EyeDecrypt — Private Interactions in Plain Sight

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Abstract

We introduce *EyeDecrypt*, a novel technology for privacy-preserving human-computer interaction. *EyeDecrypt* allows only authorized users to decipher data shown on a display, such as an electronic screen or plain printed material; in the former case, the authorized user can then interact with the system (*e.g.*, by pressing buttons on the screen), without revealing the details of the interaction to others who may be watching or to the system itself.

The user views the decrypted data on a closely-held personal device, such as a pair of smart glasses with a camera and heads-up display, or a smartphone. The data is displayed as an image overlay on the personal device, which we assume cannot be viewed by the adversary. The overlay is a form of augmented reality that not only allows the user to view the protected data, but also to securely enter input into the system by randomizing the input interface.

EyeDecrypt consists of three main components: a *visualizable encryption* scheme; a dataglyph-based visual encoding scheme for the ciphertexts generated by the encryption scheme; and a randomized input and augmented reality scheme that protects user inputs without harming usability. We describe all aspects of *EyeDecrypt*, from security definitions, constructions and analysis, to implementation details of a prototype developed on a smartphone.

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1 Introduction

Nowadays personal and sensitive information can be accessed at any time, anywhere, thanks to the widespread adoption of smartphones and other wireless technologies such as LTE and IEEE 802.11 (i.e., WiFi). This always-connected paradigm, however, comes at the expense of reduced privacy. Users access sensitive information on the train, on the subway and in coffee shops, and use public computers in airports, libraries and other Internet access points. Sensitive information is at the mercy of anyone in the user's proximity and of any piece of malware running on trusted and untrusted devices such as a personal laptop or a computer in a library. This applies not just to the content displayed on a monitor but also to the interaction users have with the system (e.g., typing a password or a social security number). Someone looking at the keyboard as one types in a password is as bad as showing the password in clear text on a login page.

We introduce *EyeDecrypt*, a technology aimed at protecting content displayed to the user as well as interactions the user has with the system (e.g., by typing). In particular, we do not trust the user's environment (e.g., "shoulder surfing"), nor do we trust the device the user interacts with as it may have been compromised (e.g., keyloggers).

In *EyeDecrypt*, the content provider encrypts and authenticates content and sends it to the device the user requested the content from (e.g., laptop, cellphone, ATM). Because the content arrives already encrypted to this untrusted device, any piece of malware running on it would not be able to learn anything meaningful about the content being displayed to the user; the user is then able to retrieve the content through her personal device (running the *EyeDecrypt* app). Similarly, the user interacts with the untrusted device using *EyeDecrypt* so that only the remote content provider learns the actual inputs provided by the user during the interaction (e.g., password or PIN code). A piece of malware such as a keylogger running on the untrusted device would not be able to learn what the user has typed. Figure 1 presents a basic system overview; the "untrusted device" (which we sometimes will just call the "display") represents the device the user requests content from and interacts with.

Let us now provide some intuition on how *EyeDecrypt* works at a high level. If we print a document with extremely small fonts, this will appear as a collection of dots with no meaning. If, however, we take a very powerful magnifying lens, we will be able to read the part of the document right underneath the lens; further, by moving the lens around, we will be able to read the whole document. Anyone without the magnifying lens (i.e., a shoulder-surfer) will see just dots. *EyeDecrypt* provides a similar experience.

In *EyeDecrypt* content is encrypted and visually encoded so that it appears as some pattern of dots, lines or other shape to anyone looking at it. In order to be able to decrypt such document or parts of it, users will have to use the *EyeDecrypt* app on their personal device (e.g., smartphone, Google Glass). Such app enables users to use the camera on their personal device as the "magnifying lens" described earlier. By leveraging the smartphone camera, for example, the *EyeDecrypt* app captures a part of the encrypted content, decrypts it and overlays the decrypted content on top of the camera view on the personal device—a form of augmented reality. By moving the smartphone around over the document, users will capture, decrypt and display different parts of the document. One key difference with the magnifying lens example is that the *EyeDecrypt* app will be able to decrypt a document only if it has the correct cryptographic keys for that document or that content provider. Just the *EyeDecrypt* app by itself is not enough to decrypt content.

Importantly, *EyeDecrypt* also protects users' interactions with the system. For example, in the case of a keyboard, a randomized keyboard layout can be encrypted and displayed to the user together with other encrypted content. The *EyeDecrypt* app will decrypt all content including this randomized keyboard layout and will superimpose such layout on the camera view as an overlay on the actual physical keyboard (i.e., using augmented reality). In doing so, there is now a random mapping between keys of the physical keyboard and keys of the randomized layout that the user can see. Any onlooker would see the user pressing, say, the 'A' key on the physical keyboard without knowing to which value it would actually map to in the randomized layout. In particular, the random mapping between physical keyboard and virtual keyboard would be known only to the user, the *EyeDecrypt* app and to the remote server that encrypted the content (see Figure 1).

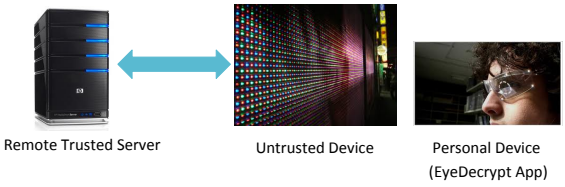


Figure 1: *System view*

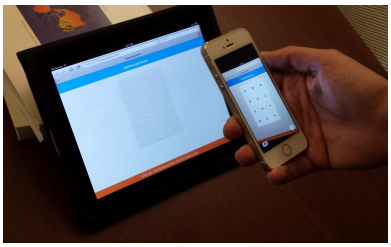


Figure 2: *Prototype view*

The untrusted device on which the encrypted document is displayed would not be aware of such mapping. Because of this, even a keylogger running on the untrusted device the user is interacting with, would not be able to learn the actual key values inputted by the user.

As mentioned above, *EyeDecrypt* aims at protecting against attacks on content displayed to the user as well as on information sent by the user (e.g., by typing). Such attacks may be due to shoulder surfing as well as to malware. While *EyeDecrypt* can leverage any device equipped with a camera, the type of device is important as different types of devices make *EyeDecrypt* more or less effective depending on the threat scenario. Let us look at a few settings.

In the most general case of shoulder surfing, the attacker can be anywhere in the victim's surroundings. In such a case, displaying decrypted content on a device such as a smartphone does not completely remove the possibility of someone being able to glance at the smaller screen of the phone even though the smaller screen of the phone does make it harder. A better solution in this scenario would be to use *EyeDecrypt* with a device such as Google Glass where the screen is very small and close to the eyes of the user making a shoulder-surfing attack much harder.

In a different type of shoulder surfing attack, the attacker has installed a small fixed hidden camera in close proximity of an ATM keypad so as to film the hands of users as they enter their PIN code. In such a scenario, a solution based on using *EyeDecrypt* with a smartphone would be perfectly fine as the hidden camera would not be able to capture the screen of the smartphone[1]. Similarly, using *EyeDecrypt* with a smartphone would be perfectly suitable to protect against an attack involving malware such as a keylogger.

When thinking about a shoulder-surfing attack it is natural to ask, "Why not just display content in a head-mounted display without any encryption?" The answer is that this would prevent shoulder surfing, but it assumes that the device that the head-mounted display is plugged into can be trusted. It does not help in the more difficult case of a modified ATM or compromised public terminal.

Another idea is to encrypt content at the server, send it to the untrusted device, and have the untrusted device forward it to the user's trusted personal device via wireless transmission, instead of using *EyeDecrypt*'s visual channel. This is definitely a viable solution and has its advantages, such as higher bandwidth. However, it has two significant downsides.

First, both the personal device and the untrusted device need to be equipped with the same wireless technology. It would not work, for example, with existing ATMs, which do not employ Bluetooth or WiFi. In contrast, *EyeDecrypt* works on any personal device equipped with a camera, and it makes no assumptions about the connectivity of the untrusted device; *EyeDecrypt* can work with existing ATMs, without requiring a hardware upgrade.

Second, wireless communication requires *secure pairing*. As in the ATM case, it may be that the user has never interacted with the public device before. Pairing is required to be sure that the personal device is communicating with the intended public device, and not some other device in the vicinity. Secure pairing by itself is a hard problem and one of the devices being untrusted (i.e., possibly misbehaving) makes it much harder. *EyeDecrypt* does not require pairing—the user knows where she is pointing her camera—making

[1]Naturally, we assume the user to be security conscious so as not to position the phone too close to the ATM keypad.

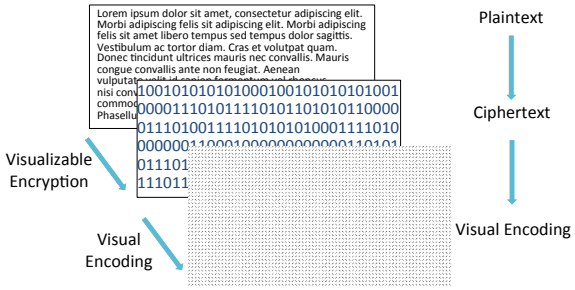


Figure 3: *EyeDecrypt overview*

the whole process much more secure and user-friendly. Notably, most of the secure pairing solutions that have been proposed involve use of the visual channel, for exactly this reason. In other words, use of the wireless channel in these scenarios already requires some mechanism like *EyeDecrypt*. We discuss secure pairing in Section 6.

Lastly, *EyeDecrypt* also works with printed content such as passports, bank statements, medical records and any other type of sensitive material. If the human eye can see it, *EyeDecrypt* can protect it.

EyeDecrypt consists of three main components: an encryption mechanism which we term *visualizable encryption*; a suitable *visual data encoding* scheme; and a combination of augmented reality and randomization for secure input. Figure 3 shows how content is encrypted and then visually encoded.

Visualizable encryption is distinct from ordinary encryption in that information is captured incrementally, frame-by-frame, and even block-by-block within a frame, in a pan-and-zoom fashion. In addition, our notion of security refers to the security of the "*EyeDecrypt* activity" and not just to the security of the encryption scheme. As such, it must also take into account what the adversary is able to observe—not only ciphertext, but also the user's interaction (e.g., gesticulation) with the system. We believe that formally defining the security of these new applications is an important contribution, in particular since our security notion does *not* directly reduce to an encryption scheme's, and can become the basis for the development of such technologies in the future. As important is the fact that our new notion and scheme are achievable (resp., realizable) using (the practical instantiations) of basic cryptographic tools, such as a pseudorandom function generator (PRFG), a collision resistant hash function and an existentially unforgeable message authentication code (MAC) (cf. Section 3).

EyeDecrypt is symmetric key-based, and the cryptographic keys needed for decryption and authentication are provisioned and directly shared between the remote content provider and the *EyeDecrypt* app running on the user's personal device. In particular, the untrusted device *does not* have access to the keys. In the ATM scenario, for example, the keys would be shared between the bank's server, which would act as the remote content provider, and the *EyeDecrypt* app running on the user's personal device. The ATM, being untrusted, would *not* have access to the keys. Thus, the key provisioning phase is the only time at which *EyeDecrypt* requires network connectivity in order for the *EyeDecrypt* app to communicate privately with the remote content provider. For everything else, *EyeDecrypt* does not require it, making it suitable for very high-security environments where network connectivity may not be permitted. Section B describes the key provisioning/management aspect in more detail.

EyeDecrypt can use any type of visual encoding (e.g., QR codes [12], Data Matrices [11], Dataglyphs [28]) as long as it satisfies some basic properties (see Section 3.3). In our proof of concept we opted for Dataglyphs as this particular encoding has very little structure such as no visual landmarks and no fixed block size. This gives us the flexibility of being able to change parameters of the underlying Visualizable Encryption scheme (e.g., cipher-block size) without affecting its visual encoding representation. In particular, we have developed a new dataglyph-based visual encoding scheme that can be decoded progressively, by zooming or moving the camera close to one part of the encoding, and panning to decode other parts. Due to our use

of augmented reality this feels quite natural. At the same time, the security of panning becomes one of the central challenges in the design of a visualizable encryption scheme compatible with our visual encoding. In Section 3.3 we discuss how *EyeDecrypt* allows for the use of other visual data encodings such as QR codes.

The rest of the paper is organized as follows. In Section 2 we present our model, give security definitions for *EyeDecrypt* and visualizable encryption, and specify requirements for visual encoding. In Section 3 we present our *EyeDecrypt* and visualizable encryption constructions, as well as the dataglhyp-based visual encoding scheme. Section 4 is dedicated to implementation details, including the design choices to overcome the various challenges arising from the visual encoding approach, while Section 5 refers to performance issues. Related work is included in Section 6. Finally, summary and conclusions are presented in Section 7. Due to space constraints, proofs and complementary material are presented in the appendix.

2 Model and Definitions

In this section we present the basic model where we envision *EyeDecrypt* operating, as well as formal definitions of the different components needed for our constructions.

In its basic form, *EyeDecrypt* operates in a setting with three components, or "parties:" a user personal device U running the *EyeDecrypt* app, a server S, an a (polynomial-time) adversary Adv, controlling both the device where the information is displayed and/or entered (the "untrusted device" in Figure 1) and the shoulder-surfer(s) surrounding the user. The user device U can be any device that can capture an image, process it, and display the result to the human user. We envision the server encrypting and transmitting data to the user by visual means (e.g., rendering a visual encoding of the [encrypted] data on a computer screen), and the user receiving a (possibly noisy) version of that data. In turn, the user can transmit data back to the server by means of pressing buttons, active areas on a touch screen, etc., of the untrusted device. We expect the user and the server to engage in an interaction where the information transmitted at each "round" is dependent on all prior communication, as well as possibly other external factors.

In this paper we treat both *passive* and *active* adversaries threatening the security of the system. A passive adversary observes the visual channel as well as other available channels of information such as the user's body language, the buttons that she presses, the areas of the touch screen that she activates, the information that is transmitted through the untrusted device, etc. (This type of adversary is also called *honest-but-curious* in the literature.) An active adversary, on the other hand, can in addition *manipulate* the communication between the server and the untrusted device, mount *man-in-the-middle* attacks, etc. This could occur, for example, if the user is interacting with a terminal infected by malware that is displaying information that is transmitted by a remote trusted server. We assume, however, that the "shoulder-surfer" component of such an adversary remains passive.

Data transmitted from S to U are partitioned into *frames*, and each frame is partitioned into *blocks*. The frames represent the change of the content over time, and blocks partition the frame into logical units. The choice of what constitutes a block depends on the parameters of the system. For example, a block could be a rectangular area in an image, or a group of characters in a text document.

2.1 Security of the *EyeDecrypt* activity

The security of *EyeDecrypt* is defined in a setting wherein the server can receive input from the user through the entry device or from another source such as a local hard drive or the Internet. A screen in the (untrusted) device is used to display information about the inputs received so far, such as outputs of a visual encoding function of the encrypted input (see below). The entry device allows the user to select values from a fixed alphabet Σ, whereas information received from other sources is viewed as arbitrary strings.

Formally, a *(stateful) EyeDecrypt scheme* is a triple of PPT (probabilistic polynomial-time) algorithms $(\mathsf{EyeDecInit}, \mathsf{EyeDecEntry}, \mathsf{EyeDecRead})$ where $\mathsf{EyeDecInit} : \mathbb{N} \to \mathcal{S} \times \mathcal{K}_{\mathsf{ED}}$ takes as input a security parameter and outputs an initial state S_0 for the *EyeDecrypt* server, and a long term key for the user viewing

device; here, $\mathcal{K}_{\mathsf{ED}}$ is the space of possible keys. $\mathsf{EyeDecEntry} : \mathcal{S} \times \Sigma \times \{0,1\}^* \to \mathcal{S}$ where $\mathcal{S}$ is the set of possible states of the scheme, and $\mathsf{EyeDecRead} : \mathcal{K}_{\mathsf{ED}} \times \{0,1\}^* \to \{0,1\}^*$ runs on the user device and outputs the information that is shown to the user. The expression $\mathsf{EyeDecEntry}(S, x, m)$ should be interpreted as the system receiving input x through the entry device, and receiving input m from another source.

For example, when considering a secure PIN entry application, $\Sigma = \{0, \ldots, 9\}$ (as well as some other symbols such as '#', 'Cancel', etc., omitted here for simplicity), and corresponding to the buttons on the keypad. In our solution for the PIN entry application, $\mathcal{S}$ will consist of the keys of the visualizable encryption scheme, and the contents displayed on the screen (see App. B for more details on the PIN entry application).

We define the security of an *EyeDecrypt* scheme in terms of the information that is "leaked" to the adversary, which may vary depending on the particular real-world application that is being modeled. Specifically, the definition of security of an *EyeDecrypt* scheme against passive adversaries is parameterized by a function $\mathsf{Leak} : \mathcal{S} \to \{0,1\}^*$ that specifies the information that is given to the adversary after each input. Looking ahead to our construction for the PIN entry case, Leak will reveal the current encrypted image displayed on the screen, as well as the number on the button that was most recently pressed by the user, but not the keys of the underlying visualizable encryption scheme. Active adversaries, as mentioned above, can in addition "tamper" with the information being transmitted (displayed as well as entered), adaptively and as a function of the current state and of what they observe. Thus, the definition of security of *EyeDecrypt* in this case is parameterized by a class of "tamper-leakage" functions of the form $\mathcal{S} \times \{0,1\}^* \to \mathcal{S} \times \{0,1\}^*$. Intuitively, these functions express in addition the ways in which the adversary is allowed to alter the information (modify the state), when communicated both to the user and to the server. Formally, the security of an *EyeDecrypt* scheme against passive and active adversaries is defined via the experiments shown in Figure 4.

$\mathsf{ExpEyeDec}(1^n, \mathsf{Adv}, \mathsf{EyeDec})$:
$S_0 \leftarrow_{\mathrm{R}} \mathsf{EyeDecInit}(1^n)$
$((x_0, m_0), (x_1, m_1), \mathsf{st}) \leftarrow \mathsf{Adv}^{\mathsf{LeakST}}(1^n, \mathsf{Leak}(S_0))$
where $(x_0, m_0) \neq (x_1, m_1)$
$b \leftarrow_{\mathrm{R}} \{0,1\}$; $\lambda \leftarrow \mathsf{LeakST}(x_b, m_b)$
$b' \leftarrow \mathsf{Adv}^{\mathsf{LeakST}}(1^n, \lambda)$
Output 1 if and only if $b = b'$

$\mathsf{ExpEyeDecNM}(1^n, \mathsf{Adv}, \mathsf{EyeDec})$:
$S_0 \leftarrow_{\mathrm{R}} \mathsf{EyeDecInit}(1^n)$
$((x_0, m_0), (x_1, m_1), \mathsf{TL}^*_{\mathsf{pre}}, \mathsf{TL}^*_{\mathsf{post}}, \mathsf{st}) \leftarrow \mathsf{Adv}^{\mathsf{TamperLeakST}}(1^n)$
where $(x_0, m_0) \neq (x_1, m_1)$
$b \leftarrow_{\mathrm{R}} \{0,1\}$; $(\lambda_{\mathsf{pre}}, \lambda_{\mathsf{post}}) \leftarrow \mathsf{TamperLeakST}(x_b, m_b, \mathsf{TL}^*_{\mathsf{pre}}, \mathsf{TL}^*_{\mathsf{post}})$
$b' \leftarrow \mathsf{Adv}^{\mathsf{TamperLeakST}}(1^n, \lambda_{\mathsf{pre}}, \lambda_{\mathsf{post}})$
Output 1 if and only if $b = b'$

$\mathsf{LeakST}(x, m)$ is stateful, and works as follows:
Initially $S \leftarrow S_0$
Given $(x, m) \in \Sigma \times \{0,1\}^*$ do:
$S \leftarrow \mathsf{EyeDecEntry}(S, x, m)$
Output $\mathsf{Leak}(S)$

$\mathsf{TamperLeakST}(x, m, \mathsf{TL}_{\mathsf{pre}}, \mathsf{TL}_{\mathsf{post}})$ is stateful, and works as follows:
Initially $S \leftarrow S_0$, $C^* \leftarrow \perp$
Given $(x, m) \in \Sigma \times \{0,1\}^*$ do:
$S', \lambda_{\mathsf{pre}} \leftarrow \mathsf{TL}_{\mathsf{pre}}(S, C^*)$
$S'' \leftarrow \mathsf{EyeDecEntry}(S', x, m)$
If challenge query, set:
$C^* \leftarrow v''$ (from S'')
$S, \lambda_{\mathsf{post}} \leftarrow \mathsf{TL}_{\mathsf{post}}(S'', C^*)$
Output $(\lambda_{\mathsf{pre}}, \lambda_{\mathsf{post}})$

Figure 4: *EyeDecrypt security game definitions for both passive and active adversaries*

Note that calls to the corresponding oracle by Adv are slightly different in each experiment, as in the case of active attacks the adversary is able to choose the tamper-leakage functions ($\mathsf{TL}_{\mathsf{pre}}, \mathsf{TL}_{\mathsf{post}}$) on the fly. Also, the design choice of having two functions in the active-attack case, as opposed to encoding all the tampering actions and leakage into just one, is to avoid having to specify another function for the initial leakage.

Definition 1 (Passive Attacks) *Let* $\mathsf{EyeDec} = (\mathsf{EyeDecInit}, \mathsf{EyeDecEntry}, \mathsf{EyeDecRead})$ *be an* EyeDecrypt *scheme, and* $\mathsf{Leak} : \mathcal{S} \to \{0,1\}^*$. *Then,* EyeDec *is a* Leak-secure *EyeDecrypt* scheme *if for all PPT*

adversaries Adv*, and all* $n \in \mathbb{N}$*,*

$$\Pr[\mathsf{ExpEyeDec}(1^n, \mathsf{Adv}, \mathsf{EyeDec}) = 1] \leq \mathsf{neg}(n).$$

Definition 2 (Active Attacks) *Let* $\mathsf{EyeDec} = (\mathsf{EyeDecInit}, \mathsf{EyeDecEntry}, \mathsf{EyeDecRead})$ *be an* EyeDecrypt *scheme, and* $\mathcal{TL}$ *be a class of tamper-leakage functions. Then,* EyeDec *is* $\mathcal{TL}$-secure against active adversaries *if for all PPT adversaries* Adv*, and all* $n \in \mathbb{N}$*,*

$$\Pr[\mathsf{ExpEyeDecNM}(1^n, \mathsf{Adv}, \mathsf{EyeDec}) = 1] \leq \mathsf{neg}(n),$$

as long as Adv *only queries the* TamperLeakST *oracle on inputs* $(x, m, \mathsf{TL_{pre}}, \mathsf{TL_{post}})$*, where* $\mathsf{TL_{pre}}, \mathsf{TL_{post}} \in \mathcal{TL}$*.*

Note that the algorithm EyeDecRead does not play a role in the above definitions. This is because it is only used to specify the functionality of the scheme that is available to the legitimate user U (i.e., the unencrypted content from the screen). Its role is in fact similar to the role of the decryption algorithm in encryption schemes.

2.2 Defining the building blocks

The basic components in an *EyeDecrypt* application specify suitable ways for the information to be displayed in the rendering device and captured by the user, as well as a method for encrypting the plaintext content. We elaborate on such visual encoding schemes along with some desirable properties at the end of the section. First, we present a definition of *visualizable encryption*—a key component in our solution.

Visualizable encryption. A *private-key visualizable encryption scheme* consists of a triple of PPT algorithms $\langle \mathsf{KeyGen}, \mathsf{Enc}, \mathsf{Dec} \rangle$, where KeyGen takes as input a security parameter $n \in \mathbb{N}$, and outputs a key; Enc takes as input a key K, a frame index f, block number i, and a plaintext m, and outputs a ciphertext; and Dec takes as input a key K, a frame index f, block number i, and a ciphertext, and outputs a plaintext.

$\mathsf{ExpVisIND\text{-}ATK}(1^n, \mathsf{Adv}, \mathsf{VisEnc})$:
$K \leftarrow_{\mathrm{R}} \mathsf{KeyGen}(1^n)$;
$(f_*, i_*, m_0, m_1, \mathsf{st}) \leftarrow \mathsf{Adv}^{\mathsf{EncATK}_K(\cdot,\cdot,\cdot), \mathsf{DecATK}_K(\cdot)}(1^n)$
$b \leftarrow_{\mathrm{R}} \{0,1\}$; $C_* \leftarrow_{\mathrm{R}} \mathsf{Enc}_K(f_*, i_*, m_b)$
$b' \leftarrow \mathsf{Adv}^{\mathsf{EncATK}_K(\cdot,\cdot,\cdot), \widehat{\mathsf{DecATK}}_K(\cdot)}(1^n)$
Let $\mathsf{view_{Adv}}$ be the view of the adversary.
Output 1 if and only if $b' = b$ and $\mathsf{Check}(\mathsf{view}) = 1$.

$\mathsf{Enc}\{\mathsf{CPA}, \mathsf{CCA}\}_K(f, i, m) \stackrel{\text{def}}{=} \mathsf{Enc}_K(f, i, m)$
$\mathsf{DecCPA}_K(C) \stackrel{\text{def}}{=} \perp$
$\mathsf{DecCCA}_K(C) \stackrel{\text{def}}{=} \mathsf{Dec}_K(C)$
$\widehat{\mathsf{DecCCA}}_K(C) \stackrel{\text{def}}{=} \mathsf{Dec}_K(C)$ if $C \neq C_*$
$\perp$ if $C = C_*$
$\mathsf{Check}(\mathsf{view})$:
Let $(f_\ell, i_\ell, m_\ell)_{1 \leq \ell \leq q}$ be the queries made to EncATK. Output 1 if and only if for all ℓ, ℓ', if $f_\ell = f_{\ell'}$ and $i_\ell = i_{\ell'}$ then $m_\ell = m_{\ell'}$.

Figure 5: *Security game definition for visualizable encryption*

Definition 3 *Let* $\mathsf{VisEnc} = \langle \mathsf{KeyGen}, \mathsf{Enc}, \mathsf{Dec} \rangle$*. Then,* VisEnc *is a* ATK-secure visualizable encryption scheme*, where* $\mathsf{ATK} \in \{\mathsf{CPA}, \mathsf{CCA}\}$*, if for all PPT adversaries* Adv*, all* $n \in \mathbb{N}$*,*

$$\Pr[\mathsf{ExpVisIND\text{-}ATK}(1^n, \mathsf{Adv}, \mathsf{VisEnc}) = 1] \leq \mathsf{neg}(n),$$

where $\mathsf{ExpVisIND\text{-}ATK}(\cdot,\cdot,\cdot)$ *is the experiment presented in Figure 5.*

In our proofs in Section 3 we require a slightly different security property from the encryption scheme, where the adversary can receive an encryption of a sequence of blocks as a challenge instead of a single block. Namely, the adversary outputs four vectors $\boldsymbol{f}_*, \boldsymbol{i}_*, \boldsymbol{m}_0, \boldsymbol{m}_1$, where $\boldsymbol{m}_0 \neq \boldsymbol{m}_1$ and receives back a vector $\boldsymbol{C}_*$ of ciphertexts of the elements of $\boldsymbol{m}_b$ with frame and block numbers at the matching positions in $\boldsymbol{f}_*$ and $\boldsymbol{i}_*$, respectively. Let us call this notion of security ATK-*security for multiple messages*. The following claim can be shown to be true by a standard hybrid argument:

Claim 4 *Let $\mathcal{E}$ be an* ATK*-secure visualizable encryption scheme. Then, $\mathcal{E}$ is also* ATK-secure for multiple messages *with a $\frac{1}{\nu}$ loss in security, where ν is the number of messages encrypted in the challenge.*

We now provide some intuition regarding the applicability of our definition to the *EyeDecrypt* setting. Recall that a main motivation for our work is to prevent "shoulder-surfing" attacks. In such a scenario, an attacker is covertly observing the content of a (supposedly) private screen or paper document; in addition, the attacker may be able to observe the activities (gesticulation, movements, etc.) of the legitimate content's owner, and infer information. For example, by measuring how long the user spends looking at a given (encrypted) document, or the sequence of buttons that the user presses, the attacker may learn a lot about the content of the document. Our definition accounts for such a scenario similarly to the way that semantic security of encryption [9] accounts for partial knowledge of the plaintext by the adversary: by allowing the adversary in the security experiment to specify all the content but a single block in a single frame, we capture any external knowledge that the adversary may have about the plaintext.

Visual encoding. Let $d_1, d_2, t_1, t_2 \in \mathbb{N}$ (see below for an explanation of these parameters), and $\mathcal{P}$ be a finite set representing possible values that can be assigned to a pixel (e.g., RGB values[2]). A *visual encoding scheme* is a pair of functions $(\mathsf{Encode}, \mathsf{Decode})$ such that $\mathsf{Encode} : (\{0,1\}^n)^{d_1 \times d_2} \to \mathcal{P}^{t_1 \times t_2}$, and $\mathsf{Decode} \equiv \mathsf{Encode}^{-1}$.

$d_1 \times d_2$ is the size of the (ciphertext) input matrix, measured in number of blocks; the size of a block is n bits. $t_1 \times t_2$ is the size (resolution) of the output (image); e.g., 640×480 pixels. One basic but useful property of a visual encoding scheme is that it preserves the relative positioning of elements (in our case, blocks) in the source object. The following definition makes that explicit.

Definition 5 *A visual encoding scheme is said to satisfy* relative positioning *if the following conditions hold:*

1. Decode *maps $\mathcal{P}^{\leq t_1 \times \leq t_2}$ to $(\{0,1\}^n)^{\leq d_1 \times \leq d_2}$;*
2. *for all $X \in (\{0,1\}^n)^{d_1 \times d_2}$, r_1 and r_2 such that $1 \leq r_1 < r_2 \leq d_1$, and c_1 and c_2 such that $1 \leq c_1 < c_2 \leq d_2$, if $Y \leftarrow \mathsf{Encode}(X)$ and $(r'_1, r'_2, c'_1, c'_2) = (r_1 \cdot \frac{t_1}{d_1} \ldots r_2 \cdot \frac{t_1}{d_1}, c_1 \cdot \frac{t_2}{d_2} \ldots c_2 \cdot \frac{t_2}{d_2})$, then $X_{r_1 \ldots r_2, c_1 \ldots c_2} \leftarrow \mathsf{Decode}(Y_{r'_1 \ldots r'_2, c'_1 \ldots c'_2})$.*

3 Constructions

We start off this section with a CCA-secure construction for visualizable encryption using basic cryptographic tools, followed by an *EyeDecrypt* scheme with two flavors (secure against passive and active attacks, respectively), which are based on it. The section concludes with the dataglyphs-based visual enconding construction.

3.1 The visualizable encryption scheme

Our construction of a visualizable encryption scheme uses a pseudorandom function generator (PRFG), a strongly collision resistant hash function family, and an existentially unforgeable message authentication code (MAC).

[2]The *RGB color model* is an additive color model in which red, green, and blue light are added together in various ways to reproduce a broad array of colors. The name of the model comes from the initials of the three additive primary colors.

Construction 1. Let F be a PRFG with key space $\mathcal{K}_{\mathsf{PRF}}$, $\mathcal{H}$ be a family of hash functions, and MAC an existentially unforgeable MAC with key space $\mathcal{K}_{\mathsf{MAC}}$. Then we construct a visualizable encryption scheme $\mathcal{E} = \langle \mathsf{KeyGen}, \mathsf{Enc}, \mathsf{Dec} \rangle$ as follows:

- $\mathsf{KeyGen}(1^n)$: Generate $K_{\mathsf{PRF}} \in_R \mathcal{K}_{\mathsf{PRF}}$; $K_{\mathsf{MAC}} \in_R \mathcal{K}_{\mathsf{MAC}}$; $H \in_R \mathcal{H}$; and output $K = (K_{\mathsf{PRF}}, K_{\mathsf{MAC}}, H)$.
- $\mathsf{Enc}_K(f, i, M)$: Compute $C_0 \leftarrow F_{K_{\mathsf{PRF}}}(H(f, i)) \oplus M$; $\tau \leftarrow \mathsf{MAC}_{K_{\mathsf{MAC}}}(C_0)$; and output $C = (C_0, \tau, i, f)$.
- $\mathsf{Dec}_K(C)$: Interpret C as a tuple (C_0, τ, i, f), and compute $\tau' \leftarrow \mathsf{MAC}_{K_{\mathsf{MAC}}}(C_0)$. If $\tau' \neq \tau$, output $\perp$. Otherwise, compute and output $M \leftarrow C_0 \oplus F_{K_{\mathsf{PRF}}}(H(f, i))$.

Theorem 1 *The visualizable encryption scheme $\mathcal{E}$ in Construction 1 is CCA-secure according to Def. 3.*

3.2 An *EyeDecrypt* scheme

We construct an *EyeDecrypt* scheme(s) based on our visualizable encryption scheme $\mathcal{E}$, and the dataglyphs-based visual encoding scheme described in Section 3.3, which for now can be thought of as satisfying Definition 5; let $\mathcal{V} = (\mathsf{Encode}, \mathsf{Decode})$ denote that scheme. Our construction is parameterized by a function g which specifies how an application converts inputs to a new visual frame. Here $g(x, m, \mathsf{frame}, \pi)$ outputs a sequence of blocks $\mathsf{frame}' = (t_1, \ldots, t_n)$ comprising the content of the new frame given the input from the user, an input from another source (such as a harddrive or the Internet), and the previous frame. The input π to g is a permutation over alphabet Σ, and its meaning will become clear in the discussion that follows the construction. In order to use the *EyeDecrypt* scheme for a particular application, one only has to plug in an appropriate g into the construction below.

Construction 2. The generic *EyeDecrypt* scheme secure against passive attacks works as follows:

- $\mathsf{EyeDecInit}(1^n)$: Run $\mathsf{KeyGen}(1^n)$ to obtain a key K, and generate a random permutation π over Σ. Output $S_0 = (K, \pi, \perp, \perp, 0)$ and K. The two $\perp$ values in the tuple corresponds to the current cleartext and ciphertext frames, which are initially empty, and 0 is the initial frame number.
- $\mathsf{EyeDecEntry}(S, x, m)$: Parse S as $(K, \pi, \mathsf{frame}, v, j)$. Generate a random permutation π' over Σ, and compute $(t_1, \ldots, t_n) \leftarrow g(\pi(x), m, \mathsf{frame}, \pi')$, set $\mathsf{frame}' = (t_1, \ldots, t_n)$, and compute $c_i \leftarrow \mathsf{Enc}_K(j, i, t_i)$ and $v' \leftarrow \mathsf{Encode}(c_1, \ldots, c_n)$. Lastly, set $S = (K, \pi', \mathsf{frame}', v', j + 1)$.
- $\mathsf{EyeDecRead}(K, v)$: Compute $(c_1, \ldots, c_n) \leftarrow \mathsf{Decode}(v)$ and $t_i \leftarrow \mathsf{Dec}_K(c_i)$, for $1 \leq i \leq n$. Output $(t_1, \ldots, t_n)$.

The intuition behind the construction is to encrypt content as it is displayed, and to randomly permute the meaning of the possible inputs that can be received from the user input device. In the PIN entry application, for example, we envision a touchscreen in the entry device where the nine digits are randomly re-ordered each time the user enters a PIN digit; see Fig. 10. Alternatively, the device may have a keypad with unlabeled buttons, and a random mapping of buttons to digits will be displayed to the user in encrypted form.

Theorem 2 *Let $\mathsf{Leak}(S) = v$. Then, the* EyeDecrypt *scheme given in Construction 2 is* Leak*-secure according to Definition* 1 *if $\mathcal{E}$ is a* CPA*-secure visualizable encryption scheme.*

Turning to active attacks, simply substituting a CCA-secure encryption scheme for the CPA-secure one in Construction 2 is not enough to achieve non-malleability of the *EyeDecrypt* scheme against an interesting class of tamper-leak functions. In addition, we must perform checks on the viewing device to see if block positions have been modified.

Construction 3. The generic *EyeDecrypt* scheme secure against active attacks works as follows: $\mathsf{EyeDecInit}(1^n)$ and $\mathsf{EyeDecEntry}(S, x, m)$ are identical to Construction 2's, except that the encryption scheme $(\mathsf{KeyGen}, \mathsf{Enc}, \mathsf{Dec})$ must be CCA-secure according to Definition 3. The viewing function is defined as follows:

– $\mathsf{EyeDecRead}(K, v)$: Compute $(c_1, \ldots, c_n) \leftarrow \mathsf{Decode}(v)$, parse each c_i as (C_0^i, τ_i, i', j') and compute $t_i \leftarrow \mathsf{Dec}_K(c_i)$ for $1 \leq i \leq n$. Let j be the current frame number. If $i' \neq i$ or $j' \neq j$ or $t_i = \perp$, return $\perp$; otherwise, output $(t_1, \ldots, t_n)$.

Note that the above construction requires the device to keep track of the current frame number, but this is an implementation issue. We now prove that Construction 3 is secure against active attacks where the adversary is limited to modifying the displayed contents in addition to the capabilities it is given in the passive attack setting. Specifically, let $\mathcal{TL}$ be the class of functions defined as follows:

$$\mathcal{TL} \stackrel{\text{def}}{=} \{\mathsf{TL}(\cdot) | \mathsf{TL}(K, \pi, \mathsf{frame}, v, j, C^*) = ((K, \pi, \mathsf{frame}, f(v), j), \mathsf{Leak}_{\mathsf{act}}(K, f(v), C^*))\}$$

where $f : \mathcal{P}^{t_1 \times t_2} \rightarrow \mathcal{P}^{t_1 \times t_2}$ and $\mathsf{Leak}_{\mathsf{act}} : \mathcal{K}_{\mathsf{ED}} \times \{0,1\}^* \times \{0,1\} \rightarrow \{0,1\}^*$ is defined as

$$\mathsf{Leak}_{\mathsf{act}}(K, u, C^*) \stackrel{\text{def}}{=} \begin{cases} (\mathsf{EyeDecRead}(K, u), u) & \text{if } u_i \neq C_i^* \text{ for } 1 \leq i \leq n; \\ (\perp, u) & \text{otherwise.} \end{cases}$$

Note that v, the visual encoding, is the value that is tamperable and that is leaked to the adversary. Also note that in the above definition we require that the adversary does not apply any tamper-leakage functions that attempt to decrypt parts of the challenge ciphertext. Every block has to be different from the blocks of the challenge. This is so because, unlike in standard (non-visualizable) encryption, here blocks must be decryptable individually. Therefore, there is no way to determine if other blocks outside the field of view have been tampered with. We can now show the following theorem:

Theorem 3 *Let $\mathcal{TL}$ be as above. The* EyeDecrypt *scheme given in Construction 3 is $\mathcal{TL}$-secure according to Definition* 2 *if $\mathcal{E}$ is a* CCA*-secure visualizable encryption scheme.*

Given the *EyeDecrypt* constructions above, specifying the function g defines the functionality of the application. In Appendix B we do this to provide a complete solution to the secure PIN entry application. Finally, as mentioned in Section 1 and made evident by the definitions and constructions above, *EyeDecrypt* is symmetric key-based. In Appendix B we also briefly sketch how the personal device running the *EyeDecrypt* app and the content generating server are able to share cryptographic keys in a secure manner.

3.3 A dataglyphs-based visual encoding scheme

Many existing visual encoding schemes are compatible with visualizable encryption (e.g., QR codes [12], Data Matrices [11], Dataglyphs [28], High Capacity Color Barcodes (HCCB) [19]), but visualizable encryption does impose some constraints.

First, the system should be able to decrypt content when zoomed in to a single block. Our chosen visual encoder should therefore not encode more than one block per code—otherwise zooming in to a single block would present the decoder with only a portion of a code. On the other hand, we are free to encode a block using multiple codes.

Second, the system must support decoding *multiple blocks* of a frame all at once. We have found that some decoders get "confused" by images containing multiple codes (we need at least one code per block) or partial codes. Sometimes, decoders that support multiple codes per image impose constraints on their arrangement (for example, multiple QR codes require a "quiet zone" between codes).

Finally, the visual decoder must not only be able to decode multiple blocks, it must also *understand their spatial arrangement*. For any given block the decoder must understand which other block is its right neighbor, etc., so that the system can detect whether an attacker has re-arranged blocks of ciphertext (cf. Construction 3 above). This is a computer vision problem that is not solved by simply reading multiple codes independently, and existing systems using multiple codes (e.g., [6]) do not implement it. Note that

simply knowing the pixel coordinates of codes within an image is not sufficient as images taken with a hand-held device exhibit rotation, skew, perspective shift, and other misalignments.

Still, within these constraints many existing visual encodings could be made to work. For our implementation we had to choose one, and we have (somewhat arbitrarily) chosen to use Dataglyphs (Figure 6(a)).

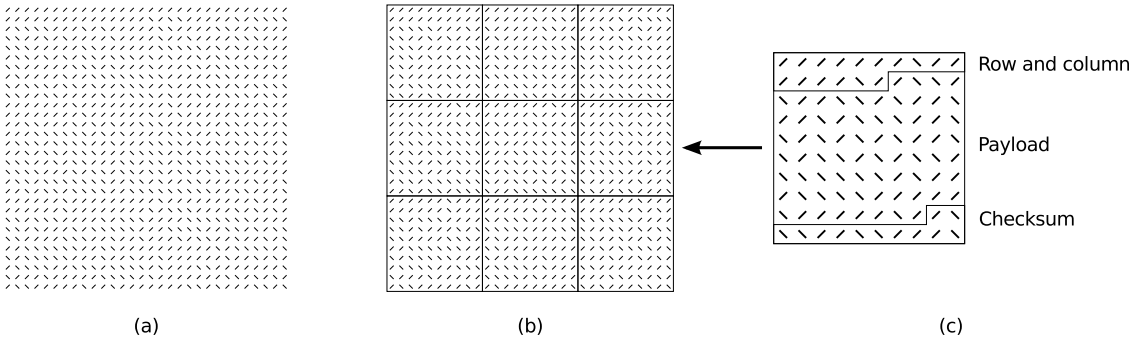


Figure 6: (a) *Dataglyph encoding* (b) *Blocks of the encoding* (c) *Structure of a block*

A (data)glyph is a marking with two possible angles, $+45^\circ$ and -45°, indicating a 0 or 1 bit, respectively. Multiple bits are encoded by organizing multiple glyphs into a grid. Decoding multiple bits therefore means reconstructing the grid structure from the pixel coordinates of glyphs within an image. While this is not a trivial task, the great advantage in our setting is that the resulting grid structure can be used not only for decoding a single glyph, but also for understanding the spatial arrangement of multiple blocks also arranged in a grid. In fact, what is shown in Figure 6(a) is actually an encoding of a grid of blocks, with each block being encoded by a grid of glyphs, as indicated in Figure 6(b). Blocks can be arranged seamlessly into a grid of arbitrary size. This gives dataglyphs a flexibility that has proven to be very useful in experimenting with parameters of the underlying visualizable encryption scheme (e.g., cipher-block size, aspect ratio).

4 The *EyeDecrypt* Prototype

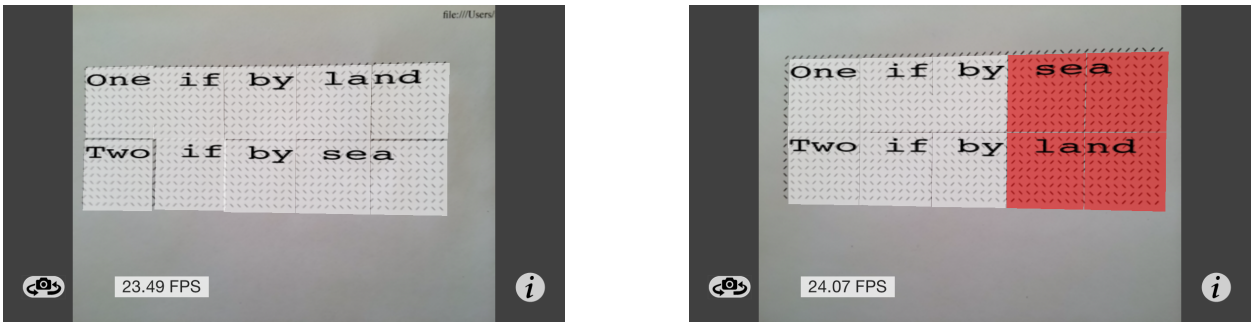
EyeDecrypt would be a natural fit for augmented-reality devices such as Google Glass [10]: the user would simply look at encrypted content and have the decrypted version displayed directly on the screen of the glasses. However, given that such devices are not yet widely available, we implemented *EyeDecrypt* on a smartphone, an iPhone 5S equipped with an 8 MP rear-facing camera.

The *EyeDecrypt* app shows a live camera view and decrypts on the fly, at a rate of 20–30 frames per second, depending on the number of blocks in view. The decrypted content is overlaid over the corresponding block of dataglyphs in the camera view itself. The only action users need to perform is to position the phone camera in front of the encrypted document they wish to decrypt and move the camera around to decrypt different parts of the document. This is illustrated in Figure 2.

Figure 7(a) shows a screenshot of the application. The encrypted message consists of ten blocks laid out in two rows. Each decrypted block is rendered independently, directly over the corresponding block of glyphs; gaps between decrypted blocks are the result of camera motion during the live capture. The decrypted blocks track the glyphs at 20–30fps, achieving a true augmented reality experience. The application verifies that adjacent blocks are correctly arranged, and displays any out-of-place blocks in red, as in Figure 7(b), making evident any rearrangement of blocks by cut-and-paste.

In the current implementation we encrypt the plaintext instantiating the PRF in the visualizable encryption scheme of Section 3.1 with AES-128, and visually-encode it using dataglyphs. Currently, no MAC is implemented and therefore our implementation is only secure against passive attacks, except for the detection of block rearrangement (Figure 7(b)).

We now list the steps that *EyeDecrypt* goes through in order to decode a visually encoded ciphertext.



(a) *A decrypted message* (b) *Detecting rearranged blocks*

Figure 7: *Screenshots of the* EyeDecrypt *application*

Removing Moiré patterns. *EyeDecrypt* works not only with documents printed on paper but also documents viewed on computer screens. In this second scenario, additional noise is introduced to the image captured by the phone camera. In particular, Moiré patterns [30] are well-known artifacts present in digital images. In order to reduce Moiré patterns when reading a visual encoding from a screen, we apply a series of low-pass filters and high-pass filters to filter out such patterns as much as possible while, at the same time, trying to enhance the dataglyphs. In our implementation we use OpenCV [13], and, in particular, we use a Gaussian Blur as low-pass filter and a Laplacian as high-pass filter.

Contour detection. We convert the image to gray scale, use the Scharr transform to perform edge detection, and the Suzuki-Abe algorithm to detect contours [26]. For each contour, we calculate its centroid coordinates and angle.

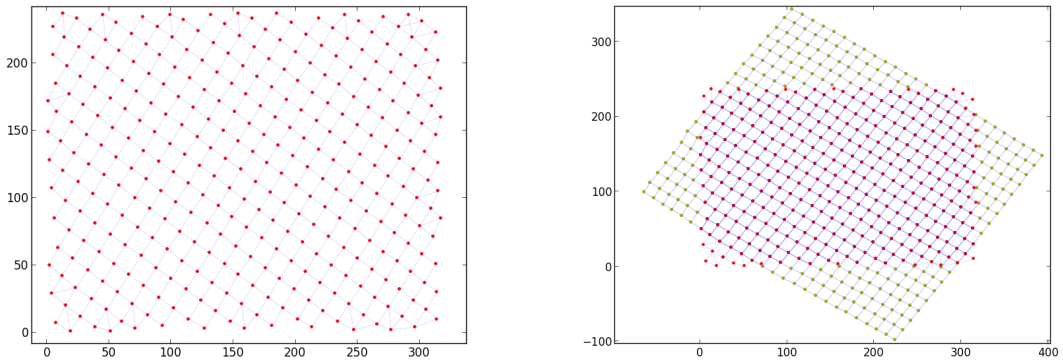
Reconstructing the grid. We build a graph by Delaunay triangulation of the glyph centroids. The result is an undirected graph in which each centroid has edges to up to 8 of its nearest neighbors. We remove "diagonal" edges so that remaining edges roughly follow the rows and columns of a grid, and each centroid is connected to at most four other centroids.

Removing noise. Camera lens deformation, non-uniform light conditions, variable distance from content and camera resolution all lead to the creation of noise and artifacts in the detection of the contours that is, in the detection of the centroids. Such artifacts are usually located at the edges of the camera field of view which translates to disconnected or missing centroids at the edges of the graph. The way users hold their phone represents another significant source of noise. In particular, given that the visual encoding we use does not have any landmark to help with alignment, if the phone is rotated by a significant amount, it may be very hard to tell left from right and top from bottom of the visually encoded content captured by the camera. Figure 8a shows this problem. As we can see, by just looking at the centroids of the contours we cannot tell the correct alignment of the ciphertext.

In order to solve all these issues, we apply various graph-theory algorithms that allow us to remove all the artifacts due to noise and reconstruct the graph. Figure 8b shows the graph reconstructed from the centroids shown in Figure 8a. We can see that we were able to remove artifacts and infer the camera rotation which is an essential step to correctly decode the content.

Decoding. The corrected graph from the previous step is next converted to a binary matrix by converting the angle information of each centroid into ones and zeros.

In the current implementation, one block of ciphertext has dimensions 10×10 bits (see Figure 6(c)). The first 16 bits of the block represent the coordinates i and j of that block in the frame, while the last 12 bits of the block represent a checksum. This checksum is the truncated output of AES-128 applied to the coordinates i, j of the block. We know we have found a valid block of ciphertext when computing AES-128 over the first 16 bits of a block, we get the same checksum found in the last 12 bits of that block. If the



(a) Rotated centroids

(b) Rebuilt graph

Figure 8: *Rebuilding a graph from noisy centroids with unknown rotation*

checksum fails, we move one column to the right in the matrix and perform the same check on the new block until we have tested all the bits of a 12x12 matrix. If a valid block is found, each block of the matrix is decrypted. Finally, the decrypted content from all the decrypted blocks is displayed as an overlay on the phone camera view.

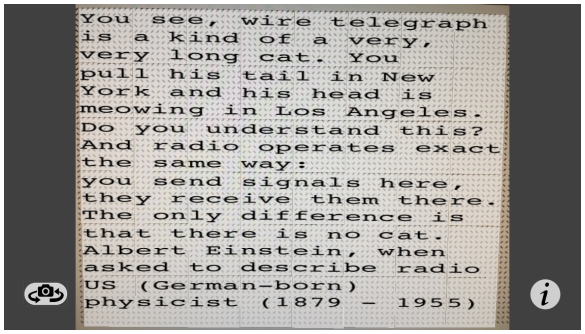


Figure 9: *Decoding and decryption of 4,800 bits of ciphertext with Moiré noise*

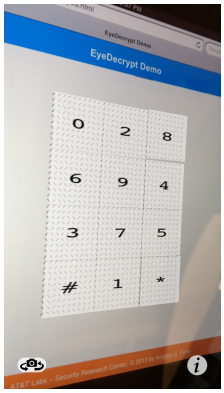


Figure 10: *Decoding and decryption of a randomized keypad*

5 Performance Evaluation

As mentioned in the previous section, each block of ciphertext has a dimension of 10×10 bits. Figure 6(c) shows the structure of the block. The first 16 bits are used to encode the coordinates i, j corresponding to the position of the block in the document, while the last 12 bits are used for the block checksum. This leaves 72 bits of encrypted payload per block. Given that the visualizable encryption scheme is length-preserving (uses a one-time pad approach; see Section 3.1), we can encrypt 72 bits of data in each block. In the case of text, this means that we can encrypt nine characters per block of ciphertext.

In general, users will hold their device so that multiple blocks will be decoded at once, that is, a multiple of nine characters will be displayed at once to the user. Increasing the ciphertext block size would reduce the overhead due to block coordinates and checksum. A larger block size, however, would also mean that users have to hold their devices at a larger distance from the encoded image in order to fit at least one block

in the camera field of view. The larger distance would add additional noise, possibly leading to a higher probability of decryption failure.

Figure 9 shows the correct decoding and decryption of 4,800 bits of ciphertext displayed on a computer screen, where the decoding was successful despite the presence of Moiré patterns. In such case, the decoding took an average time of 250 milliseconds (i.e., 4 frames per second). This time, however, largely depends on the camera resolution being used and the number of cipher-blocks visible in the same frame. For the decoding shown in Figure 9, we used a resolution of 640x480 pixels and decoded 48 cipher-blocks in a single frame. In the case of a numerical keypad, as shown in Figure 10, the visual encoding includes 12 cipher-blocks in a single frame which we were able to process at a rate of about 18 frames per second.

The resolution of the camera plays an important role in *EyeDecrypt*. On one hand, higher resolution means that the camera has better accuracy in reading the image, and hence a larger number of cipher blocks can be correctly decoded in a single frame. Also, decoding can happen at greater distance. On the other hand, higher resolution means that the device has to process a larger image, i.e., more information, and the decoding takes longer. Furthermore, with higher resolution Moiré noise gets amplified as well so that accuracy does not increase linearly with resolution. A consequence of this is that decrypting content in printed form is much more reliable and accurate than decrypting electronic content where Moiré noise is present. Different camera resolutions imply a tradeoff between accuracy, decryption speed and maximum decoding distance.

The visual encoding based on dataglyphs could be easily enhanced to increase the amount of information it conveys. As we mentioned in Section 3.3, we currently use only two angle values to encode ones and zeros—namely, -45° for bit 1 and $+45^\circ$ for bit 0.

Naturally, the problem in having only two possible values is that less information can be conveyed in the dataglyph encoding. In particular, by using 0°, $+45^\circ$, -45° and 90°, each dataglyph could encode two bits of information. This, however, would make dataglyphs less resilient to noise. Other ways to enhance dataglyphs would be by using different colors and sizes so that for each dataglyph we can now specify angle, color and size. If we assume four possible angles, four independent colors and two different sizes, one dataglyph could now convey 5 bits of information. Enhancing the visual encoding so to convey more information as described above is left for future work.

6 Related Work

Human-computer interactions almost universally involve human vision, and so *EyeDecrypt* or any other HCI technology is subject to the security limitations of vision. In particular, vision is susceptible to interception, by means as simple as shoulder surfing or as sophisticated as capturing the reflection of images from the surface of the eye [18, 1, 2]. *EyeDecrypt* protects against many interception attacks by encrypting the visual channel between the encoding and a personal device. The visual channel from the personal device to the eye remains unprotected by *EyeDecrypt* itself; it is intended for use only when the personal device remains inaccessible to adversaries. When eye reflections are a concern but it is still desirable to use the visual channel, we know no protection short of an enclosed display. *EyeDecrypt* is compatible with such a display.

On the other hand, vision has some inherent security advantages. Humans generally know with certainty what physical object they are looking at (as opposed to what device has sent them a wireless transmission), and vision is resistant to active tampering. For example, there are a few techniques to overload camera sensors but a user can detect this by comparison with their own vision. Consequently, visual encodings are widely use in security for key establishment, wireless device pairing, and trusted display establishment [16, 24, 25, 6]; *EyeDecrypt* can be used for these purposes as well.

Computer vision researchers have been studying visual encodings for decades, seeking to increase their capacity and their robustness against lens distortion, image compression, non-uniform lighting, skew, motion blur, shake, low camera resolution, poor focus, etc. [15, 29, 20]. Techniques for zooming into visual encodings include recursive grids of barcodes [21] and nested barcodes [27]. Fourier tags [23] handle the

opposite case of zooming out: at close distance, they can be completely decoded, but as the camera zooms out, fewer bits can be decoded; low-order bits are lost before high-order bits.

Encrypted content is often used in single barcodes (e.g., [3]) but less often in multiple barcodes. Fang and Chang describe a method for encoding a large encrypted message in multiple barcodes [6]. All barcodes must be decoded and decrypted to view the message, and the barcodes must be presented in a known order, unlike our blocks which can be viewed independently. They are concerned with *rearrangement attacks* in which the adversary is able to rearrange the order of the barcodes so that the message cannot be decrypted. Their solution is to use a visual cue (numbers in sequence) over which each barcode is interleaved. The user can manually verify that the barcodes are in the correct order, while the device handles the decoding and decryption of the actual data. In our solution, visual clues are not necessary, as the frame and block numbers of adjacent regions are directly encoded and can be read and compared automatically by the device.

Many defenses against shoulder surfing during PIN entry have been proposed; we discuss a representative sampling here. We emphasize that unlike *EyeDecrypt*, these systems do not encrypt the device display, so they are not appropriate for *displaying* private information, only entering it.

EyePassword [14] and Cued Gaze-Points [8] are two systems that use gaze-based input for password/PIN entry. These systems require the public device (e.g., an ATM) to have a camera and they work by computing the point on the screen that the user is looking at. In the Cued Gaze-Points system PIN entry works by the user selecting gaze-points on a sequence of graphic images. In EyePassword, the user gazes at a standard onscreen keyboard. The key assumption in both cases is that the adversary does not see the input at all (the adversary does not have a view of the user's eyes). In contrast, *EyeDecrypt* assumes that the adversary can see the input but only in obfuscated form (randomized and encrypted).

Roth *et al.* [22] require users to enter PINs via *cognitive trapdoor games*, e.g., a sequence of puzzles that are easy to solve (by an unaided human) with knowledge of the PIN, but hard to solve without it. Their scheme emphasizes useability and is intended only to defend against attackers that are unaided humans (for example, with human short-term memories). Unlike gaze-entry systems, and similar to *EyeDecrypt*, it can work without modifying ATM hardware.

In the ColorPIN system [5], a user's PIN is a sequence of colored digits, and the ATM displays a ten-digit keypad where each digit appears with three colored letters. For example, the digit "1" could appear above a black "Q," a red "B," and a white "R," and the user would enter "black 1" by hitting "Q." Each letter appears with multiple digits, so that a sequence of letters is associated with multiple sequences of digits. A shoulder-surfing observer thus gets partial information about the PIN (e.g., for a four-digit pin the observer knows that it is one of $3 \times 3 \times 3 = 81$ possibilities). *EyeDecrypt*'s visual encryption protects against this sort of leakage.

MobilePIN [4], like *EyeDecrypt*, uses a trusted personal device to aid PIN entry. In MobilePIN, the ATM displays its wireless address and authentication token onscreen as a QR code, and the user reads the code using the camera of the personal device. The personal device can then establish a secure wireless connection between with the ATM (secure pairing using the visual channel). The user enters her PIN on the trusted personal device, which transmits it to the ATM over the wireless channel. MobilePIN therefore has similar assumptions as *EyeDecrypt*, except in addition it assumes that the ATM is equipped with a radio.

Most other shoulder-surfing-resistant PIN entry methods involve changing the authentication process, e.g., by using graphical passwords or security tokens, or by requiring network connectivity or device pairing.

Naturally, *EyeDecrypt* is related to the cryptographic technique known as *visual cryptography* ([17] and follow-ups), which allows visual information (pictures, text, etc.) to be encrypted in such a way that decryption becomes a *mechanical* operation that does not require a computer, such as for example over-imposing two (transparent) images in the Naor-Shamir visual secret-sharing scheme.

Finally, *EyeDecrypt* has the additional ability to ensure that only legitimate users can view the information that is openly displayed, and in that sense bears some similarity to broadcast encryption ([7] and numerous follow-ups), with closely related applications such as pay-TV. A fundamental difference in *EyeDecrypt* is the public-view nature of the rendering device.

7 Summary and Conclusions

In this paper we introduced *EyeDecrypt*, a novel technology aimed at protecting content displayed to the user as well as interactions the user has with the system (e.g., by typing). In particular, we do not trust the device the user interacts with as it may have been compromised (e.g., root-kits, key-loggers) nor do we trust the user's environment. ("shoulder surfing"). Although we presented a visual encoding scheme based on Dataglyphs, *EyeDecrypt* can easily support any other visual encoding. It protects electronic content (e.g., displayed on a computer screen or a smartphone display) as well as non-electronic content (e.g., passports, medical records). *EyeDecrypt* does not require network connectivity to operate except for the initial key exchange with the content provider.

We envision *EyeDecrypt* being applied to very different scenarios. For example, *EyeDecrypt* can protect interactions users have with their laptops or smartphones (i.e., running the *EyeDecrypt* app on Google Glass); *EyeDecrypt* can protect users when buying in stores using mobile payment platforms (e.g., Square) where they have to input their PIN on a store device. Similarly, *EyeDecrypt* could be used to encrypt personalized ads in public settings (e.g., showing personalized ads in a movie theater) without violating users privacy. If the human eye can see it, *EyeDecrypt* can protect it.

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A Proofs

We repeat the statements of the claims here for convenience.

Theorem 1 *The visualizable encryption scheme $\mathcal{E}$ in Construction 1 is CCA-secure according to Def. 3.*

Proof sketch. The proof follows by describing a sequence of hybrid arguments from the security definitions of F, $\mathcal{H}$, and MAC. We next sketch the sequence of games that gives us the proof.

- Game 0: This is the original ExpVisIND-ATK experiment.
- Game 1: Game 1 proceeds identically to Game 0, except that Check(view) is modified as follows. Check(view)$'$: Proceed as in Check(view), but output 1 if and only if for all ℓ, ℓ', if $H(f_\ell, i_\ell) = H(f_{\ell'}, i_{\ell'})$ then $m_\ell = m_{\ell'}$. Game 1 and Game 0 will proceed identically, unless the adversary finds a strong collision in H.
- Game 2: Game 2 proceeds as Game 1, except that $F_{K_{\mathsf{PRF}}}$ is replaced by a random function R with the same range and domain. The fact that Game 2 and Game 1 proceed identically (except with negligible probability) follows from the pseudo-randomness of F.
- Game 3: Game 3 proceeds as Game 2, except that we further modify Check(view) to output 0 if the adversary has queried the decryption oracle on two ciphertexts $C = (f, i, C_0, \tau)$ and $C' = (f, i, C_0', \tau')$ where $(C_0, \tau) \neq (C_0', \tau')$, and both queries resulted in non-$\perp$.

This concludes the proof. □

Theorem 2 *Let* $\mathsf{Leak}(S) = v$. *Then, the* EyeDecrypt *scheme given in Construction 2 is* Leak*-secure according to Definition* 1 *if $\mathcal{E}$ is a* CPA*-secure visualizable encryption scheme.*

Proof sketch. We prove the theorem by reducing the security of the *EyeDecrypt* scheme to the security of $\mathcal{E}$. Let Adv be an adversary that breaks Leak-security of *EyeDecrypt*. Then, we construct Adv' that breaks the CPA-security for multiple messages of $\mathcal{E}$. Then, by Claim 4, we obtain the security of *EyeDecrypt*.

Our adversary Adv' works as follows. Initially, Adv' simulates $\mathsf{EyeDecInit}(1^n)$ except that no encryption key is generated. Adv' then simulates Adv. To answer a query (x, m) to the LeakST oracle, Adv' works as follows. Adv' computes $(t_1, \ldots, t_n) \leftarrow g(\pi(x), m, \mathsf{frame}, \pi')$, and obtains $c_i = \mathsf{Enc}_K(j, i, t_i)$ for $1 \leq i \leq n$ by querying its EncCPA oracle. All other steps are identical to EyeDecEntry. Adv' then computes and returns $v' \leftarrow \mathsf{Encode}(c_1, \ldots, c_n)$ to Adv.

When Adv submits the challenge tuple $(x_0, m_0), (x_1, m_1)$, Adv' computes $\mathsf{frame}_b \leftarrow g(\pi(x_b), m_b, \mathsf{frame}, \pi')$ for $b \in \{0, 1\}$. If $\mathsf{frame}_0 = \mathsf{frame}_1$, then Adv' gives up, and outputs a random bit. Otherwise, Adv' submits $(\mathsf{frame}_0, \mathsf{frame}_1)$ as its challenge in the ExpVisIND-CPA experiment. Given a vector of ciphertexts $(c_1^*, \ldots, c_n^*)$, Adv' constructs the challenge ciphertext as above, and returns the encoded version to Adv. The simulation is concluded naturally.

Given the above construction, Adv' simulates Adv perfectly in the ExpEyeDec experiment, except when $\mathsf{frame}_0 = \mathsf{frame}_1$. However, in this case, Adv obtains no information about b in the challenge. Therefore, Adv' wins with the same advantage as Adv. □

Let $\mathcal{TL}$ be the class of functions defined as follows:

$$\mathcal{TL} \stackrel{\text{def}}{=} \{\mathsf{TL}(\cdot) | \mathsf{TL}(K, \pi, \mathsf{frame}, v, j, C^*) = ((K, \pi, \mathsf{frame}, f(v), j), \mathsf{Leak}_{\mathsf{act}}(K, f(v), C^*))\}$$

where $f : \mathcal{P}^{t_1 \times t_2} \to \mathcal{P}^{t_1 \times t_2}$ and $\mathsf{Leak}_{\mathsf{act}} : \mathcal{K}_{\mathsf{ED}} \times \{0,1\}^* \times \{0,1\} \to \{0,1\}^*$ is defined as

$$\mathsf{Leak}_{\mathsf{act}}(K, u, C^*) \stackrel{\text{def}}{=} \begin{cases} (\mathsf{EyeDecRead}(K, u), u) & \text{if } u_i \neq C_i^* \text{ for } 1 \leq i \leq n; \\ (\perp, u) & \text{otherwise.} \end{cases}$$

Theorem 3 *Let $\mathcal{TL}$ be as above. The* EyeDecrypt *scheme given in Construction 3 is $\mathcal{TL}$-secure according to Definition* 2 *if $\mathcal{E}$ is a* CCA*-secure visualizable encryption scheme.*

Proof sketch. The proof proceeds by a relatively straightforward reduction to the CCA-security of the underlying visualizable encryption scheme $\mathcal{E}$. Intuitively, the decryption condition in the definition of Leak prevents the adversary from querying the challenge ciphertext, unless she is able to change the block number of a ciphertext block. However, the position of the block that is obtained by decrypting the ciphertext is verified by $\mathsf{EyeDecRead}$ to match the position of the block in the field of view. □

B Constructions (cont'd)

Instantiating *EyeDecrypt* for secure PIN entry. Here we provide a complete to the secure PIN entry application. Given the *EyeDecrypt* constructions above, the missing piece is the function g which defines the functionality of the application. The exact nature of g will depend on the content being protected by the PIN. However, any PIN-protected application must allocate some of the output blocks of g to display a permuted numeric keypad. Suppose that the user input device is a (fixed) numeric keypad, and suppose (wlog) that blocks $t_1, \ldots, t_i$ in the plaintext visual frame are allocated to the permuted keypad. Let $P(\mathsf{pin}, \mathsf{data})$ be a program that, given the PIN and additional data, generates blocks $t_{i+1}, \ldots, t_n$. Then, $g(\mathsf{pin}, \mathsf{data}, \mathsf{frame}, \pi)$ computes $(t_{i+1}, \ldots, t_n) \leftarrow P(\mathsf{pin}, \mathsf{data})$, and computes blocks $t_1, \ldots, t_i$ by generating an image that shows the digit d written on the physical button that has the digit label $\pi^{-1}(d)$.

Key establishment. As mentioned in Section 1 and made evident by the definitions and constructions above, *EyeDecrypt* is symmetric key-based. Here we briefly sketch for completeness how the personal device running the *EyeDecrypt* app and the content generating server are able to share cryptographic keys in a secure manner. The personal device is provisioned with a master key using standard methods (e.g., by performing a key exchange with the content provider on a connection that is authenticated with the user's credentials). Then, whenever a new content is being viewed by the user, it will first contain a visually (e.g., QR-, Dataglyph-) encoded nonce; by applying a key-derivation function (KDF) to the per-document nonce the viewer and the content provider are able to derive the same key from the shared master key.[3]

[3] Naturally, in the case of active attacks, standard additional precautions need to be taken (e.g., to guarantee freshness, avoid replay attacks, etc.).