



UNIVERSITY OF PADOVA
ENGINEERING DEPARTEMENT

Computer Engineering Master Degree

ACCAPPCHA:
DESIGN, DEVELOPMENT AND SECURITY ANALYSIS
OF AN INVISIBLE CAPPCHA BASED ON
AN ACOUSTIC SIDE-CHANNEL

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To my parents, that always help
me to be happy doing what I love
and support me reaching my goals.

“Most people assume that once security software is installed, they’re protected. This isn’t the case. It’s critical that companies be proactive in thinking about security on a long-term basis.”

Kevin Mitnick

“You have to learn the rules of the game. And then you have to play better than anyone else.”

Albert Einstein

“Si come il ferro s’arrugginisce senza esercizio, e l’acqua si putrefà o nel freddo s’addiaccia, così lo ’ngegno senza esercizio si guasta.”

Leonardo da Vinci

Contents

1	Introduction	1
2	State of the Art	3
2.1	Traditional CAPTCHAs	4
2.1.1	Audio-based CAPTCHAs	5
2.1.2	Game-based CAPTCHAs	5
2.1.3	Image-based CAPTCHAs	6
2.1.4	Math CAPTCHAs	9
2.1.5	Slider CAPTCHAs	10
2.1.6	Text-based CAPTCHAs	11
2.1.7	Video-based CAPTCHAs	11
2.2	Modern CAPTCHAs	13
2.2.1	Biometrics-based CAPTCHAs	13
2.2.2	Behavioural-based CAPTCHAs	14
2.2.3	Sensor-based CAPTCHAs	15
2.3	CAPTCHA security	16
3	Side-channel attacks	21
3.1	Local side-channel attacks	22
3.2	Vicinity side-channel attacks	24
3.3	Remote side-channel attacks	25
4	Invisible CAPPCHA	29
4.1	Motion detection	29
4.2	Communication between Client and Server	30
4.2.1	Elliptic Curve Digital Signature Algorithm (ECDSA)	31
4.3	Security analysis	32
4.3.1	Strength against popular attacks	32
5	Design of AcCAPPCHA	35
5.1	Time correspondence	35

5.2 Deep learning classification	36
6 Development of AcCAPCHA	39
7 Experimental results	41
8 Security Analysis	43
Bibliography	43

Chapter 1

Introduction

CAPTCHA (Completely Automated Public Turing Test to Tell Computers and Humans Apart) is a program used to distinguish human users from bots. A bot is a malicious application that automates a task, gathering useful information about user credentials or pretending to be a human interaction with Web application. Hence the term "*bot*" is an abbreviation of the words "software robot".

The CAPTCHAs are traditionally used in Web applications for[1]:

- **Online Polls**
CAPTCHAs prevent the creation and the submission of a large number of votes, favouring a party.
- **Protecting Web Registration**
CAPTCHAs prevent the creation of free mail account to bot instead of human users. The goal of the use of CAPTCHAs is to remove the possibility that the hacker could take advantages from the large amount of registrations.
- **Preventing comment spam**
CAPTCHAs prevent the insertion of a large amount of posts made by bot on pages of social platforms or blogs.
- **Search engine bots**
CAPTCHAs are used to guarantee that a website should be unindexed to prevent the reading of the page through search engine bots. The CAPTCHAs are added because the html tag, used to unindex the web page, doesn't guarantee unindexing.
- **E-Ticketing**
CAPTCHAs prevent that a big events would sell out minutes after

tickets become available. In fact ticket scalpers that make large number of ticket purchases for big events.

- **Email spam**

CAPTCHAs are used to verify that a human has sent the email.

- **Preventing Dictionary Attacks**

CAPTCHAs prevent bot to guess the password of a specific user. The hacker could guess the password, taking it from a dictionary of passwords. The use of the CAPTCHA challenge prevents the iteration of the login phase made by the bot using all the words of the dictionary. After a certain number of failures POST requests, the CAPTCHA challenge is shown to the user.

- **Verifying digitized books**

ReCAPTCHA can verify the contents of a scanned piece of paper analysing responses in CAPTCHA fields. A computer cannot identify all the words from a digital scan.

The application submits two words to the user in the CAPTCHA challenge: the first one that the machine has already recognized and the other for which it can correctly associate a word. If the user types the two words and the first one was correctly detected, it assumes that also the second one is correct.

In this case the second word is added to a set of words that are going to be added to other users' challenges. If the application receives enough responses with the same typed word related to the unknown word, the program establishes that typed word is the CAPTCHA is related only to the first word and the challenge related to the second word is exploited by the application to scan digitally the paper.

Another useful application of CAPTCHA is the support to the authentication process. This application is going to be analysed in details in the next chapters, looking at the authentication from smartphone.

In Chapter 2 there is a description of the state of art of CAPTCHA, looking at types of CAPTCHA and the related tests from which this challenge is born.

In Chapter 4 Invisible CAPTCHA is described in details.

DESCRIPTION OF THE CONTENT OF THE CHAPTERS

Chapter 2

State of the Art

CAPTCHA takes inspiration and is related to three main elements[2]:

1. **Turing test**

it's used to determine how much a machine can think like a human. The test is made by three figures: a human examiner, an human and a machine. The examiner asks some questions to both other two figures and, after a fixed amount of time, evaluates if the two answers are different or not.

If they are similar w.r.t. the point of view of the examiner, the machine is an AI (Artificial Intelligence) similar to an human. The test is very important if the answers have many possibilities.

2. **Human-Computer Interaction (HCI)**

according to cognitive psychology studies, a human process data in a specific way and this test evaluates the interaction between humans and machines. The HCI model is divided into five levels:

- task level
- semantic level
- syntactic level
- interactive level
- a level of physical devices

Then the obtained information is processed by:

- reasoning
- problem solving
- skill acquisition

- error

3. Human Interactive Proof (HIP)

it's used to make differentiation between machine and human users and computer user programs. The test require a type of interaction, that is simple to be done by human instead of bot. The main goals of this type of test are:

- To differentiate the humans from the computers
- To differentiate a category of the humans
- To differentiate a specific human from the category of humans

HIP has the test program that is subjected to the human and the computer. As a result, only a specific group of humans can positively solve the test and then the test results can be validated by the computer.

In order to guarantee a good level of security, a CAPTCHA has to satisfy the following requirements:

- The solution to the CAPTCHA isn't conditional and shouldn't depend on the user's language and/or age.
- The solution of the CAPTCHA must be easy for the humans and hard for the bots. Hence, humans in no longer than 30 seconds with very high success rate
- The creation of the CAPTCHA must not disturb the user privacy (not linked to the user).

2.1 Traditional CAPTCHAs

The traditional CAPTCHAs are based on the knowledge and correct insertion of solution by the user. These CAPTCHA schemes are designed to exploit character recognition, image understanding and speech recognition to guarantee that the challenges will successfully block bots.

The main types of these CAPTCHAs are described in the following sections but the details about specific implementations can be found in the article of Walid Khalifa Abdullah Hasan[3]. With respect to user experience, the most enjoyable traditional CAPTCHAs are usually the game-based and image-based ones but the most frustrating CAPTCHA is the text-based one[4]. A summary of usability and security issues is shown in Table 2.2.

2.1.1 Audio-based CAPTCHAs

This type of CAPTCHAs asks the user to type the words listened by an audio file (see Figure 2.1). It's developed for vision-impaired users. It usually has problems in usability related to the language dictionary, from which words are taken, and the similarity of the sound between several words. It has been proved that this CAPTCHA is a hard task even for blind users, in fact only 46% of the challenges were solved by participants to an experiment[5].

One of the most popular CAPTCHAs is *Audio reCAPTCHA*, developed at Carnegie Mellon University and then bought by Google. In this scheme, the user needs to recognize and write a set of 8 spoken characters from a noisy audio file with background voices. If the user makes a mistake, the test declares that he's a bot.

Audio-based CAPTCHAs are vulnerable to many Automatic Speech Recognition (ASR) programs[6] but also Deep Learning techniques (e.g. DeepCRACK[7]). A good overview about results, obtained by several classification methods, is described in the work of Jennifer Tam et al.[8].

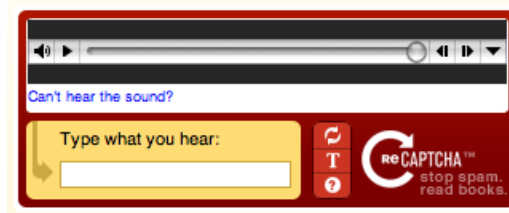


Figure 2.1: Example of audio-based CAPTCHA.

2.1.2 Game-based CAPTCHAs

This type of CAPTCHAs performs the verification of the user nature through a set of several kind of games (see Figure 2.2). The strength of this CAPTCHAs is relative to the comprehension phase of the rules that only humans can perform.

This type of CAPTCHAs is called *Dynamic Cognitive Game (DCG)* is usually developed using Flash and HTML5 with JavaScript. These technologies download the game code to the client and execute it locally.

The only difficult for the bot to attack the challenge is the encryption/obfuscation of the code. This strategy prevent the store of the code onto different internet domains. However for example, there exists a bot attack, called *Stream Relay Attack*, that obtains good results bypassing these challenges [9] (see Section 2.3).



Figure 2.2: Examples of game-based CAPTCHAs.

2.1.3 Image-based CAPTCHAs

Image-based CAPTCHAs require to understand a written text describing a task that needs an image evaluation to pass the test. This type of CAPTCHAs can be categorized into the following classes, looking to the task that the user needs to perform:

- **Click-based CAPTCHAs**
this type of CAPTCHAs shows an image and a text that explains where the user needs to click (see Figure 2.3).

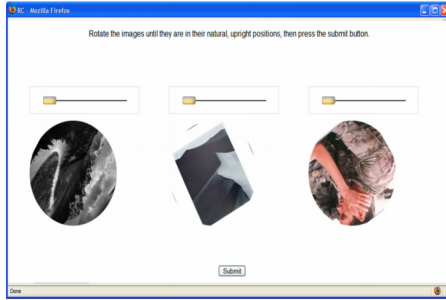
Please click the *circle*, *heart* and *pentagram* regions with different styles:



Figure 2.3: Example of click-based CAPTCHA.

- **Sliding image-based CAPTCHAs**

this type of CAPTCHAs asks the user to use the slider to solve an image-based challenge such as adjusting the orientation of an image, selecting the correct form of an image, or moving a fragment of an image to the correct location (see Figure 2.4).



(a) Orientation based.



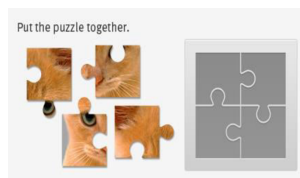
(b) Form based.

Figure 2.4: Examples of sliding image-based CAPTCHAs.

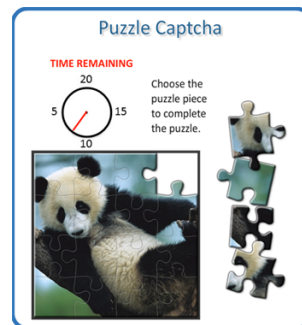
- **Drag & Drop-based CAPTCHAs**

this type of CAPTCHAs usually asks the user to complete a visual puzzle, created by dividing a given image in a set of pieces[10] (see Figure 2.5a).

The task isn't easy for users because this type of CAPTCHAs takes more time to solve the puzzle but the security level is very high[10]. To improve the usability of the CAPTCHA, there exists a variant of the puzzle-based CAPTCHA in which needs to insert only some pieces of the puzzle instead of completing the whole puzzle (see Figure 2.5b).



(a) Completing the puzzle.



(b) Inserting only some pieces.

Figure 2.5: Examples of puzzle-based CAPTCHAs.

- **Selection-based CAPTCHAs**

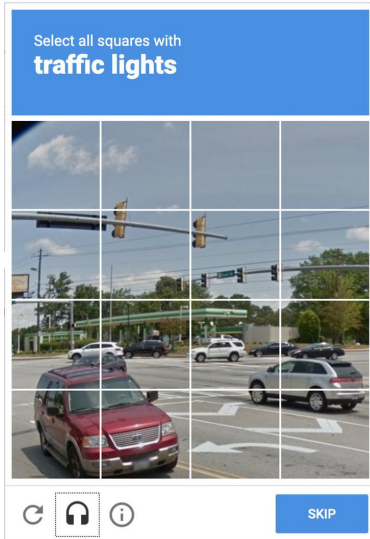
the user usually needs to select the images that contain a requested subject. The set of images, on which the user needs to identify the subject, can be implemented in different ways, for example:

- An image is divided into a set of sub-squares and each of them is a candidate image 2.6a
- There are many images, each one with a unique different subject (see Figure 2.6b)

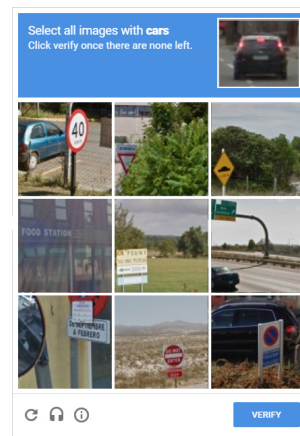
This type of CAPTCHAs is vulnerable to different Object Recognition techniques developed for Computer Vision purposes.

An extension of this type of CAPTCHAs, called *FaceDCAPTCHA*, has been introduced[11]. It incorporates elements of face detection. The human brain is very effective in the process of natural face segmentation even if there are complex backgrounds. This approach increases the security efficiency because the Computer Vision programs can easily detect if there is a face, e.g. Viola-Jones algorithm[12], but have many problems differentiating real and non-real photographs of faces.

Face, fingerprint and eye detections in images remain also a difficult challenge to be performed by computers. For this reason these results were used to develop a new variant of image-based CAPTCHA called *MB CAPTCHA*[13].



(a) With an image divided in sub-squares.



(b) With several images.

Figure 2.6: Examples of selection-based CAPTCHAs.

- **Interactive-based CAPTCHAs**

the user needs to discover a secret position in an image using mouse movement or swiping gesture

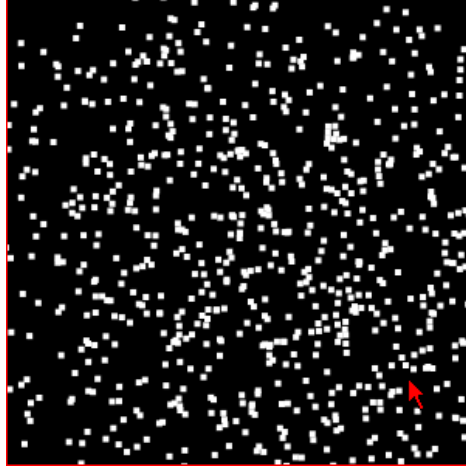


Figure 2.7: Example of interactive-based CAPTCHA.

2.1.4 Math CAPTCHAs

Looking to an operation specified in a frame, the user needs to insert the result in a text field. The operation is written in plain text or, to improve the security of this challenge, it's warped like text-based CAPTCHAs (Figure 2.8). These classical math-CAPTCHAs, also known as *arithmetic CAPTCHAs*, are vulnerable to OCR (Optical Character Recognition) techniques.

An advanced version of this CAPTCHA is used in the Quantum Ran-

(a) With plain text.

(b) With wrapped text.

Figure 2.8: Example of arithmetic CAPTCHAs.

dom Bit Generator Service (QRBGS) sign-up Web Page[14] (see Figure 2.9). This type of CAPTCHA asks user to solve an advanced math expression. It prevents the use of free or commercial OCRs because many mathematical symbols are not considered in their detection algorithm. However, it's vulnerable to side-channel attack [14].

Hence many math symbols are wrongly translated by bot programs and the challenge is very secure. The only problem is that this CAPTCHA is very complex for normal users and many of them could not solve the challenge correctly.

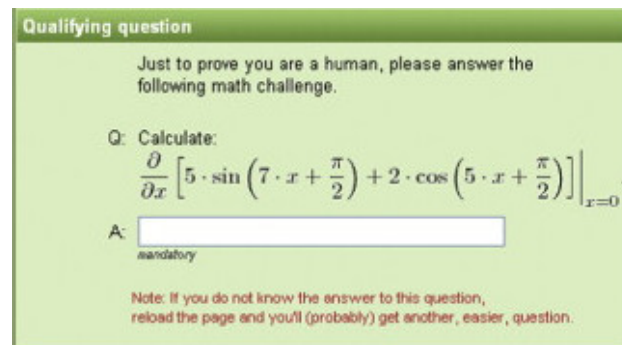


Figure 2.9: Example of Quantum Random Bit Generator Service (QRBGS) sign-up Web Page [14].

2.1.5 Slider CAPTCHAs

Slider CAPTCHAs only asks users to move the slider across the screen. Hence, image recognition is not part of the challenge to be classified as a human.

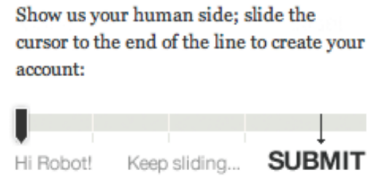
The most popular CAPTCHAs are the following:

- **CAPTCHA used by Taobao.com**
it asks the user to drag the slider from the start to the end of the sliding bar to verify his identity (see Figure 2.10a).
- **CAPTCHA used by TheyMakeApps.com**
it asks the user to move the slider to the end of the line to submit a form[15] (see Figure 2.10b).

Different variations of this type of CAPTCHAs have been bypassed with a simple JavaScript code and puppeteer.



(a) Example of TaoBao.com CAPTCHA.



(b) Example of TheyMakeApps.com CAPTCHA.

Figure 2.10: Examples of slider CAPTCHAs.

2.1.6 Text-based CAPTCHAs

In text-based CAPTCHA schemes a random series of wrapped characters and/or numbers is displayed on the screen inside an image (see Figure 2.11). The user needs to understand which are the characters that compose the shown sequence and then type them inside a text-field. The text-based CAPTCHAs can be also classified in three main classes looking to the type of wrapped characters:

- **2D**
the digits are wrapped on a 2D plane, parallel to the screen plane
- **3D**
the digits are wrapped on a 3D plane oriented in the space and then a 2D image is taken from a specific point of view

This type of CAPTCHAs is vulnerable to several type of attacks, related to Computer Vision techniques, that are:

- OCR techniques[16]
- Segmentation techniques (e.g. DECAPTCHA[17])
- Machine Learning and Deep Learning techniques

In the design phase of a text-based CAPTCHA there are many issues, related to Computer Vision techniques, to be considered. For each of them, there is usually a solution in the design phase of the CAPTCHA that reduces the possibility that the challenge would be broken by a bot[17].

2.1.7 Video-based CAPTCHAs

This type of CAPTCHA is not very common because of the weight of the file to be downloaded[3]. The traditional video-based CAPTCHA is composed

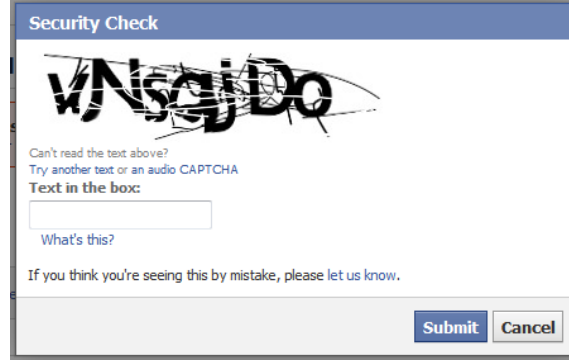
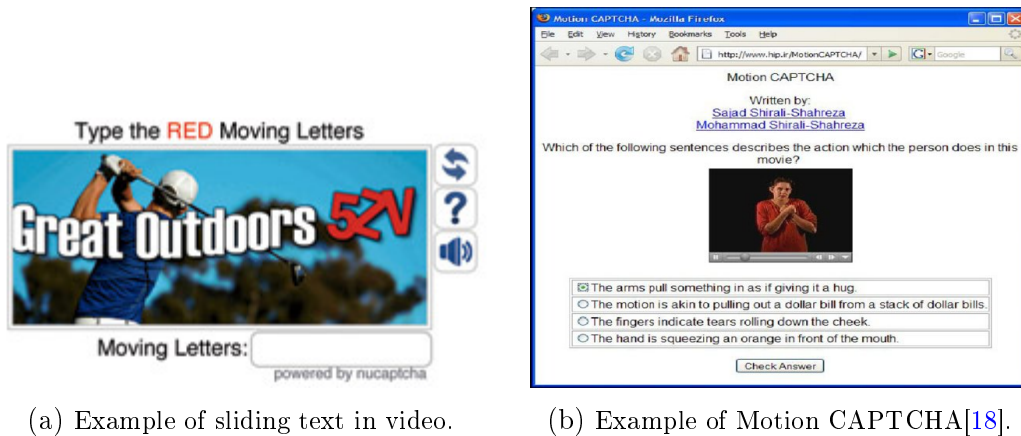


Figure 2.11: Example of text-based CAPTCHA.

by a video in which a sliding text is shown (see Figure 2.12a). The user needs to type this message in a text field to pass the challenge. Some implementations of this type of CAPTCHAs are vulnerable to machine learning attacks. Another variant of this CAPTCHA is the *Motion CAPTCHA*[18], developed by M. Shirali-shahreza and S. Shirali-shahreza, in which the user needs to watch a video. Then he needs to select which action was performed in the played file, choosing it from multiple answers (see Figure 2.12b). The strength of these implementations of CAPTCHAs depends on the relationship between the multiple choices submitted to the user[19].

A similar implementation of the previous variant, it's the one developed by Kluever et al. in which the user watches a video and needs to write three words that describe what he sees[20]. The same authors also performed a tag frequency-based attack to evaluate the security of their CAPTCHA schemes achieving a success rate of 13%.



(a) Example of sliding text in video.

(b) Example of Motion CAPTCHA[18].

Figure 2.12: Examples of video-based CAPTCHAs.

2.2 Modern CAPTCHAs

The type of CAPTCHAs and authentication mechanisms described in the following section are far from traditional CAPTCHAs and aren't based on cognitive knowledge of the human user but on other parameters, such as behavioural analysis and sensors readings. In the following sections there is a summary of the most known CAPTCHA schemes of this type.

2.2.1 Biometrics-based CAPTCHAs

The most known authentication mechanisms, that use biometric parameters of the user, are based on the following CAPTCHA schemes:

- **Bio-CAPTCHA voice-based Authentication**

This authentication method was developed starting from good results reached in the authentication phase of cloud systems (Alexa for Amazon, Siri for Apple, Cortana for windows)[21]. This particular implementation uses a random voice-based password challenge. This password changes at every login of the user and this method uses CAPTCHA challenge to provide unpredictability and ambiguity to the authentication process. The experiments reveals that unauthorized access probability decreases, while it keeps high usability because it needs only a mic.

- **rtCAPTCHA**

this type of authentication method is a Real-time CAPTCHA that asks users to perform some tasks like smile, blink or nod in front of the camera of the mobile phone. The recorded video is sent to the service provider that checks if in the file, there is the expected user performing the required action.

This implementation of CAPTCHA solves many problems of similar CAPTCHAs that are also based on liveness mechanisms and video capture. The attackers can extract patterns or features from existing or captured images and embed them into a new generated video in attack in the compromised device.

In the work of Erkam Uzun, Simon Pak Ho Chung, Irfan Essa and Wenke Lee[22], there is a detailed comparison between other similar authentication mechanisms and rtCAPTCHA, looking to all possible Computer Vision attacks.

2.2.2 Behavioural-based CAPTCHAs

In 2014 Google announced that today's Artificial Intelligence can solve even the most difficult variant of text-based CAPTCHAs at 99.8% accuracy[23]. For this reason, the company develops the following CAPTCHA schemes:

- **Google no CAPTCHA**

Google developed in 2015 a new CAPTCHA system that is simpler than traditional CAPTCHAs in terms of user interaction[24]. This CAPTCHA system is composed by two layers of protection:

1. Checkbox "*I'm not a robot*" to be clicked by user as in Figure 2.13 (or image-based CAPTCHA on mobile devices)

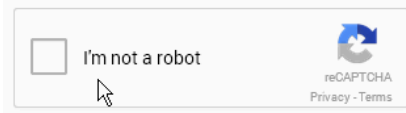


Figure 2.13: Example of Google no CAPTCHA checkbox.

2. Traditional text-based CAPTCHA with two warped words

The second layer is reached only if the user doesn't succeed in the first one. For the checkbox step, the application evaluates in background the user's behaviour (e.g. the mouse movement, where the users click, how long they linger over a checkbox). Then the program performs an *advanced risk analysis*, by looking results of first step but also spam traffic and passed/failed CAPTCHAs. It understands in this way if the test is passed or not.

The tests done confirms that this phase was very inefficient and many times the first layer failed even if a human user was performing correctly the task. A problem of this type of CAPTCHA is that many attacks exploits the image-based CAPTCHA and text-based CAPTCHA using attacks based on known Computer Vision techniques or their variants (e.g. CAPTCHA breaker made by Suphannee Sivakorn, Jason Polakis and Angelos D. Keromytis[25]).

- **Google Invisible ReCAPTCHA**

It's a top layer over the *Google noCAPTCHA v2.0*, adding the option to bind directly to the form's submit element[24]. It usually requires the use of cookies, used to track the user's behaviour. There exist two version of this CAPTCHA:

– **ReCAPTCHA v2.0**

it was developed in 2017. It's not really invisible because Privacy & Policy badge must be included on every page of app or website in which the CAPTCHA is used. Computer Vision and Artificial Intelligence algorithms can break the challenges by recognizing object in the pictures in the image-based CAPTCHA phase.

– **ReCAPTCHA v3.0**

it was developed in 2018. With constantly analyzing human behavior, mouse movements, typing speed and other features incorporated into NO CAPTCHA technology, Google collected enough sample data to perfectly fine-tune their Google invisible reCAPTCHA v2.0 with this new version. This type of CAPTCHA uses Artificial Intelligence and Machine Learning probability scores, hostname, timestamp and action validations.

Google removes image recognition and looking only the score, it evaluates if the user is a human or a bot. The main difference w.r.t. previous versions is that this CAPTCHA returns a probability score (*risk score*) in the range $[0.0, 1.0]$: 0.0 if the user is a bot, 1.0 otherwise. The administrator of the website can decide what range of scores he wants to manage, declaring the the site is under attack and what actions need to be performed.

Some characteristics related to this version of *Invisible ReCAPTCHA* are:

- * If a user accesses a Web page using incognito mode or private mode, he is classified with a very low score (*high risk*).
- * If a human is wrongly classified as a bot, the user can login into its Google account to increase its score. If this doesn't change the classification, you cannot do anything else.

2.2.3 Sensor-based CAPTCHAs

This type of devices have natively many sensors, like gyroscope and accelerometer, and the CAPTCHA schemes, described in the following sections, exploit their presence to improve security of the authentication.

- **Completely Automated Public Physical test to tell Computer and Humans Apart (CAPPCHA)**

this is a way to enforce the PIN authentication phase by mobile phone[26]. The user needs to tilt the device to a specified angle specified on the screen (see Figure 2.14). The CAPPCHA security is based on the *Secure Element (SE)* present in the device. It prevents brute force, side

channel and recording attacks. The usability results are good and then some of the comments made by users were considered in the implementation.



Figure 2.14: CAPPCHA and PIN authentication[26].

- **Invisible CAPPCHA**

It will be described in details in Chapter 4.

2.3 CAPTCHA security

The process used for breaking CAPTCHAs is organized into the following phases[27]:

1. **Pre-processing phase**

In this phase, several techniques are applied to remove background, separate foreground from the background, to delete noise and to remove some particular pattern (e.g. Canny Detection and Scale-Invariant Feature Transform (SIFT) application).

2. **Attack phase**

the following techniques are usually applied:

- ***Object Segmentation attacks***

Segmentation techniques (e.g. vertical histogram, colorfilling, snake segmentation and JSEG) are used to split the CAPTCHA image into segments to facilitate recognition

- ***Object recognition attacks***

The most used techniques are pattern matching (e.g. shape context matching, correlation algorithm]), OCR recognition, SIFT and machine learning.

- ***Random Guess Attacks***

The attacker's program tries to break the CAPTCHA scheme by guessing the correct answer. This attack is effective on CAPTCHAs with few number of different challenges.

- ***Human Solver Relay Attacks***

The bot forwards the CAPTCHA challenge to a remote human worker that will solve it.

Many CAPTCHAs have yet the following known issues:

- **Session issue**

Some types of CAPTCHAs have a big issue because they don't destroy the session, after the correct answer is inserted by the user[1].

Hence, the hacker can crack following accesses using the same session id with the related solution of the challenge, after connecting to the web page of CAPTCHA. In this way the attacker can make hundreds of requests before the session expires and the previous operation must be computed again.

- **Resilience to both automated and human solver relay attacks**

Many CAPTCHA schemes are designed to be robust against a possible AI attack but the new generation of CAPTCHA involves the use of remote bot or human solver. Traditional CAPTCHA schemes are vulnerable to this type of attacks.

Invisible reCAPTCHA and other academic proposals haven't been attacked yet, but works over thousands of different IP addresses and simulate the human behavior. Sensor-based CAPTCHAs are also vulnerable to solver relay attacks. An exception of this issue is the *Invisible CAPTCHA*, that will be analysed in following sections and it's designed to block this type of attacks.

- **Limited number of challenges**

An issue of sensor-based CAPTCHA schemes is the limited number of challenges because the design of many usable gestures is very hard. This problem could be solved relying on trusted hardware.

- **Trade-off between Friction-heavy and Frictionless CAPTCHAs**

A trade-off between usability and security aspects is always considered analysing CAPTCHA schemes. This condition is highlighted in behavioural and sensor-based CAPTCHAs.

- **User's privacy**

Sensor-based and behavioural CAPTCHAs usually send useful infor-

mation to a remote server that analyses it to establish if the user was a human or a bot. If an hacker attacks the server side of this application, he can access to users' private data.

In some CAPTCHAs, the information are evaluated on the client side by a trusted hardware and the server receives only the results of the analysis. In this case, we need to be sure that trusted hardware is secure enough to guarantee privacy of user's information.

- **Compatibility with different devices**

Many CAPTCHA schemes, e.g. behavioural ones, use specific forms factors but a good challenge should be compatible with different factors.

Type	Scheme	Usability issues	Security
Audio	<i>Audio reCAPTCHA</i>	Issues of recognition: <ul style="list-style-type: none"> • Knowledge of English dictionary by the user. • Some character sounds very similar to others. 	It's vulnerable to: <ul style="list-style-type: none"> • ASR programs. • Deep Learning and ML techniques.
Game	<i>Dynamic Cognitive Game (DCG)</i>	Comprehension of rules.	Vulnerable to Stream Relay Attack.
Image	<i>Click-based</i> <i>Drag & Drop-based</i> <i>Sliding-based</i> <i>Selection-based</i> <i>Interactive-based</i>	Difficulty in identification of images caused by: <ul style="list-style-type: none"> • Blur of images. • Low vision condition. 	Vulnerable to: <ul style="list-style-type: none"> • Segmentation techniques • Deep Learning and ML techniques • OCR techniques
Math	<i>Arithmetic</i> <i>QRBGS</i>	It requires basic or advanced math knowledge.	Vulnerable to: <ul style="list-style-type: none"> • OCR techniques • Side-channel attacks
Slider	Taobao.com TheyMakeApps.com	Simple and intuitive interaction.	Simple bypassed by Javascript code and puppeteer.
Text	<i>2D</i> <i>3D</i>	Many problems have to be solved by user: <ul style="list-style-type: none"> • Multiple fonts • Font size • Blurred Letters • Wave Motion 	It can be identified by: <ul style="list-style-type: none"> • OCR technique • Segmentation techniques • Deep Learning and ML techniques
Video	<i>Motion CAPTCHA</i>	Heavy file to be downloaded	

Table 2.1: Survey of main types of traditional CAPTCHAs[10].

Type	Scheme	Usability issues	Security
<i>Audio</i>	<i>Audio reCAPTCHA</i>	Issues of recognition: <ul style="list-style-type: none">• Knowledge of English dictionary by the user.• Some character sounds very similar to others.	It's vulnerable to: <ul style="list-style-type: none">• ASR programs.• Deep Learning and ML techniques.
	<i>Dynamic Cognitive Game (DCG)</i>	Comprehension of rules.	Vulnerable to Stream Relay Attack
<i>Image</i>	<i>Click-based</i>	Difficulty in identification of images caused by:	Vulnerable to: <ul style="list-style-type: none">• Segmentation techniques• Deep Learning and ML techniques
	<i>Drag & Drop-based</i>	• Blur of images.	OCR techniques
	<i>Sliding-based</i>	• Low vision condition.	
	<i>Selection-based</i> <i>Interactive-based</i>		
<i>Math</i>	<i>Arithmetic</i>	It requires basic or advanced	Vulnerable to: <ul style="list-style-type: none">• OCR techniques• Side-channel attacks
	<i>QRBGS</i>	math knowledge.	
<i>Slider</i>	Taobao.com	Simple and intuitive interaction	Simple bypassed by Javascript code and puppeteer
	TheyMakeApps.com		
<i>Text</i>	<i>2D</i>	Many problems have to be solved by user:	It can be identified by: <ul style="list-style-type: none">• OCR technique• Segmentation techniques• Deep Learning and ML techniques
	<i>3D</i>	• Multiple fonts	
		• Font size	
<i>Video</i>		• Blurred Letters	
		• Wave Motion	
	<i>Motion CAPTCHA</i>	Heavy file to be downloaded	

Table 2.2: Survey of main types of traditional CAPTCHAs[10].

Chapter 3

Side-channel attacks

A side-channel attack is an attack in which the malicious user exploits a side-information of transmitted encrypted data, to give access to user private data. This type of extra information is usually: timing information, power consumption, electromagnetic radiations, sound and so on.

The first types of side-channel attacks requires the physical access to the victim's device. Nowadays, side-channel attacks are evolved and can be conducted by remote hackers using malicious code (e.g. cache-timing attacks, DRAM row buffer attacks), even exploiting information from sensors on mobile devices[32].

Side-channel attacks can be classified as:

- **active**
the hacker influences the behaviour of the victim's device
- **passive**
the attacker only analyses the leaking information

Another categorization can be the following one:

- Local attacks
- Vicinity attacks
- Remote attacks

In the following sections there is a survey of the most popular attacks, organized with respect to the previous classifications (see Table 3.1). The main sensors, that are usually exploited by an hacker to obtain side-channel information on mobile devices, are[31]:

- Location sensors (e.g. GPS, proximity)

- Motion sensors (e.g. accelerometer, gyroscope, magnetometer)
- Environmental sensors (e.g. for ambient light, temperature, barometer)
- Biometric sensors for wearable devices (e.g. heart rate sensor, ECG)
- Audio sensors (microphone)
- Video sensors (camera)

	Local	Vicinity	Remote
Passive	Power Analysis	Network Traffic Analysis	Linux-inherited procs Leaks
	Electromagnetic Analysis Attacks	USB Power Analysis	Data-Usage Statistics
	Differential Computation Analysis	Wi-Fi Signal Monitoring	Page Deduplication
	Smudge Attacks		Microarchitectural Attacks
	Shoulder Surfing and Reflections		Sensor-based Keyloggers
	Hand/Device Movements		Fingerprinting Devices/Users
Active			Location Inference
			Speech Recognition
			Soundcomber
	Clock/Power Glitching		
	Electromagnetic Fault Injection (EMFI)	Network Traffic Analysis	Rowhammer
	Laser/Optical Faults		
	Temperature Variation		
	Differential Computation Analysis		
	NAND Mirroring		

Table 3.1: Survey of the most popular side-channel attacks[32].

3.1 Local side-channel attacks

The attacker needs to get the target device or to be very near to it. In many cases the hacker physically needs to manipulate the the device or to obtain access to the chip.

Passive attacks

The following attacks are used to break cryptographic system implementations:

- ***Power Analysis***

this type of attacks are based on the analysis of the power variations in transistors. There exist several attacks[29]:

- ***Simple Power Analysis (SPA)***

the attacker analyses the power consumption of the system, that depends on the microprocessor used. This analysis can be useful to understand which operations are performed by different implementations of cryptographic algorithm (e.g. RSA, DES).

- ***Differential Power Analysis (DPA)***

these attacks collect data and then makes statistical analysis and error correction techniques from data to extract information correlated to secret keys.

- ***High Order DPA (HO-DPA)***

While DPA obtains information across a single event, HO-DPA correlates between multiple cryptographic sub-operations.

- ***Electromagnetic Analysis Attacks***

the attacker can analyse indirectly the power consumption by accessing electromagnetic. This type of attacks depends on the used instruments (e.g. EM probes) and on the analysed location of the chip, affecting the signal-to-noise ratio.

- ***Differential Computation Analysis***

the attacker tries to exploit white-box cryptographic implementations. In this model the attacker, even if he has access to code, can't extract the secret key. The attacker needs to have full control over the target device and the execution environment. Then using binary instruments, he can control the intermediate state or memory operations (e.g. reading/writing operations)[33].

- ***Smudge Attacks***

the attacker can exploit fingerprints and smudges on the screen of mobile devices to evaluate the user's input.

- ***Shoulder Surfing and Reflections***

the attacker can exploit the lightness of the device display and obtain the user's activity by its reflection on sunglasses or tea pods.

- ***Hand/Device Movements***

the attacker exploits the user's movements of fingers and hand to understand the interaction of the victim with the device.

Active attacks

The following attacks require that the hacker physically gets the device for a while:

- ***Clock/Power Glitching***
in the past the attacker can fault inject on embedded devices by exploiting variations of the clock signal, (e.g. overclocking). To do it, he needs to use an external clock source.
- ***Electromagnetic Fault Injection (EMFI)***
the attacker uses short (e.g. nanoseconds), high-energy electromagnetic pulses to change the state of memory cells. This attack allows to target specific regions of a microchip by locating the EM probe (e.g. on the instruction memory, the data memory, or CPU registers).
- ***Laser/Optical Faults***
the attacker needs to decapsulate the chip to obtain access to it and, using a laser beam, it change the state of a transistor (e.g. changing bit value of a memory cell).
- ***Temperature Variation***
the attacker can change the temperature in which the target device, causing malfunctioning of the hardware. Temperature higher than the maximum one, supported by hardware, causes faults in memory cells. Temperature too lower changes the speed, for which the content of the RAM disappear, after turning the device off.
- ***Differential Computation Analysis***
the attacker needs to have full control of the white-box environment, manipulating intermediate values in the system computation.
- ***NAND Mirroring***
the attacker exploits the duplication of the data, usually used to recover data after faults, to restore a previous system state. The hacker can force the reset of the state as demonstrated by Skorobogatov for the Apple case[?].

3.2 Vicinity side-channel attacks

The attacker needs to wiretap or eavesdrop the network communication of the victim or to be in the neighbourhood of the target.

Passive attacks

- ***Network Traffic Analysis***

the attacker can exploit meta data, related to the encrypted data, transmitted over the network. This information gives access to sensitive information about the traffic.

For example a Web-application works between two parties: the client and the server. For this reason the communication channel is usually encrypted and the requests made by the user work through the *HTTPS* protocol.

This solution isn't enough to prevent an attacker to exploit reserved data because each web page has a distinct size, loads resources of different sizes. Hence the attacker can fingerprint the page even if *HTTPS* protocol is used.

Another cause of these attack on Web-services is given by the trend of Web to work on Stateful Protocols, providing better performance to the client by keeping track of the connection information. TCP session for example works on Stateful Protocol because both systems maintain information about the session itself during its life[28].

- ***USB Power Analysis***

the attacker can modify USB charging stations for mobile devices to obtain analysis about power consumption and related sensitive information.

- ***Wi-Fi Signal Monitoring***

Wi-Fi devices continuously monitor the wireless channel (channel state information (CSI)) to transmit data. Any environmental variation (e.g. finger motion) affects Wireless signals, generating unique pattern in CSI series. For example the attacker can exploit these variations to unlock patterns on smartphones[35].

Active attacks

- **Network Traffic Analysis**

the attacker, after obtaining information about transmitted packets, can interfere the traffic (e.g. delay of packets).

3.3 Remote side-channel attacks

These attacks are software-only based and they depend on the installation of the malicious code on the target device. **Passive attacks**

- ***Linux-inherited procfs Leaks***

the attacker can obtain a large amount of information for each process running on Linux File System, by looking to the content of the files, reported in Table 3.2.

File path	Information
<code>/proc/[pid]/statm</code>	Virtual and physical memory sizes of process with identifier <code>[pid]</code>
<code>/proc/[pid]/stat</code>	CPU utilization times of process with identifier <code>[pid]</code>
<code>/proc/[pid]/status</code>	Number of context switches of process with identifier <code>[pid]</code>
<code>/proc/interrupts</code>	Interrupt counters
<code>/proc/stat</code>	Context switches

Table 3.2: Survey of the most popular side-channel attacks[32].

- ***Data-Usage Statistics***

the attacker can access to information about incoming and outgoing network traffic for each application without any permission.

- ***Page Deduplication***

To reduce the overall memory footprint of a system, some operating systems perform deduplication, searching for identical pages within the physical memory and merge them even across different processes. When a process tries to write on a deduplicated page, a copy-on-write fault occurs and the process gets its own copy of this memory region again.

- ***Microarchitectural Attacks***

By measuring execution times and memory accesses, the attacker can obtain sensitive information from processes running in parallel on the same device. This type of information can be evaluated from CPU caches, that are a big source of information leaks.

- ***Sensor-based Keyloggers***

in mobile devices, the attacker can exploit information from equipped sensors with any permission. The user's interaction with the device can be evaluated by analysing information from sensors.

- ***Fingerprinting Devices/Users***

the attacker can obtain identity of the device and the user and fingerprint by exploiting hardware issues and cookies.

- ***Location Inference***

the attacker can obtain user's location without using GPS sensor, that requires permission to be accessed. For example, the accelerometer and the gyroscope can be used to infer car driving routes.

- ***Speech Recognition***

the access to the microphone is protected by permissions. The attacker can also exploit gyroscope to obtain information about human speech near to the device.

- ***Soundcomber***

the attacker can obtain sensitive information (e.g. credit card numbers) on automated menu services of phones after he obtains permission of access to the microphone.

Active attacks

- ***Rowhammer***

the attacker can induce hardware faults by frequent accesses to main memory. This happens because nowadays the size of DRAM cells decreases to increase the density of memory cells in DRAM causing electromagnetic coupling effects between cells.

Chapter 4

Invisible CAPPCHA

The *Invisible CAPPCHA* is an evolution of CAPPCHA, in terms of usability[36]. The main difference with respect to CAPPCHA is that the challenge isn't explicitly submitted to user but it's hidden behind the PIN authentication phase. This type of challenge works only on smartphones as its ancestor. This CAPTCHA is a method developed in 2018 and based on motion side-channel information, obtained by sensors on mobile device. The main steps that this CAPTCHA follows are:

1. Motion detection
2. Communication between Client and Server

In fact, the micro-movements of the device, generated by the interaction of the user with the touch-screen, are evaluated by the *Secure Element (SE)*. Then credentials are shared with the remote Service Provider if the input is inserted by a human or not. The Invisible CAPPCHA is very effective as support of Password-based authentication methods.

4.1 Motion detection

The accelerometer of the device detects the acceleration over the three axis in g-force units, as a sequence of vectors over time:

$$\{A_i\}_{i=1}^n = \{(a_1^x, a_1^y, a_1^z), \dots, (a_n^x, a_n^y, a_n^z)\}$$

This type of side-channel information from embedded accelerometer has been exploited in different attacks for the single and double tap detection. These attacks analyse the acceleration over the z-axis over by comparing them to thresholds and timing conditions.

In Invisible CAPPCHA, the side-channel information is stored on the memory of the mobile device. Depending on the device, a smartphone built-in vibration can be generated only along Z axis or along more than one axis (Figure 4.1). Instead the finger tap event creates accelerations similar and higher on Z-axis (Figure 4.2).

In Invisible CAPPCHA, the difference between built-in vibration and tap acceleration is evaluated by a simple algorithm. This algorithm relies on negative and positive peaks which are detected by comparing acceleration along Z axis against predefined thresholds. The user's tap cannot be simulated by malware using the vibration motors.

The most important requirement is that Invisible CAPPCHA uses a Secure Element that embedded the accelerometer, blocking the access to the sensor by malicious code. Nowadays there exists a smart card, called SIMSense, that already integrates motion sensor.

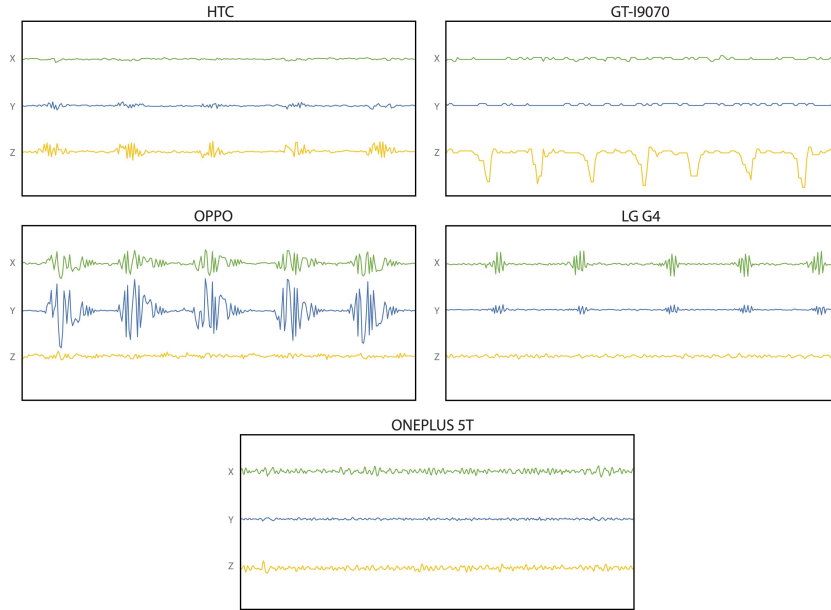


Figure 4.1: Example of accelerations caused by smartphone built-in vibration.

4.2 Communication between Client and Server

When the user fills a form or provides other information to a cloud application/service, the Secure Element checks if a micro-movement is measured when a user tap is detect. If this happens the input inserted by user is con-

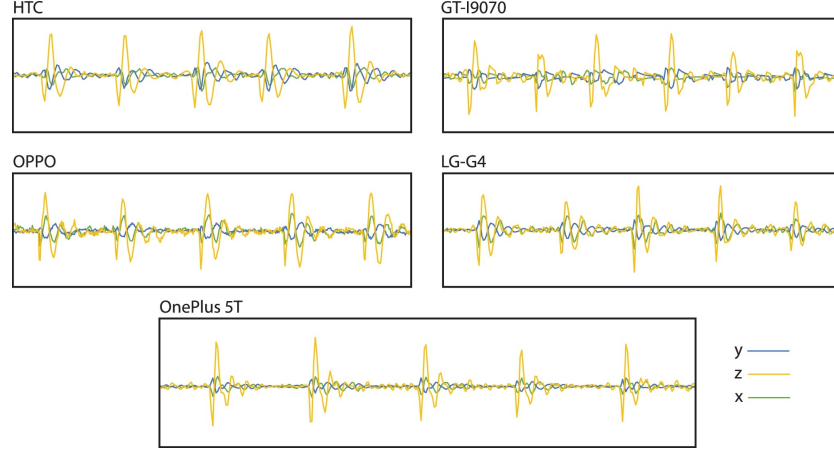


Figure 4.2: Example of accelerations caused by finger tap detection.

sidered valid, generated by a human, otherwise the algorithm tells that the input was generated by a malware.

An extra message, that tells if the task was performed by a user or not, is sent to the server side. The integrity of this message is guaranteed by the Secure Element, that can be equipped with a digital signature. The identity of the device can be associated to the sent message and then it can be checked and verified. The Secure Element signs the verification message through ECDSA.

4.2.1 Elliptic Curve Digital Signature Algorithm (ECDSA)

This type of encryption works similarly to RSA but it's based on elliptic cryptography and uses keys of smaller sizes. The algorithm is divided in two phases:

- **Sign generation**

If Alice wants to send a message, protected with digital sign, to Bob, they need to share the following parameters $(curve, G, n)$. $curve$ is the equation of the curve, G base point of prime order on the curve and n is the multiplicative order of G for which $n \times G = O$.

Alice generates a private key d_A in the range $[1, n - 1]$ and a public key $Q_A = d_A \times G$, where \times is scalar multiplication of a point of the curve. Alice needs to perform Algorithm 1 to sign a message.

- **Sign verification**

Bob wants to verify the digital signature sent by Alice. To do it, he needs to perform in order Algorithm 2 and 3.

Algorithm 1: Sign generation.**Input:** m = message to be signed**Output:** (r, s) = digital sign

```

1  $e \leftarrow HASH(m)$  where  $HASH$  is an hash function (e.g. SHA-2)
2  $z \leftarrow$  string composed by the  $L_n$  most left bits
3   where  $L_n$  is the bit length of the group of order  $n$ 
4  $r \leftarrow 0$ 
5  $s \leftarrow 0$ 
6 while  $r = 0 \bmod n$  or  $s = 0 \bmod n$  do
7    $k \leftarrow RANDOM([1, n - 1])$ 
8    $(x_1, y_1) = k \cdot G$  of the elliptic curve
9    $r \leftarrow x_1 \bmod n$ 
10   $s \leftarrow k^{-1}(z + rd_A) \bmod n$ 

```

In Invisible CAPPCHA the message m is bitwise concatenated with a signed unique value, nonce n , so the signed message sent to the server is (r, s, m, n) and not (r, s, m) .

4.3 Security analysis

After the sign of the verification, the communication must be also encrypted to ensure integrity and authenticity of exchanged messages.

The Secure Element can be accessed only through PIN authentication of the off-card communication party. If the malicious code has enough privileges to access Secure Element, it can't brute force the password because of limited number of permitted attempts. If the number of attempts is higher than the maximum one, the attacker is performing a Denial Of Service (DOS) attack. The attacker can also try to steal the password through side-channel information.

4.3.1 Strength against popular attacks

The most popular attacks, that have been analysed, are[36]:

- **Replay attack**

Algorithm 2: Verification that public key is on the elliptic curve.

Input: Q_A = public key to be verified**Output:** **check** = true if public key is correct

```

1 check  $\leftarrow$  true
2  $\backslash\backslash$ Valid coordinates
3 if  $Q_A = O$  then
4    $\backslash$  check  $\leftarrow$  false

5  $\backslash\backslash$ Element of the curve
6 if  $Q_A \in curve$  then
7    $\backslash$  check  $\leftarrow$  false

8  $\backslash\backslash$ Correctness of order
9 if not  $n \times Q_A = O$  then
10   $\backslash$  check  $\leftarrow$  false

```

- **Reverse engineering attack**

Even if the attacker can de-obfuscate the code of the application running on the browser, he can access to reserved data on the server only if the verification message for human interaction was correctly signed by the Secure Element. Hence this type of attack can't be performed.

- **Human-solver relay attack**

The Invisible CAPPCHA is strong to this type of attack because it doesn't require any additional task to be sent to a remote human solver, as in standard CAPTCHAs.

- **Brute force and password replay attacks**

Invisible CAPPCHA can be used to validate every input before it considers it as a possible attempt for a password. If the password was inserted by a malware or was wrong, the number of attempts decreases. Hence this approach prevents a brute force attack. This also prevents the access to the Secure Element by the attacker in replay attacks.

- **Denial Of Service (DOS)**

If a malware tries more than the maximum amount of attempts of passwords can do a Denial Of Service (DOS) of the Secure Element. To prevent this attack, the Secure Element can block access to itself if three invalid passwords inserted by a human. If an invalid password is inserted by a malware, detected by Invisible CAPPCHA, the Secure

Algorithm 3: Sign verification.

Input: (r, s, m) = digital sign and message

Output: m = message to be signed

```

1  $e \leftarrow HASH(m)$  where  $HASH$  is an hash function (e.g. SHA-2)
2  $z \leftarrow$  string composed by the  $L_n$  most left bits
3 where  $L_n$  is the bit length of the group of order  $n$ 
4 if not  $r \in [1, n - 1]$  or not  $s \in [1, n - 1]$  then
5    $\lfloor$  *Invalid sign*
6  $e \leftarrow HASH(m)$ 
7  $z \leftarrow$  string composed by the  $L_n$  most left bits
8  $w = s^{-1} \bmod n$ 
9  $u_1 = zw \bmod n$ 
10  $u_2 = rw \bmod n$ 
11  $(x_1, y_1) = u_1 x G + u_2 x Q_A$  of the elliptic curve
12 if  $r \equiv x_1 \pmod{n}$  then
13    $\lfloor$  *Verified sign*
14 else
15    $\lfloor$  *Not accepted sign*
```

Element is blocked.

Chapter 5

Design of AcCAPPCHA

The structure and behaviour of AcCAPPCHA are similar to the ones proposed in Invisible CAPPCHA application but adding also other task to improve the efficiency. The two phases of the verification are:

- Evaluation of the user activity
- Communication of the password to remote service

In the first phase, the application exploits data from the microphone instead of using other sensors as described in AcCAPPCHA. The CAPPCHA records two audio signals: the first one created during the insertion of the password by the user and the second one created before this activity for noise evaluation. The second signal is exploited to evaluate a noise threshold usefull for the computation of amplitude peaks in the first audio.

During the insertion of the password, the instant of the time when each character was typed by the user is stored. Then the first verification is performed by looking if there exists a sequence of time instants of the peaks in the first signal that matches with the time instants stored manually for each character.

In the second phase, the username and the password of the user will be signed through ECDSA and sent by client to the authentication service if and only if the insertion was performed by a human.

5.1 Time correspondence

The correspondence between the sequence of time instants, stored looking at the software clock, and the time instants of the audio signal is performed looking for a subsequence of audio peaks.

First of all, the program records an audio of 1 second before asking user to insert the password. The signal will be analysed to find its maximum value, that will be used as a threshold for the identification of the peaks. In fact, the signal samples of the audio recorded during the insertion, with value higher than the last threshold, will be considered as feasible peaks.

These samples are then grouped in several 5 ms windows and for each of them, the application find the time instant related to the maximum value of the signal in this window. For example, given *the sampling period or interval* t_s and a specific window of samples:

$$x = [x_t, x_{t+t_s}, \dots, x_{t+\lceil \frac{10ms}{t_s} \rceil * t_s}]$$

then we compute $t' = \operatorname{argmax}(x)$.

Then we declare that there is a time correspondence if given the sequence of computed time instants relative to max value of each window $t = [t_1, t_2, \dots, t_n]$ if there exists a subset of it t^* with size equal to the length of the password and that matches with a threshold with the sequence of time instants stored during the password insertion.

5.2 Deep learning classification

When pressed each key of the keyboard produces a variation of the signal, called *press peak*, for a time window of about 8-10 ms[38]. This signal trend can also be divided in three consecutive and distinctive areas:

- **touch peak**
peak in a window of 2-3 ms, caused by the finger touching the key
- **noisy meaningless area**
- **hit peak**
peak in a window of 2-3 ms, caused by the finger and the key hitting the keyboard supporting plate.

To obtain a prediction of each key pressed by the user, we can extract information from the touch peak, that is the most significant, and the hit peak, that increases the information related to the pression.

Following the idea of Asonov and Agrawal, I exploit deep learning to classify each pressed key. I use three different approaches, the first two were taken from the work of Asonov and Agrawal and the last one was based on modern sound classification techniques.

Respectively to the method used, the feature for each key was composed by:

- FFT coefficients of the touch peak
- FFT coefficients of the hit peak and the touch peak
- Features obtained from the hit peak and the touch peak using a deep learning pre-trained model

In the first two cases, the coefficients are extracted from a window of 3 ms around the peaks and then they are normalized in floating point values in range $[0, 1]$ (see Figure 5.1).

In the third case, the touch peak and the hit peak samples were concatenated, creating a new signal on which the spectrogram is computed. From the spectrogram, I extract a feature composed by 512 values through the use of VGG16 pre-trained convolutional neural network.

In this way, I remove the last fully connected layers, used for classification of other task, and take the intermediate results as feature. The reason of this approach is that a pre-trained network already extracts very well features for classification of a lot of common images and so it can extract features better than a NN created from scratch.

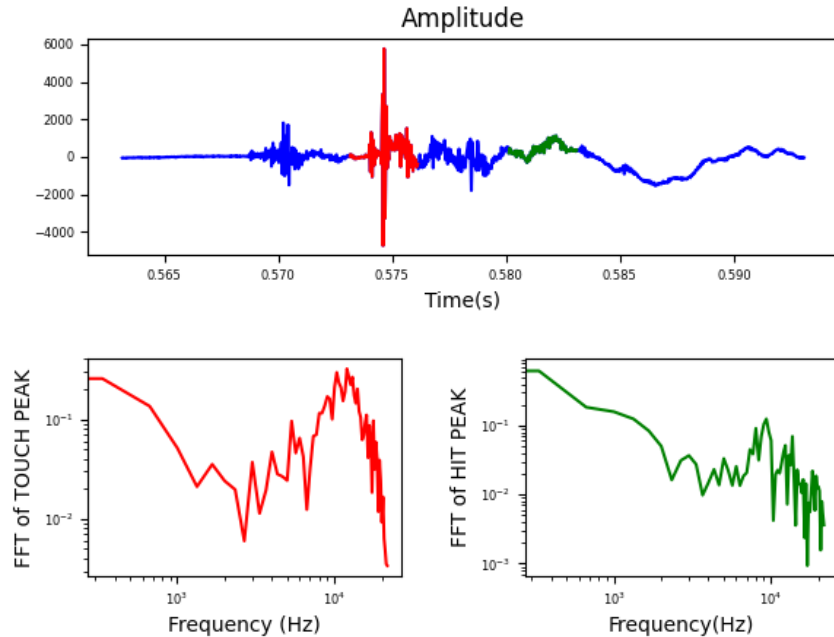


Figure 5.1: Example of normalized FFT computation for the touch and the hit peak.

The audio signal taken, during the insertion of the password, is analysed

and then organized in windows as specified in the previous Section, but the prediction can be done in two different ways:

- on every window previously computed
- on the windows that contains the time instants related to the time correspondence

In the first approach the application uses the maximum value of each window as the touch peak and looks for the related hit peak, taking it about 10 ms after the previous peak. Then I collect the most probable keys predicted from the Neural Network for this peaks and I repeat the procedure for every window initially computed on the audio. This method is very weak because after this phase, the algorithm tries to find an ordered sequence of characters, one from each window, that corresponds with the password inserted by the user. If this exists, AcCAPPCHA declares that the user was a human, otherwise a bot. The main problem of this approach is that there is no correspondence in time between a character belonging to the final sequence and the moment in which the same character was inserted physically by the user. In fact there can be false positives caused by the prediction from peak that are not related to the absolute maximum one. In other terms, in the set of the maxima of all the windows there can be someone that is not related to the touch peak but to a local maximum.

The second approach solves the previous problem because the windows, where the maxima are looked for, are obtained by the correspondence time approach. In this case, AcCAPPCHA verification becomes more accurate in theory even if in practice the deep learning technique is not very efficient.

Chapter 6

Development of AcCAPTCHA

Chapter 7

Experimental results

Chapter 8

Security Analysis

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