functionalities like routing, state management and layout styling of the UI. For these purposes we used:

- *React Router* - a routing library that keeps the user interface in sync with the corresponding URL. It manages the redirection, lazy code loading and dynamic route matching.
- *Redux* - a state management tool, that keeps track of each component's state and stores them into a global place, so that data becomes accessible from any component.
- *Semantic-UI-React* - a collection of UI standards defined as a singular style. Instead of recreating the layout of commonly used web elements (Buttons, Grids, Modals, Input Fields etc.), it is more efficient to use a library with all of those elements already created.

Chapter 5

Application

In this chapter we are going to have an in-depth look at the architecture of our application - **ExtWatcher**, that represents a solution for the enunciated problem in this thesis.

5.1 Design

ExtWatcher is a software application assembled from multiple components using different technologies (see Figure 5.1). In the following we will introduce you into its implementation design starting from the low level and we will explain what role each component plays in the context of providing a truly effective security solution.

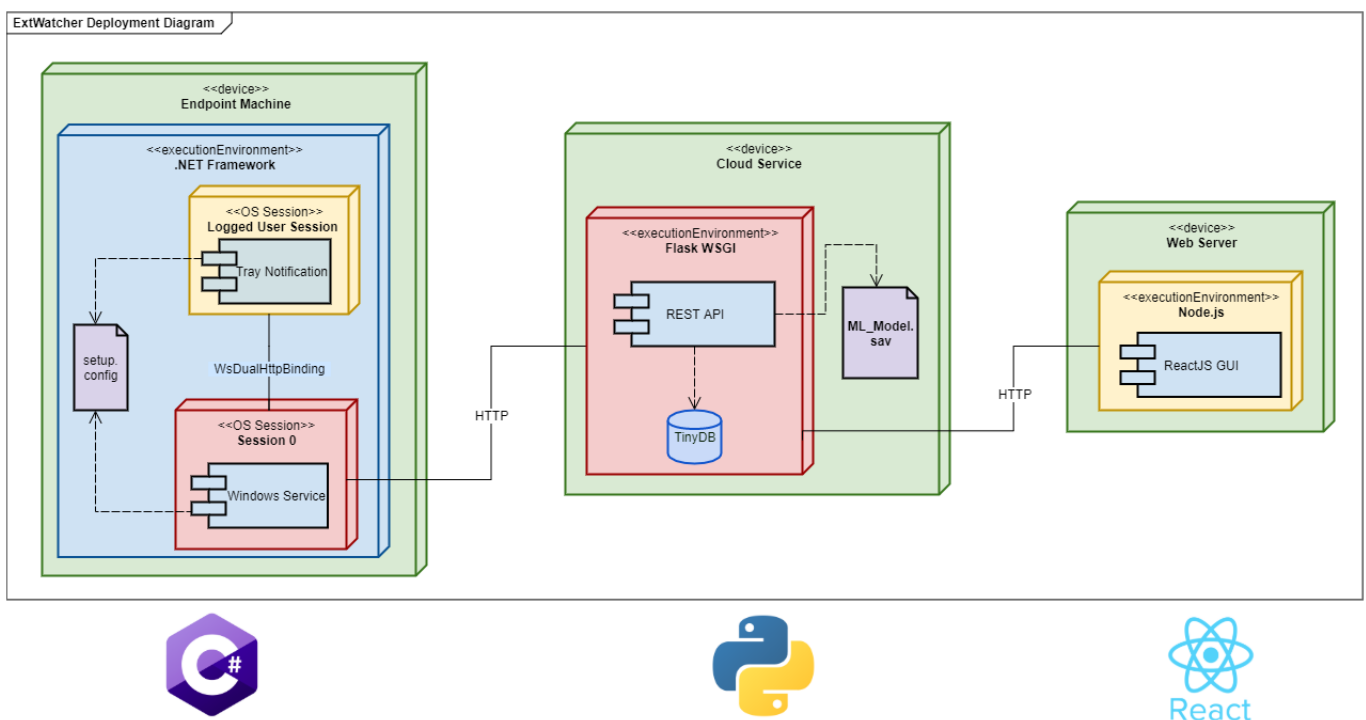


Figure 5.1: Deployment Diagram of the application and used technologies

The core of the entire software application is the *Cloud Analyzer*, which provides the security measure against malicious PDF documents. ExtWatcher has two different, independent approaches for getting access to the Cloud Analyzer.

- The first one implies automatic file detection and requires the installation of *ExtWatcher Service*, which will establish a connection through HTTP to the Cloud Analyzer and will instantly remove detected malicious files from the user's computer.
- The second approach is an *out-of-the-box* functionality, the user being able to analyze a file by accessing the Cloud Analyzer Dashboard (web graphical user interface) and entering the URL of the file. The dashboard submits the URL to the Cloud Analyzer and the later downloads the file, classifies it and sends back the verdict. This solution is fit for mobile devices, as it requires no additional installation, ExtWatcher Service being currently supported just on Windows OS.

In order to properly work, our application requires permanent Internet connection, because the core of analysis is remotely located. The advantage of this is the fact that Cloud servers are better at applying Machine Learning models for malware detection, thereby reducing the workload on personal computers.

5.2 ExtWatcher Service

This section will describe how the Windows Service manages to simplify the user responsibility and to automate the task of detection and uploading of PDF files to our analysis engine. As previously mentioned, this is not a mandatory component, rather just a help utility for users whose computers work on Windows platform. However, this tool itself integrates two separate executables (the service and the app aimed to send system notifications), each with its own configuration files. Of course, field knowledge is required in order to correctly configure this tool and to let it run errorlessly. To solve this problem and to make *ExtWatcher Service* accessible for everyone, we created a Setup Installation File, which packages all the necessary files and installation information into a *MSI* file. The user should just launch the installer executable to get *ExtWatcher Service* properly working on their computers. Under the hood, the used Windows Installer, unpackages those two applications and their configuration files, moves them to the corresponding installation folder, writes the suitable registry keys to set the *Tray Notification App* to launch at the user's login, installs the service into Windows Service Manager and starts the utility right after the installation is done.

After ExtWatcher Service is up, it should guarantee the security of the user's computer. By default, the filesystem's C:\ and D:\ disks are monitored. However, modifying the `setup.config`

configuration file found in the installation folder of the software, allows to add new filepaths for continuous monitoring. In this way the user can be sure, that once he downloads any PDF file to his computer, the integrity of the system is protected by our application. Basically, the Windows Service detects that a new file of type PDF was downloaded, blocks and hides it, so that the user cannot access the file until it is not scanned. Next, the Windows Service submits the file to the remote server for analysis. While waiting for the response, it sends an event to the *Tray Notification Application*, which is responsible for pushing System Notifications to the user, saying that the downloaded PDF is being scanned (see Figure 5.2). After the analysis response in JSON format is caught by Windows Service, it takes the corresponding action on the PDF file, based on the *verdict* extracted from JSON.

- **benign** - this verdict means that the Windows Service can take out the applied restrictions (block and hide) from the file.
- **malicious** - Windows Service should immediately remove the file from the disk.

The above described flow can be visualized in Fig. 5.3. The implementation design of ExtWatcher Service takes in consideration further evolution of our product. So, it can be easily configured using same `setup.config` to monitor more file extensions, when the Cloud Analyzer will contain support for analyzing more file formats.

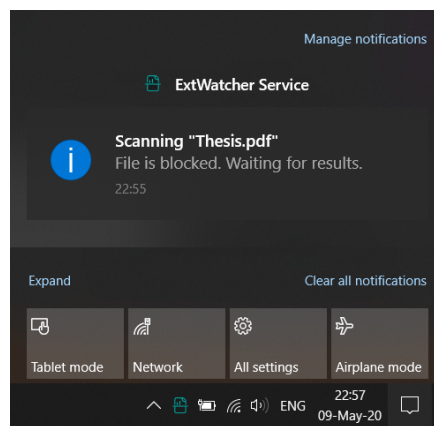


Figure 5.2: Screenshot of the System Notification sent by ExtWatcher Service

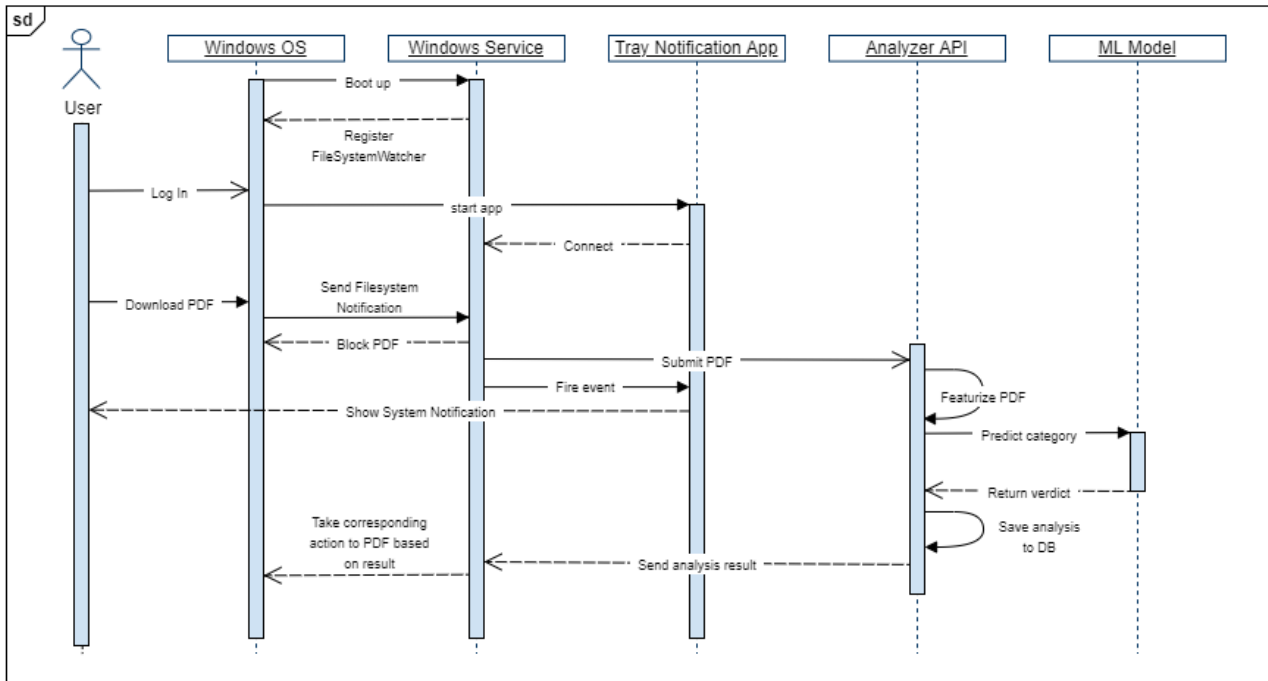


Figure 5.3: Sequence Diagram showing interaction between User, Windows Service and Cloud Analyzer

5.3 Cloud Analyzer

Next we will finally cover the core of our product - the Cloud Analyzer. As mentioned in section 5.1, there are multiple ways to access the core, as it is a Cloud based solution. The first two methods are straightforward and make the use of the Cloud application intuitive. Nevertheless we designed our API keeping in mind the REST¹ architecture. As effect, we have a strong separation between the server and client side, thus giving the opportunity to our API to be integrated in multiple ways. Beside the *visual* method (web Dashboard Interface) and the *automation* method (ExtWatcher Service), this framework can be adapted to more use-cases. The custom client can access it via the exposed REST interface, no limitations being currently applied. This independence of the Cloud Analyzer assured by the RESTful design makes it flexible and portable, permitting to configure it in different types of environments. It was not the purpose of this thesis to deploy the framework to any Cloud service, but it was a main goal to achieve its portability and ease of configuration.

As it was clear that our framework is going to be a resource for just retrieving data from it, without requiring any information about client's state, we fulfilled another REST paradigm - *Stateless*. Due to this, the application achieves scalability and performance, the communication between client and server being simple and not relying on implementation of interfaces. The

¹REpresentational State Transfer (REST)

pattern of interchanging data is based on requests and responses, where the HTTP communication protocol is used.

In order to retrieve information about a PDF file, the *ExtWatcher Service* uses a **POST** HTTP method to upload the file to the framework. The request contains two main parts: *Header*, which contains all the information about the request, in our case the content type of the body: **application/pdf**; and the *Body*, which basically contains the content of the uploaded file. Specifying the content type is really important, because that ensures that the server is able to process the request. Once the PDF is uploaded to the server, first of all, the MD5 hash of the file is calculated to check in the database if the same file was not already analyzed. If the hash is not found, the file is being analyzed by applying the ML model for predicting the file maliciousness. The result together with a HTTP status code (*200* - for successful process; *400* - for bad request) is then sent back as response.

The web Dashboard's integration with the Cloud Analyzer is a bit different. Mostly it accesses the server in order to retrieve stored information about previous analyses. That is achieved via **GET** HTTP methods. The response is in JSON format and can be easily processed by the Javascript client in order to offer an intuitive visualization of it. An in-depth particularization of all exposed methods from our framework can be studied in the Table 5.1.

Table 5.1: REST Resources of the Cloud Analyzer API

Resource	Method	Purpose
/api/file-upload	POST	Uploading files for analysis
/api/url-submit	POST	Submitting URL to a file that should be downloaded and analyzed
/api/feed	GET	Retrieve the history of events (who and what kind of analysis type started)
/api/analyzed-files	GET	Obtain a list of informations about all analyzed files
/api/search-files	GET	Search files using queries for filtering by different file attributes
/api/extwatcher-service	GET	Download ExtWatcher Service Installer

5.4 Dashboard Interface

ExtWatcher also offers an intelligent solution for interacting with the Cloud Analyzer API and to visualize the data that passed through it. This is a responsive web Dashboard with the help of which users can interact with the API from any device, be it laptop or smartphone. An overview of the Dashboard capabilities is presented in Figure 5.4.

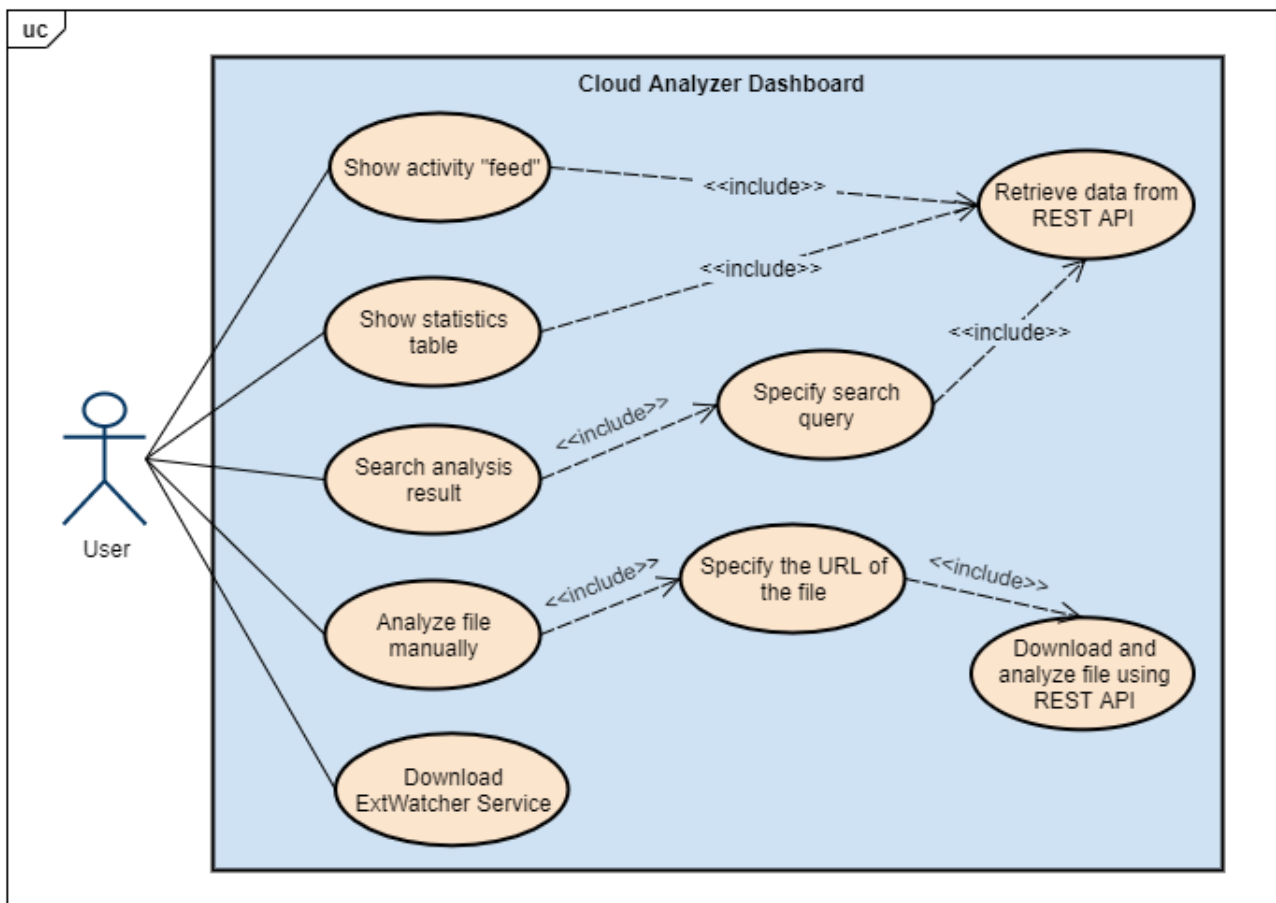


Figure 5.4: Use Case Diagram showing interaction between User and Cloud Analyzer using web GUI

It was implemented separately from the server, so it calls just the API methods it requires, without being forced to implement a concrete server interface. The connection between these two is established via HTTP protocol and mostly the Dashboard works with the GET methods to access the server's resources (see Table 5.1) and to present them to users. At the moment, any user that accesses the Dashboard has the possibility to view statistics about all files ever scanned, including file details such as: filetype, MD5 hash of the file, filename, date when it was scanned and result of analysis (see Figure 5.5).




Filetype	MD5	Filename	Date	Result
	b670c89b7ce8489e76c7bb2a1f95802a	V1Logik.pdf	08/03/2020 - 16:16:01	✓ benign
	4baabe9c0902ea95dec4bdbfa647bafb	V9Logik1.pdf	08/03/2020 - 21:38:46	✓ benign
	0dba8b5fd66c91e294adea1566f15e15	JSPopupCalendar.pdf	08/03/2020 - 21:40:01	⚠ malicious

Figure 5.5: Screenshot of the ExtWatcher Dashboard table of file informations

Also the dashboard presents a "feed", that serves as a history of using the Cloud Analyzer (see Figure 5.6). It includes information about how each file came to be analyzed: by being uploaded by the ExtWatcher Service or by manually submitting the URL of the file, as well as information about the IP the file was originated from.

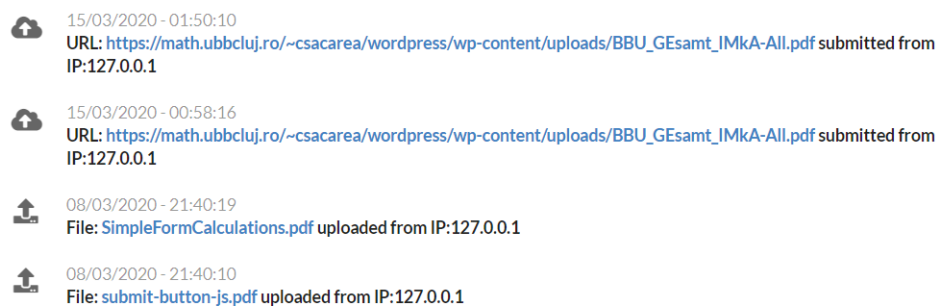


Figure 5.6: Screenshot of the ExtWatcher Dashboard activity feed

Of course, to simplify the interaction with this web application, it provides also a *searchbar*. The user can quickly find information about any file, by specifying a basic search query (see Figure 5.7).

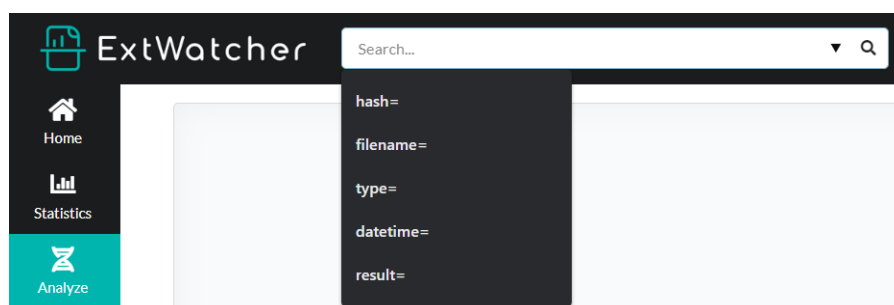


Figure 5.7: Screenshot of the ExtWatcher Dashboard searchbar and types of search queries

For those users who adopt the automatic detection and submission to the Cloud Analyzer approach, using the *ExtWatcher Service*, the Windows Installer can be downloaded directly from the Dashboard (see Figure 5.8).

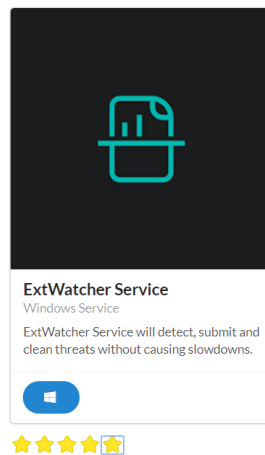


Figure 5.8: Screenshot of the ExtWatcher Dashboard download page for ExtWatcher Service Installer

However, we took in consideration the alternative case, when not all users would prefer this method or some just don't have a computer with Windows OS (single OS for which ExtWatcher Service has support yet). There is another method to analyze PDF files directly from the web Dashboard. The user should just specify the URL of the file he wants to analyze and the rest of the workload is taken by the Cloud Analyzer. In this way, the user can be confident that no PDF file can harm his device, because it is first downloaded by the Cloud Analyzer and is analyzed on a remote, safe environment. After the analysis result is showed, the user can decide what to do with that file (see Figure 5.9).

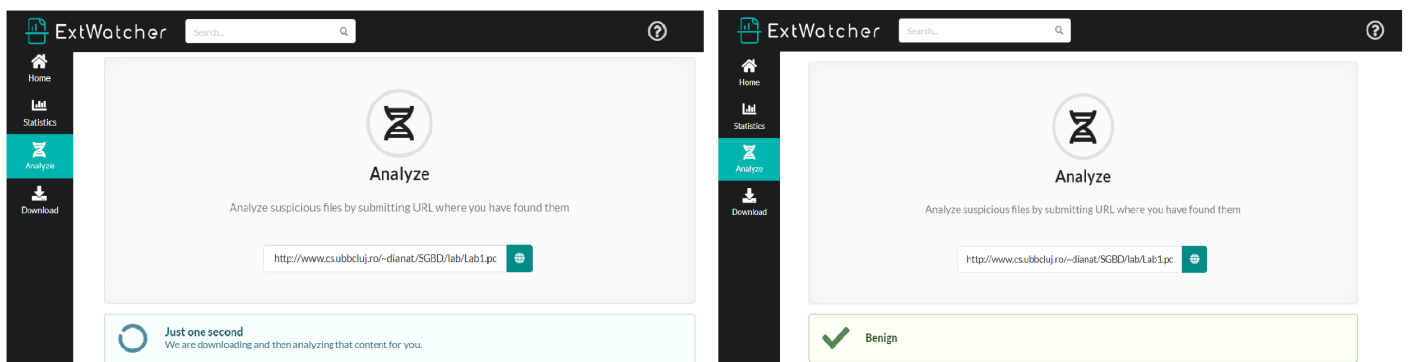


Figure 5.9: Screenshot of the ExtWatcher Dashboard analyze page

Chapter 6

Conclusion and future work

The main objectives behind the proposed approach for creating a Cloud application, which could scan PDF documents and return a verdict was successfully fulfilled. This paper demonstrates the capabilities of Machine Learning algorithms applied on cybersecurity tasks, which in some cases can provide even better results than a classic antivirus application. In addition to the Machine Learning framework responsible for PDF scanning, we also provide an automated solution for file uploading, which can take an according action to the scanned file based on its result, in order to assure the safety of user's computer. The symbiosis of these two creates a complex system that distributes the performance-expensive task of malware analysis from an endpoint machine to a remote server. This way the user should not worry that his computer will be compromised by any PDF document, which these days is one of the most exchanged file formats.

The next step in extending our created product will be making the framework publicly available, by deploying it on a Cloud service. Currently the automatic file uploader is supported only on Windows OS and the users have the alternative to manually submit the URL of a PDF file in order to scan it. In the future we plan to develop a similar background application for automating file upload for Android OS and possibly other operating systems. The Cloud application is also included in our upgrades plan. Its architecture already permits the integration of other Machine Learning models for classification of new file formats. The purpose of the upcoming research will be Microsoft Office Document formats (DOC, XLS, PPT), as well as PE (Portable Executable) and DLL (Dynamic-link library) files.

We think that now is the era for transferring all of the performance draining applications to the Cloud.

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