# On the Pitfalls of End-to-End Encrypted Communications: A Study of Remote Key-Fingerprint Verification

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# ABSTRACT

Many widely used Internet messaging and calling apps, such as WhatsApp, Viber, Telegram, and Signal, have deployed an end-toend encryption functionality. To defeat potential *man-in-the-middle* attackers against the key exchange protocol, the approach crucially relies upon users to perform a *code verification* task whereby each user must compare the code (a fingerprint of the cryptographic keys) computed by her app with the one computed by the other user's app and *reject* the session if the two codes do not match.

In this paper, we study the security and usability of this humancentered code verification task for a prominent setting where the end users are *remotely located*, and compare it as a baseline to a potentially less frequent scenario where the end users are in close proximity. We consider several variations of the code presentation and code verification methods, incorporated into representative real-world apps, including codes encoded as numbers or images, displayed on the screen, and verbally spoken by the users. We perform a carefully-designed human factors study in a lab setting to quantify the security and usability of these different methods.

Our study results expose key weaknesses in the security and usability of the code verification methods employed in the remote end-to-end encryption apps. First, we show that generally most code verification methods offer *poor security* (high false accepts) and *low usability* (high false rejects and low user experience ratings) in the remote setting. Second, we demonstrate that, security and usability under the remote code verification setting is *significantly lower* than that in the proximity code verification setting. We attribute this result to the increased cognitive overhead associated with comparing the codes *across two apps* on the same device (remote setting) rather than *across two devices* (proximity setting). Overall, our work serves to highlight a serious fundamental vulnerability of Internet-based communication apps in the remote setting stemming from human errors.

# **1** INTRODUCTION

Many widely deployed Internet-based messaging and calling applications, such as WhatsApp [14], Viber [12], Telegram [10] and Signal [8], have deployed an end-to-end encryption (E2EE) feature, to hide the communications from the attackers and even from the service providers. Using this approach, all the communication between the end users gets encrypted/authenticated with a key held only by the communication parties. To share the secret key, the end users run a key exchange protocol (e.g., [7, 9, 16, 35]) over the insecure public Internet (or a channel controlled by the application service provider). The key exchange protocol then results in an initial master key that is used subsequently to generate session keys for encrypting all the messages, including text, data, and voice. In contrast to typical client-to-server encryption or PKI-based secure communication (e.g., TLS), E2EE reduces the unwanted trust onto third parties (e.g., an online server), because such services may themselves get compromised, be malicious or under the coercion of law enforcement authorities. However, the key exchange protocol runs over unauthenticated insecure channel and is therefore susceptible to a Man-in-the-Middle (MITM) attack [1, 36]. To defeat potential MITM attacks against the key exchange protocol, E2EE apps compute a readable/exchangeable "security code" (a fingerprint of the key exchange protocol) that is used to provide end-to-end authentication.

The E2EE apps crucially rely upon the users to perform a *code verification* task whereby each user exchanges and compares the security code computed on her end with the one computed by the peer's device, and must *reject* the session if the codes *do not* match. In this context, the failure of the users in matching the codes (i.e., accepting completely or partially mismatching codes) will be catastrophic in terms of security as it will lead to the success of the MITM attacker and exposure of all communicated messages. The users are usually in possession of only their mobile devices using which the communication takes place, not any other devices or aids (such as paper-pencil), during this code verification task.

**Remote vs. Proximity Code Verification:** Security code verification has long been used in multiple security applications, primarily by the users that are located in a *close physical proximity* (e.g., in device pairing [27] and decentralized trust management [18] applications). However, Internet messaging and voice applications open up an important area of *remote communications* for people who are at distant locations, and have never met each other or are likely to start communicating using the apps before they meet in person.

The remote communication paradigm presents many challenges for code verification compared to proximity settings, especially due to the lack of physical interaction between the users. Therefore, the users are required to exchange the code over an auxiliary channel (e.g., a voice call or an out-of-band channel such as SMS and email), and then compare the codes *across two apps* (e.g., an SMS messaging app and the E2EE app) on the same device. Such "cross-app comparisons" might impose cognitive burden on the users, since they may be required to memorize the received code and compare it with the one displayed on the E2EE app. In contrast, in the proximity setting, code comparisons seem much simpler since the users are close by and compare the codes *across two devices*. Figure 1 and 2 depicts the proximity and remote settings, respectively.

**Our Focus–Security and Usability Study of Remote Code Verification:** In this paper, we study the security and usability of the human-centered E2EE code verification specially in a "remote setting". As a baseline, we compare the results with a "proximity



- 1. The users open the code verification screen and compare the computed code on their screen with the one computed on the peer's device ("cross-device code comparison").
- 2. The MITM attack succeeds if the two users fail to verify the mismatching codes.

Figure 1: Proximity setting (cross-device comparison)

setting". Although the security and usability of the code verification for various security applications in a proximity setting has been studied in literature before [21, 24, 27, 28, 34], to our knowledge, this is the first study of the code verification in a potentially more common remote setting in the context of end-to-end messaging and voice apps.

We study several remote/proximity code presentation and verification methods covering approaches deployed by popular E2EE apps, including, WhatsApp [14], Viber [12], Telegram [10], Signal [8], Threema [11], Wickr Me[15], and ChatSecure [2].

The founding hypothesis of our study is that remote code verification will be highly error prone for end users to perform due to the challenges associated with the remote setting outlines above. Our goal is not to argue on the attackers' ability to manipulate the code (via either tampering with the key exchange protocol or tampering with the out-of-band channel) or the amount of the manipulation, but rather to mainly determine how well the users can detect the mismatching codes in the presence of an attack that can partially manipulate the code.

To test this hypothesis, we design a human factors study in a controlled lab setting to measure the accuracy of the users in verifying the security codes. In the study, we present the participants with several matching codes, representing a benign, "attack-free" scenario, and mismatching codes representing an MITM attack case. For the security assessment, we use False Accept Rate (FAR) as our metric specifying instances of accepting the mismatching codes by the users. Failure of detecting the mismatching codes indicates the success of the attack.

For the usability assessment, we quantify user perception through System Usability Scale (SUS) questionnaires [20] and user perception ratings. As an additional usability metric, we use False Reject Rate (FRR) indicating the instances of rejecting the matching codes or the benign case by the users. Rejecting the benign cases may force the users to restart the protocol, and therefore, affects the usability of the system as the process would need to be repeated possibly annoying the users and delaying their communications.

For our security and usability assessments, we consider several representative remote code presentations and code verification methods, including, numeric and image codes exchanged over outof-band messaging channels (e.g., SMS and email), and verbally spoken codes exchanged over Internet calls. In the proximity setting, we consider the QR, compared almost automatically by the apps, numeric and image code, compared visually by the users.



- 1. The users open the code verification screen and transfer the code over an auxiliary channel.
- 2. The users compare the computed code on their E2EE app screen with
- the one received from the peer's device ("cross-app code comparison"). 3. MITM attack succeeds if the users fail to verify mismatching codes.

#### Figure 2: Remote setting (cross-app comparison)

While our study involves several code presentation and verification methods, the primary goal of our study is to compare the remote setting with the proximity setting and *not* to compare between different methods.

An Important Aspect of Our Study Methodology: Since our hypothesis is a negative one (i.e., we mainly expect the security of E2EE apps to be relatively poor in the remote setting), we methodically design our study tailored for the near best defense conditions. To prove our hypothesis, we recruit 25 young, educated, and technology-aware participants with reasonably good computer and security background to perform the code verification task willingly and diligently, and with full awareness of the security task, in a controlled observable lab environment. Given that in the existing applications, the code verification task is optional, in practice, the attack might be more difficult to detect, especially for average users who are not informed about the security risks of neglectful code verification, and may often skip or click through the code verification procedure. Moreover, in our study, we set the code verification task as the participants' only primary task. In real-world, in contrast, the code verification task will be a secondary task, the primary task being setting up the communications. Thus, if our study participants do not perform well with a single task at hand, the real-life would potentially do even worse since they have to manage two tasks whereby the security task may not be the high-priority task.

This study design is in contrast to the traditional usability study designs where the goal is to demonstrate that the system is secure or usable, in which case there is a need to prove security/usability by recruiting a large sample of users with average technical skills and emulating real-world conditions as much as possible.

**Our Primary Results:** Our results are aligned with our hypothesis, and show that the code verification methods deployed in E2EE apps suffer from several security and usability issues arising from human errors in verifying the codes in remote settings:

(1) Low Security for Remote Code Verification: All the remote code verification methods have high FARs, ranging on average from about 13% for image code verification to 40% for numeric code verification. Further, if the attacker has more control over the number of matching characters between an attacked code and a legitimate code, the success rate of the attack would increase. For instance, the FAR increases to about 60% in numeric code verification, when only one digit is mismatching between the codes. These error rates are exhibited by young educated

participants in a unidirectional authentication setting. In practice, users with more diverse background may perform worse than the participants in our study. Also, the error rate increases to *almost double* in a *bidirectional authentication* setting, where the attacker may deceive any of the two parties in an E2EE secure channel establishment session.

- (2) Low Usability for Remote Code Verification: The results also point out the usability issues with the remote code verification methods. Except for the audio-based code verification, the other remote schemes have about 20% FRR. Further, in terms of system usability scale and the users' personal ratings, results are indicative of a poor user experience underlying the remote setting (e.g., SUS scores around only 50%).
- (3) Remote Setting vs. Proximity Setting: As our baseline condition, we measured the security of the code verification in a proximity setting, which shows that users could successfully detect the benign and attack settings with negligible error rates. However, in a remote setting which is the primary model of the E2EE apps, the error rates—FAR and FRR—are (statistically) significantly higher. Moreover, the user perception ratings in the remote scenario were (statistically) significantly lower compared to the proximity setting.

Generalizability and Broader Impacts: Overall, we believe that our work highlights a serious fundamental vulnerability of a broadly deployed and extensively used representative class of secure Internet-based remote communication apps. This vulnerability does not arise from the underlying cryptographic protocol or the software implementation of the protocols, but rather from the human errors committed by naive users of these apps. It mainly stems from the fact that, in the remote setting, comparisons of security codes need to be performed across the apps, which is burdensome for the users and thus highly error-prone. Such cross-app comparisons also significantly impact the usability of the code verification process. Although our study focuses on many currently deployed apps for a larger impact to real-world systems, our work is generalizable in that it shows the security-usability pitfalls of cross-app comparisons broadly applicable to the fundamental design of remote E2EE code verifications.

Addressing this vulnerability and related usability issues will be a challenging problem, but we hope that our work will encourage the app designers to make necessary changes to their systems to improve the levels of security and usability in the face of human errors. Based on the results of the study, we also provide insights and future directions for the designers of the apps to improve the security and usability of their systems, without affecting the current threat models.

# 2 BACKGROUND

# 2.1 End-to-End Encryption Apps

Recently, several instant messaging (IM) and Voice over IP (VoIP) applications adopted the E2EE protocol to provide secure communication of messages/calls. Examples of such applications are Signal [8], WhatsApp [14], Facebook Messenger [5], Google Allo [6], Viber [12], Telegram [10], and Threema [11] (a more comprehensive list can be found in Appendix A.3).

Different E2EE protocols have been proposed and implemented by the apps targeting the specific needs and challenges facing the IM and VoIP communications. Off-the-Record Messaging (OTR) protocol [19] by Borisov et al. is an E2EE protocol specifically designed for IM communication, with the goal of perfect forward secrecy (PFS) through ephemeral key exchanges to avoid long-lived keys, authenticity of the parties, non-deniability of the messages, and confidentiality through encryption.

Many of the current E2EE applications are constructed on top of OTR, however, they adapted OTR to work with asynchronous transport (which is specific to the smartphone environment) [7]. The encryption protocol introduced by Open Whisper System is one of the leading protocols that was first developed by Signal [8], and later implemented in WhatsApp [14], Facebook Messenger [5], and Google Allo [6]. The protocol is based on OTR combined with Silent Circle Instant Messaging Protocol (SCIMP) [30] for improved forward secrecy. The protocol is also enhanced to allow asynchronous messaging, and to simplify non-deniability [4]. Viber [12, 13] and Telegram [9, 10] have also adopted similar protocols.

#### 2.2 MITM Attack Resistance

The encryption key in the E2EE applications is typically exchanged between the endpoints during an initial key exchange protocol over the insecure channel (or a channel fully controllable by the service provider) and is then refreshed during the message exchanges. The basic key exchange protocol is based on the well-known Diffie-Hellman (DH) key exchange protocol [3]. However, the basic Diffie-Hellman key exchange protocol is not authenticated and therefore is susceptible to the MITM attack. Hence, the applications add a manual authentication scheme, which we refer to as "code verification" to the key exchange to protect against MITM attack.

Regardless of the differences in the E2EE protocols developed by different apps, they all rely on the human users to perform this code verification task in an attempt to defeat the MITM attack. This human-centered task is the focus of our work.

# 2.3 Code Generation and Presentation

For authentication, users can compare the public keys (or a fingerprint/hash of the public keys) of other users over an auxiliary channel (e.g., an out-of-band channel such as text or email, or a human voice channel). To simplify the manual comparison, the public key or the fingerprint is encoded into a readable/exchangeable code. We refer to this code as "security code" or in short "the code".

Specifically, the generated code is presented as a human readable code or an exchangeable object. Often a long code is represented as blocks (or chunks) of few digit numbers for readability (e.g., 30-digit presented as 6 chunks of 5-digit numbers). Figure 8 in Appendix A.2 shows some of the common code presentations described here:

• **QR Code**: The code is encoded into a QR code. Since the QR code is automatically captured and compared by the app without relying on human user, it can contain the full public key of the parties. Figure 8(a) shows the QR code presentation for What-sApp, which includes a version number, the users' identifier, and the public key for both parties.

- Numeric: The code is presented as a sequence of numeric digits. WhatsApp, Signal, Telegram, and Viber use this form of presentation. Figures 8(a), 8(d), and 8(b) show the code in numeric presentation in WhatsApp, Signal, and Viber application.
- **Images**: The code is encoded into an image. Examples of such images are also presented in prior literature (e.g., [22, 31]). Telegram encodes the code in a shaded blue square as shown in Figure 8(c).

Usually a set of one or more of the mentioned presentation is used by the apps. Other encodings such as words [26], alphanumeric, Base32 and Base64, sentences, and phrases, have also been proposed in literature, however, they are not being used at this moment by any of the popular E2EE apps we study in this paper.

#### 2.4 Code Exchange and Verification

There are two notable approaches to verify the security codes in security applications, Copy-Confirm and Compare-Confirm as introduced in [34]. In Compare-Confirm, the code is displayed on each peer's screen, they exchange their respective code, and both accept or reject the connection by comparing the displayed and received code. In Copy-Confirm, one party reads the code to the other party, who types it onto his/her device, and gets notified whether the code is correct or not. The E2EE apps follow the Compare-Confirm.

In a proximity setting, where the two parties are physically colocated, the code verification can happen by visually matching the codes (e.g., comparing the 60-digit numerical code in WhatsApp, or comparing the graphic in Telegram app). Some apps provide automated code comparison by embedding the code in a QR code that can be captured and compared by the app.

In a remote setting, the two parties can exchange the codes over an out of band channel, for example, through a text message, or an email. This approach is very common among several apps such as Whatsapp, and Signal. Another method of code exchange in a remote setting is transferring the code over an authenticated channel, for example, through a voice call (e.g., used by Viber). This approach assumes that the human voice channel over which the code is exchanged is authenticated.

#### 2.5 Threat Model

In this work, we study the common threat model followed by the E2EE applications. It is a setting where two trusted parties, Alice and Bob, intent to start a secure communication over an insecure channel using only their mobile devices. In this threat model, Alice's and Bob's devices are trusted. However, the communication channel over which the key is exchanged is assumed to be fully controlled by the attacker. That is, the attacker can intercept and modify the key exchange messages.

The key exchange protocol is followed by an authentication phase to defeat MITM attacks. In the proximity setting, the code exchange channel is physically-authenticated since the users are in close proximity and can verify each other's identity. In the remote setting, the channel over which the code is transferred should somehow be authenticated. An example of a supposedly authenticated channel is out of band messaging (e.g., SMS, email or social media). Another authenticated channel used by the applications is voice channel. The assumption is that the users can recognize each other's voice, and therefore, can authenticate each other when the code is spoken. However, as we discuss below, even the out-of-band or voice channels may be tampered with, at least partially.

Attacker Capability: We consider two levels of capability for the attacker. First, we assume that the attacker does not have any control over the out-of-band or voice channel. This assumption is generally made by the app designers and motivates them to transfer the code over such channels. Even though the attacker has zero control over the channel, she can interfere with the key exchange protocol and run a preimage attack<sup>1</sup> on the security codes to generate attacked codes that are the same or at least partially similar to the legitimate security codes (in a hope that the user accepts it due to similarity with the legitimate code). The attacker's goal is to guess the public key pairs that generate codes with maximum similarity to the protocol's legitimate security code. However, the computational cost limits the success level of the attack. This level of capability is considered for the attacker in several prior studies about public key fingerprint security [21, 25].

Second, we assume that the attacker has control over some part of the messages transferred over the out-of-band or voice channel. That is, the attacker may be able to tamper with the exchanged codes partially. The attacker first interferes with the key exchange protocol, which results in two different codes at the two parties. Then during the code exchange, the attacker tampers with the messages transmitted over the out-of-band or voice channel by inserting or modifying one or more bits of the transmitted code. For example, if  $code_A = 1234$  and  $code_B = 4567$ , the attacker may change  $code_B$ , while it is being transmitted to Alice, to 1534 (a code that is different from  $code_A$  in only 1 digit).

As an example for the voice-based channel, the attacker may have access to some pre-recorded samples of the user's voice, speaking some of the digits that appear in the code (1, 3, and 4 in  $code_A$ , but not 2). The attacker then tampers with the voice messages of Bob, while Bob reads the code to Alice, and injects those pre-collected samples (i.e., change 4 to 1, 6 to 3, and 7 to 4) so that  $code_B$  received by Alice is 1534. Such an attack is known as a voice MITM attack [32], which allows the attacker to tamper with the voice channel by mimicking users' voice or playing the pre-recorded samples.

Another instance of such part manipulation pertains to altering the codes transmitted over the text-based channels, such as SMS, emails, or even social media posts. Most of the E2EE apps allow exchanging and sharing of the codes on different messaging and social media applications. This gives the attacker the opportunity to compromise any of these applications or the user accounts to modify the exchanged code. Also, email and SMS spoofing<sup>2</sup> is a common problem that would make such attacks highly feasible in practice. Since some of these apps have a character limit (e.g., Twitter and SMS apps), they may not be able to accommodate the code in one message, and therefore have to split the code into few parts. If the attacker is able to modify some of these fragmented parts, the attacked code appear to be similar to the legitimate code.

In summary, we allow these two levels of capability for the attacker, that is, the attacker may have zero or partial control over the code, and can modify it partly via a pre-image attack indirectly

<sup>&</sup>lt;sup>1</sup>A preimage attack on hash functions tries to find a message with a specific hash.

or via tampering with the auxiliary channel directly. It is worth noting that the attacker who has *full control* over the code may change the code such that it completely matches a legitimate code and be impossible for the users to detect. In this light, such a full manipulation attack is not the focus of our study, since this attack may have 100% success rate (unless a user mistakenly rejects this "attacked" matching code, which as our study shows happens up to only about 20% of the times).

# **3 STUDY PRELIMINARIES AND GOALS**

## 3.1 Study Objectives

The specific goals of the study are outlined below:

**Robustness:** *How accurate are the users in verifying the code*? Robustness directly impacts two important properties of the system: security and usability.

- *For security assessment*, we are interested in determining how often users accept mismatching security codes. *False Accept Rate (FAR)* denotes the probability of incorrectly accepting such instances. False acceptance implies the success of the MITM attack and the compromise of the system.
- For usability assessment, we are interested in finding out how often users reject matching security codes. False Reject Rate (FRR) represents the probability of incorrectly rejecting benign instances. False rejection forces the users to restart the protocol affecting the overall usability.

**User Experience and Perception:** *How usable do the users find the code verification task.* We define the following parameters to measure the usability of the system:

- *System Usability Scale (SUS):* How easy or difficult do the users find the system? Can the user easily learn how to use the system? Do they need the support of a technical person?
- *Comfort:* How comfortable are users with the system?
- *Satisfaction:* How satisfied are the users with the system in verifying the codes?
- Adoptability: Are they willing to use the system in real-life?

# 3.2 Selected Applications

We selected a collection of highly popular and representative apps, based on the *number of installations and ratings*, to comprehensively cover different code verification methods including QR, textual, image, and voice verification. In the textual presentation, we only picked numeric presentation, given that it is the most commonly adopted method.

To cover all the state-of-the-art code presentation and verification methods, and based on the popularity of the apps, we picked WhatsApp (v.2.16.201), Viber (v.6.2.1251), Telegram (v.3.10.1), and Signal (v.3.15.2) in our study. The complete list of studied apps is described in Appendix A.3.

**App #1—WhatsApp:** WhatsApp displays the code as a QR code and a 60-digit number represented as 12 blocks of 5-digit number. The QR code includes a version number, the user's identifier, and the identity key for both parties. WhatsApp generates its 60-digit (480-bit code by concatenating the 30-digit fingerprint of the users' public Identity Keys<sup>3</sup>. To calculate the fingerprint, iteratively SHA-512 of the public key is computed for 5200 times and the first 30 bytes of the final result is output as the security code.

Users have two options to verify each other's identity. First, they can scan the QR code of the peer user; the app then compares and verifies the codes. This feature is helpful if the users are in close proximity. Second, the app allows the users to exchange the code through email or messaging applications and then manually verify the code. This feature can be used in the remote setting.

**App #2—Viber:** In Viber, both devices perform DH key exchange using their own private keys and the peer's public key. The DH result is hashed using SHA256 and trimmed to 160 bits. The code is encoded as 48 digits, displayed as 12 blocks of 4-digit numbers.

To verify the code, the two parties should make a Viber call, during which they can open the verification screen. The users verbally announce the displayed code to each other and validate the identity of the peer if the spoken code and the displayed code match. Viber does not support any other out-of-band or automated code verification method.

**App #3–Telegram:** Telegram generates the code by using the first 128 bits of SHA1 of the initial key (generated when Telegram Secret Chat is first established) followed by the first 160 bits of SHA256 of the key used when the Secret Chat is updated to layer 46<sup>4</sup>. The code is displayed to the users as a shaded blue image along with a string of 64 hexadecimal characters. Telegram does not provide a facility to send the code directly from the app.

**App #4—Signal:** The version of Signal used in the study displays the full 256 bits of the public key hash as a hexadecimal string and a QR code. The users can scan the QR codes to verify each other's identity in a proximity setting or transfer it over an out-of-band channel in a remote setting.

## 3.3 Study Assumptions and Hypotheses

Our hypothesis is that the apps offer a low security level, due to human errors, in verifying the code and that the users find the code verification to have poor usability.

Since our hypothesis is negative (apps provide a low level of security and poor usability), we design our study tailored for the near best possible success of the attack. We assume that the applications inform the users about the E2EE feature and importance of the code verification task. We also assume that the users are required to perform the code verification task. Also, we target young, and educated users who are technology-aware. We also assume that the users perform the code verification task whether they are planning to start a conversation with a peer or not. This assumption implies that users consider the code verification task as a primary task. In practice, the primary task of the users is to pursue a conversation and only the secondary task is to verify the code.

All these assumptions make the attack more difficult since: (1) the users are well-informed about the security risks associated with incorrect code verification, (2) the users are enforced and willing to verify the code, (3) the users perform the task carefully, and (4) they are only focused on a single task of code verification.

<sup>&</sup>lt;sup>3</sup>Identity Key is the long-term Curve25519 key pair generated at install time

<sup>&</sup>lt;sup>4</sup>In Telegram, the layer number is initialized at 8 when the Secret Chat is created and is updated after receiving packets (for details, see https://core.telegram.org/api/end-toend.)

## **4 STUDY DESIGN**

Our study was designed to evaluate the security and usability of the code verification according to the objectives defined in Section 3.1. The study was approved by our Institutional Review Board and standard ethical procedures were followed, e.g., participants being informed, given choice to discontinue, and not deceived.

# 4.1 Code Verification Challenges

We considered two types of code verification challenges in the study, representing benign and attack cases:

**Mismatching Codes:** For each set of code verification tasks, we defined three instances of mismatching code pairs representing the attack setting<sup>5</sup>. To study the accuracy of the participants in recognizing the attacked session, except for Telegram app<sup>6</sup>, we created a code with only one mismatching character, a code with one block of mismatching characters (the position of the mismatching character/block(s) was randomly selected), and a completely incorrect code. We recall that the threat model allows partial manipulation of the codes through the preimage attack or access to part of the messages transferred over the auxiliary channel.

**Matching Codes:** For each set of code verification tasks, we had two instances of matching codes representing the benign case.

#### 4.2 Experimental Setup and Tested Schemes

To support our study, we designed a survey using the LimeService platform. The survey presented all the information and instructions to the participants and guided them to complete the tasks.

To perform the tasks, each participant was provided with an Android phone. The four applications (WhatsApp, Viber, Telegram, and Signal) were setup on the phone and five contact names and numbers, associated with the study examiner, were stored in the contact list. Android is one of the most popular platforms and all of our participants perfectly knew how to operate the smartphone.

The examiner (we call him Bob) acted as the peer in the communication set-up only to read, transfer, or to show the security codes to the participant (we call her Alice). In the benign case, Bob displayed or read the correct codes, while in the attack case, he showed incorrect codes.

In the proximity setting, Alice and Bob sat next to each other. The proximity setting consisted of three types of code verification methods summarized in Table 2 (Appendix A.2):

- P1-QR Signal QR Code Verification: In this task, Alice opens the code verification screen for each contact on the Signal app to capture the QR code for Bob. The app then compares the internal copy of Alice's code with the captured one.
- P2-Image Telegram Image Code Verification: Alice and Bob open the code verification screen for a particular conversation. Bob shows the image to Alice who should compare and verify the image.
- P3-Numeric WhatsApp Numeric Code Verification: Alice and Bob open the code verification screens for a particular



Figure 3: Protocol Flow of the user study.

conversation. Bob shows the screen to Alice who observes and verifies the code.

In the remote setting, Alice and Bob sat in two different rooms to simulate a remote communication scenario. The remote setting consisted of three types of code verification methods (summarized in Table 2, Appendix A.2):

- **R1-Audio Viber Audio Code Verification**: In this method, Alice calls the given contacts on the Viber app. Bob picks up the Viber call, and the two open the code verification screens. Then, Bob speaks the code and Alice compares the spoken code and the displayed one.
- **R2-Image Telegram Image Code Verification**: In this method, Bob sends the image in a text (SMS) message to Alice. Alice compares the code on the Telegram screen with the code on the text message screen by switching between the two apps. That is, Alice needs to open one app to memorize the image code, then move on to the second app and compare the code.
- R3-Numeric WhatsApp Numeric Code Verification: This
  type of code verification works similar to the image code verification method. The only difference is that the numeric code is
  exchanged in a text message or email, and Alice compares the
  numeric code on the WhatsApp screen with the code on the text
  message screen by switching between the two apps.

# 4.3 Study Protocol

Figure 3 provides the high-level design protocol flow of the study. After a brief introduction to the study, the participants were navigated by the examiner to a computer desk that had the survey web-site open, and were provided with a smartphone. The participants were informed about the E2EE feature and the risk of accepting incorrect codes. They were asked to follow the instructions on the survey website and perform the tasks diligently as presented on the website. The study was composed of three phases: the pre-study, the main study, and the post-study phase.

*4.3.1 Pre-Study Phase.* The pre-study phase consisted of several qualitative and quantitative questions grouped into three categories, as summarized below:

<sup>&</sup>lt;sup>5</sup>Implementation of the MITM attack is not within the scope of this work and all of the codes were generated manually to emulate the attack.

<sup>&</sup>lt;sup>6</sup>Since we did not have access to the Telegram image generation tool and the encoding from the fingerprint to the image was unknown to us, we do not have control over the number of incorrect/mismatching characters.

**Demographics**: The participants were asked to fill out a demographic questionnaire. These questions polled for each participant's age, gender and education.

*Technical Background*: The participants were asked about their general computer and security skills to uncover their initial attitude towards security.

*Familiarity with the Topic*: To understand the participants' experience in performing the tasks, they were asked about their familiarity with messaging applications and the E2EE feature offered by the apps.

4.3.2 Main-Study Phase. During the main-study phase, we presented several code verification challenges to the participants. We also asked them to rate their experience, after finishing each set of the tasks, for a particular app. The six groups of questions (Table 2, Appendix A.2) were presented *randomly* using a 6x6 Latin Square and the questions within each group were also *randomized*. We group the main-study questions into two sets:

*Code Verification Task:* For each set of challenges, we asked the participants to follow the instruction on the website to verify the code for a given contact. The list of the verification methods and the steps they need to take to verify the code is presented in Table 2 (Appendix A.2). The code verification in our study was performed in one direction (i.e., only the participant compared the code, not the examiner).

*Feedback Questions:* After completing a set of code verification tasks for a particular application, we asked the participants to rate their experience by answering feedback questions, including System Usability Scale (SUS) questions [20], and three additional 5-point Likert scale question polled for their comfort, satisfaction, and need for the system. A complete list of the SUS question is included in Appendix A.1. The other three feedback questions were as follows:

- How comfortable are you with this code verification method?
- How satisfied are you with this code verification method?
- Do you want to use this feature in the future?

4.3.3 *Post-Study Phase.* In the post-study questions, we asked the participants about their opinion about the code verification task. We also asked them if they found any of the code verification methods easier or more difficult than the others.

# 5 ANALYSIS AND RESULTS

#### 5.1 Pre-Study and Demographics Data

We recruited 25 participants from a pool of students in our university. Participation in the study was voluntary and the time allocated to each participant to finish the study was 1 hour. There were 54% males and 46% females among the participants in our study. Most of the participants were between 18 and 34 years old (34% 18-24 years, 58% 25-34 years, and 8% 35-44 years). 9% of the participants were high school graduates, 9% had a college degree, 46% had a Bachelor's degree and 36% had a Graduate degree. 34% of them declared that they have excellent, and 62% declared they have good, general computer skills. 17% had excellent, 50% had good and 33% had fair security skills (demographic information is summarized in Table 3) in Appendix A.2. About half of the participants said they are extremely to moderately aware of the E2EE feature on the apps. Based on the collected data, the most popular apps among the participants in our study are WhatsApp, Viber, Telegram, and Signal (these apps are also the most popular in the market according to Table 4). Although the participants declared they have heard about the E2EE feature and used it on the apps, it seems they had not performed the code verification task much.

#### 5.2 Proximity Code Verification Analysis

In our study, we tested the code verification task in the proximity setting with QR code of Signal (P1-QR), image code of Telegram (P2-Image), numeric code of WhatsApp (P3-Numeric). The FAR and FRR for the proximity setting are reported in Figure 4.

**Error Rates:** *Task P1-QR:* For the QR code presentation, the code verification task is performed almost automatically. The participants captured the QR code, and after the app verified the code, they reported the success or failure of code verification on the survey form. Since in this model the participant is not involved in the task of manual code comparison, we expected the error rates (both FRR and FAR) to be near zero. This approach can be considered as the baseline of the user study. Indeed, as expected, FRR (instances of rejecting a benign session) for the QR code verification is 0%. However, the FAR (instances of accepting an attack session) is 1.34%. This error happened when one participant incorrectly reported that the code verification was successful even though the app deemed it as not matching.

*Task P2-Image:* For the image code verification method, the participants compared the image displayed on his/her screen with the one displayed on the examiner's screen, and verified whether the codes on the two devices match or not. Using this method, the FRR was 0%, which indicates that none of the benign cases was rejected. The FAR was 2.67%, only slightly higher than FRR.

*Task P3-Numeric:* For the numeric code verification method, the participant compared the code displayed on his/her screen with the one displayed on the examiner's screen, and verified whether the codes on the two devices match or not. Similar to the image code verification, the FRR was 0% while the FAR was 2.67%.

The Friedman test to compare the FAR among multiple proximity code verification methods rendered a Chi-square value of 1.400 and was not statistically significant.<sup>7</sup>

**User Experience and Perception**: The SUS for the QR code method (66.51) was the highest among all the methods in the proximity setting. A system with SUS score of below 71 is considered to have an "OK" [17] usability. Since the involvement of the users in QR code verification was less compared to the other two methods, we expected the users to prefer this method over the other two methods. To measure the other user perception parameters, the participants answered Likert scale questions, rating the comfort, satisfaction, and adoptability from 1 to 5. The answers to this set of questions are summarized in Figure 5. It seems that, after QR code, the numeric code has the next best user perception ratings.

A Friedman test was conducted to compare SUS, comfort, satisfaction and adoptability, among multiple proximity code verification methods and rendered a Chi-square value of 1.167, 1.214, 1.578, and 4.252 respectively, which were not statistically significant.

<sup>&</sup>lt;sup>7</sup>All results of statistical significance are reported at a 95% confidence level.



Figure 4: The error rates in performing the code verification task in proximity setting.



Figure 5: Mean (Std. Dev) of user perception in performing the code verification task in proximity setting.

The results of the user study shows low error rates (both FRR and FAR) and moderate user perception ratings for all the approaches in the proximity setting, demonstrating that the tested E2EE fared quite well in this setting.

#### 5.3 Remote Code Verification Analysis

In the remote setting, we tested audio-based code verification of Viber (R1-Audio), image code presentation of Telegram (R2-Image), and numeric presentation of WhatsApp (R3-Numeric). The FAR and FRR for the remote setting are reported in Figure 6.

**Error Rates:** *Task R1-Audio:* In this task, the code was spoken by the examiner over a Viber call and the participants compared it with the code displayed on their device. The FRR was 0% in this setting, which shows that none of the valid sessions was rejected by the participants. However, the average FAR was on average 26.45%. The result also suggests that the error rate increased as the number of mismatching characters decreased as shown in Table 1 (i.e., the success rate of the attack would increase if the attacker has more control over the number of matching and mismatching characters in the code). Further, we observe that even if the attacker can generate a code that is different from the valid code in only one block, the attacker can compromise about one third of the sessions.

*Task R2-Image:* For the remote image code verification method, in which the image was sent as a text message, the FRR was 18.94%. This result might lower the usability of the system, since the users would need to repeat the key exchange protocol and the code verification process. The FAR was 13%, which indicates that the participants could not detect some of the attack sessions. In general, it seems that the users had some difficulty comparing the images. Perhaps they could not memorize and compare the images that appeared on two different apps (i.e., text message app, and Telegram app). Since we did not have access to Telegram image generation source code or tool, we did not have control over the number of mismatching characters.

*Task R3-Numeric:* For the numeric code verification method, the examiner sent the code in a text message and the participants compared it with the copy of the code that their app generated. The



Figure 6: The error rates in performing the code verification task in remote setting.



Figure 7: Mean (Std. Dev) of user perception in performing the code verification task in remote setting.

result shows that the users could not easily compare the numeric codes across the E2EE and SMS app. The average FRR was 22.94% and the average FAR was 39.69%. Further, the FAR increased when the number of mismatching characters decreased, as illustrated in Table 1. We saw that the attacker can compromise about half of the sessions, if there is a block of mismatching characters in the code. The numeric code verification method is deployed by many apps and is one of the major code verification methods used in the remote setting. The high error rate in comparing the code shows that such comparison offers low security and possibly low usability.

The Friedman test to compare the FAR among multiple remote code verification methods rendered a Chi-square value of 6.306, and was not statistically significant.

**User Experience and Perception:** Viber audio-based code verification received the highest SUS score (58.05) among all the remote code verification methods, followed by WhatsApp numeric code verification (53.78). It seems users did not find Telegram image code verification very usable in the remote setting (SUS=45.53). Systems with SUS scores of below 50 are considered to have "poor" usability [17]. Users also seem to rank Viber audio-based code verification the highest with respect to comfort, satisfaction, and adoptability, followed by WhatsApp. Figure 7 summarizes the answers to the user feedback questions.

The Friedman test was conducted to compare SUS, comfort, satisfaction and adoptability score, among multiple remote code verification methods and rendered a Chi-square value of 3.021, 3.381, 4.251, and 6.732 respectively, which were not statistically significant. Thus, based on our study, we do not observe much statistical difference between the different remote code comparison methods in terms of user perception ratings. Most ratings seem to indicate a poor level of usability for all of these methods. We recall that comparison between different methods is not the focus of our study. The primary focus is rather to compare between the remote and the proximity settings, which we analyze next.

#### 5.4 Remote vs. Proximity Setting

**Error Rates:** The Wilcoxon Signed-Rank test indicates a statistically significant difference between the average FAR and the average FRR of the methods tested in the proximity setting and the methods tested in the remote setting, with the p-value of 0.00 for both FAR and FRR. Thus, in remote setting, the FAR and FRR are significantly higher than the proximity setting, implying that code verification method offers a significantly lower security and a higher chance of rejecting valid sessions. The pairwise comparisons also showed statistically significant difference between FAR and FRR in proximity setting and that of remote setting in most cases (detailed statistical analysis can be found in Table 5 in A.4).

**User Experience and Perception:** Apart from the error rates, responses to the feedback questions (user perception) shows that SUS for all the code verification methods in the remote setting was lower than the methods in the proximity setting. Also, users generally were less satisfied and comfortable with the code verification, and were less willing to use the remote verification methods.

The Wilcoxon Signed-Rank test indicates a significant difference between the average SUS, comfort, satisfaction, and adoptability ratings of methods in the proximity setting and methods in the remote setting, yielding a p-value of 0.005 for the SUS, 0.007 for comfort, 0.004 for satisfaction, and 0.003 for adoptability (detailed statistical analysis can be found in Table 5 in A.4).

#### 5.5 Bidirectional Authentication

In the user study, we asked the participants to compare and verify the code only in one direction. In practice, the E2EE applications ask both users involved in the conversation to verify each others' code. However, the code verification on the two devices work independently, that is, Alice may verify Bob, while Bob does not verify Alice. This situation may work in favor of the attacker. If only one party (Alice *or* Bob) accepts the attack session, he/she may continue to send messages, files, or photos that can be eavesdropped (or tampered) by the attacker.

Therefore, for the attack to be successful, compromising only one side of the connection is enough to intercept several messages (even if we assume that one end-point who does not verify the code does not send any messages or does not initiate any call). Hence, in practice, the FARs will be higher than the one reported in our study. For example, FAR is 40% in numeric code verification considering the attack in only one direction. Same error reaches 64% (=  $40\% + 40\% - 40\% \times 40\%$ ) if the attacker can deceive one of the two parties. This result essentially shows that, in practice, in the most common- use case of E2EE apps (the remote setting), the human errors in comparing the codes could result in the success of the MITM attack with a high chance.

Table 1: Effect of number of mismatching character(s) on FAR for remote audio-based and numeric code verification.

	Mismatching Characters							
Task ID	1 Character	1 Block	Whole Code					
R1-Audio	37.27%	29.32%	12.75%					
R3-Numeric	60.25%	51.69%	7.12%					

#### 5.6 Post Study Analysis

At the end of the study, we asked the participants to give us openended comments about the study. We also asked them if they would prefer proximity setting over the remote setting. The participants commonly agreed that proximity code verification methods in which "they are sitting side by side" are easier. Many users found "QR code to be more user friendly" than the rest of the methods. Some of the participants found the numeric and image code comparison in the remote setting to be "*frustrating*" and "*time consuming*", as they have to "switch between windows".

#### 6 DISCUSSION AND FUTURE WORK

#### 6.1 Strengths and Limitations of Our Study

We believe that our study has several strengths. The analysis of the pre-study questionnaire responses shows that the participants in our user study are above the level of average app users in terms of age, education and computer skills, which suggests that these participants might have performed better than the average users in detecting the attacks and might have found the code verification methods more usable (in terms of SUS, satisfaction, comfort, and adoptability rating) than average users. The participants in our study are young and educated students who have declared that they have excellent and good general computer and security background, and have used the E2EE feature at least on one of the apps prior to the study. This sampling of user population serves as a sound counter-example to support our hypothesis that E2EE apps may not provide the promised security and usability, specially in a remote setting. In practice, these apps are used by a more diverse group of users who may be less technology-aware, and therefore, may perform worse than our study participants, thereby granting more opportunity to the attacker to succeed. Similarly, the average realworld users may find the code verification task much less usable compared to our study participants.

Finally, in the controlled and monitored lab setting, users might be subject to the Hawthorne effect compared to real world settings. Thus, our work shows that the E2EE apps may provide a lower level of security and usability in practice than what was observed in our study.

Further, in our study, the participants were involved in one single task of code verification as the primary task. At the beginning of the study, we informed the participants about the security risks of careless code verification and asked them to perform the task diligently to avoid the attack as much as possible. However, in real-life, the code verification is an optional task in all the studied apps. Even those users who verify the codes, may skip through the process (as reported in prior proximity-based device pairing studied [29]), since their primary task is to establish the connection (send a message, or start a call), while verifying the code is only their secondary optional task. Therefore, in practice, the error rates might be higher than the one reported in our studies. This means that the E2EE apps would be even more vulnerable to attacks and less usable in real-life than what our study has found.

To achieve collision resistance, the current apps aim to use longer codes. However, longer codes are not easy for human users to compare. Therefore, some apps truncate it to a shorter code. Since we studied the real apps, one limitation of our study was that we did not have control over the length of the code, although these codes is what the users are being subject to in real-life. In our study, only Viber code was 160 bits, while other codes were still the same length, 256 bits.

## 6.2 Potential Mitigations & Future Directions

While our work exposes a fundamental vulnerability of the E2EE apps in the remote setting that arises from the human behavior that may be challenging to counter, we sketch two of the potential mitigation strategies and directions that may help curb, if not eliminate, the said vulnerability.

(1) Multi-Windowing: The post-study open-ended questions revealed that in the remote setting, many users had difficulty comparing the codes received through an out of band messaging application due to the single-tasking interface of the smartphones (i.e, only one application is displayed on the screen at a given time). Some of the smartphones allow the users to split the phone's screen into two sections and open one app in each portion of the screen. Using this feature, for code verification, the user can open the E2EE app's code verification screen in one portion of the screen. Since multi-windowing is not available on all smartphones, we have not evaluated this approach in our study. However, this option would perhaps make the code verification easier and more robust to errors, since the user can see both codes at once. This method should be studied as part of future research.

(2) Automated Code Verification: Human errors in comparing the codes lead to the success of the MITM attacks against E2EE apps. Apart from informing the users about the code verification task and its importance pertaining to the security of the system, one natural defense against the attack is to reduce the involvement of the human users by automating the code verification task itself. Since the threat model assumes trusted devices, the code may be verified automatically by the E2EE app by reading directly from within the out-of-band app. However, due to privacy issues, this automation may not be securely implemented by allowing the apps to directly access each other's data (e.g., reading the code from the SMS by the E2EE app may create privacy concerns). Further investigation is necessary to explore such a model.

Another possibility for semi-automation is through the use of the clipboard. In fact, Signal has most recently (after our study was accomplished) implemented a code verification method for the remote setting, in which the user copies the received code to the phone's clipboard and asks the app to compare and verify the locally generated code with the one stored in the clipboard. Therefore, the users do not need to manually compare the code. Although this method is a step towards automation, further studies are required to evaluate its security and usability. For example, one problem with this approach could be that the user copies all data currently in the clipboard (which may contain sensitive information) and makes it accessible to the E2EE app.

# 7 RELATED WORK

A great number of papers are available that compare different code verification methods for the device pairing setting (e.g., [27, 28, 34]). This line of work mainly targets the way the code is exchanged over a location-limited out-of-band channel (e.g., audio vs video), or the way it is compared (e.g., Copy-Confirm vs. Compare-Confirm). Unlike our study, these studies assume the exchange of short codes (e.g. 6-digit code) in a *proximity setting*.

Other work [24, 25] compared different forms of representation of cryptographic keys, such as textual and graphical representations. In our work, we also consider several practical examples of code presentation, but more importantly, we study the proximity and remote code exchange, comparison and verification methods in the context of real-world smartphone apps geared for end-to-end remote security. That is, unlike these prior studies, our primary goal is not to compare across different methods, but rather to compare between the remote and the proximity settings.

Another recent study [33] has investigated the security and usability of the code comparison in end-to-end encrypted VoIP apps in the presence of data and/or voice MITM attack. Their studies consider short codes (mainly 2-4 words) that are communicated over the voice channel. Their results show that users' failure in verifying the code results in accepting on average about 30% of the attacked sessions. While their study covers remote audio-code verification methods with short words, we consider several long code presentation and code verification methods that are deployed widely by existing popular messaging and VoIP applications. We did not consider word representation of codes in our study as these are not deployed by the most popular apps we focus on in our work, but the analysis of security and usability of the short word presentation can be found in [33].

A recent paper by Dechand et al. [21] conducted a usability study to evaluate performance and usability of the different textual code representations. In their online study, participants were presented with several instances of code pairs and were asked to compare the displayed code to evaluate the performance of the users with respect to the different representations of the codes (e.g., numeric, hexadecimal and sentence). They concluded that the use of large words provided the fastest performance, and sentences achieve the highest attack detection rate. This study does not compare the code exchange method and code verification process for any specific app. The aim of this study was to evaluate how easily different representations can be compared from the users' point of view in a proximity setting, where two codes are shown side by side. Another limitation is the online study itself that does not capture the exact user interface of the apps. Our work, in contrast, focuses on the remote setting and its comparison with the proximity setting. In addition, our work shows the usability and security of actual phone apps, not studied before.

# 8 CONCLUDING REMARKS

In this paper, we ran a user study to investigate the security and usability of the human-centered code verification task deployed by a representative class of E2EE apps. Our study discloses several security and usability issues stemming from the human errors in performing the code verification task in a remote setting. Specifically, we noticed that several code verification methods offer low security and low usability in the remote setting (much lower than the proximity setting). Our study design with the security task being the only task at hand and with well-informed and young participants who performed the security task diligently and willingly, implies that in real-life situations, the security offered by these apps could be much lower given that these apps do not inform the users about the security risks of erroneous code verification, the real-world users will not be as tech-savvy as our study participants, the real-world users' primary task will not be security-centric and the real-world users may rush through the verification process by simply accepting all (including attacked) sessions. Besides, in real-world, the attacker's success may increase as she can deceive any of the users involved in a conversation, whereas we studied the attack only in one direction.

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# A APPENDIX

#### A.1 SUS Questionnaire

- (1) I think that I would like to use this system frequently.
- (2) I found the system unnecessarily complex.
- (3) I thought the system was easy to use.
- (4) I think that I would need the support of a technical person to be able to use this system.
- (5) I found the various functions in this system were well integrated.
- (6) I thought there was too much inconsistency in this system.
- (7) I would imagine that most people would learn to use this system very quickly.
- (8) I found the system very cumbersome to use.
- (9) I felt very confident using the system.
- (10) I needed to learn a lot of things before I could get going with this system.

#### A.2 Additional Tables and Figures

#### A.3 Messaging Apps

Table 4 shows 10 highly popular E2EE apps. The total number of the installations and the rating of the apps are derived from the Play Store and was last updated on this submission on November 06, 2016. iTunes store does not disclose the number of app installations. Although an estimation can be inferred [23], we believe the current data from Google Play Store serves well to provide information about the popularity of the apps.

Some recently introduced apps such as Google Duo and Google Allo have not yet deployed any code verification method. For other applications, the code presentations and code verification methods in proximity and remote setting is given in the table. Some of the apps such as Telegram and Signal do not offer a feature to directly transfer/exchange the code from the app. Such applications rely on the users to compare the codes through an authenticated out of band channel of their choice. On the other hand, apps such as Viber and Silent phone do not have an explicit way to compare the code locally.

Considering the popularity of the application and to cover a variety of code presentations and code verification methods, we picked the first four popular apps that offer code verification, namely,

	Task ID	Presentation	Арр	Verification Flow / Instruction
gu	P1-QR	QR Code	Signal	<ol> <li>Tap on contact name in the conversation view.</li> <li>Tap on 'Verify identity'.</li> <li>Scan the other user's QR code.</li> </ol>
imity Setti	P2-Image	Image	Telegram	<ol> <li>Open the chat with the contact.</li> <li>Tap the contact name at top.</li> <li>Tap the 'Encryption key' to view the image.</li> <li>Verify whether the image matches with that of the other contact.</li> </ol>
Prox	P3-Numeric	Numeric	WhatsApp	<ol> <li>Open the chat with the contact.</li> <li>Tap on the name of the contact to open the contact info screen.</li> <li>Tap 'Encryption' to view the 60-digit number.</li> <li>Verify the code displayed on your phone and on the other contact's phone.</li> </ol>
ing	R1-Audio	Audio	Viber	<ol> <li>Open the conversation with the contact.</li> <li>Click on the Gear icon.</li> <li>Scroll to the bottom of the conversation info screen and select "Trust this contact".</li> <li>Choose "Free Viber Call".</li> <li>While on Viber call, click on the Lock icon to see the code.</li> <li>Listen to the code spoken by the other user.</li> <li>Verify whether the spoken code and the displayed code match.</li> </ol>
Remote Setti	R2-Image	Image	Telegram	<ol> <li>Open the chat with the contact.</li> <li>Tap the contact name at top.</li> <li>Tap the 'Encryption key' to view the image.</li> <li>Receive the image from the other user as a text message.</li> <li>Verify whether the image matches with the image received in the text message.</li> </ol>
	R3-Numeric	Numeric	WhatsApp	<ol> <li>Open the chat with the contact.</li> <li>Tap on the name of the contact to open the contact info screen.</li> <li>Tap 'Encryption' to view the 60-digit number.</li> <li>Receive the 60-digit number of the other user as a text message.</li> <li>Compare both numbers.</li> </ol>

#### Table 2: The code verification tasks in the user study.



This image is a visualization of the encryption key for this secret chat with **Andrei**.

(c) Telegram Encryption Code.

Figure 8: Presentation of the security codes

(d) Signal Fingerprint.

# Table 3: Demographic information of the participants

	N = 25
Gender	
Male	54%
Female	46%
Age	
18-24 years	34%
25-34 years	58%
35-44 years	8%
Education	
High school graduate or diploma	9%
Some college credit, no degree	9%
Bachelor's degree	46%
Graduate degree	36%
General Computer Skills	
Excellent	34%
Good	62%
Fair	4%
Poor	0%
General Security Skills	
Excellent	17%
Good	50%
Fair	33%
Poor	0%
Awareness about E2EE Feature	
Extremely aware	17%
Moderately aware	37%
Somewhat aware	16%
Slightly aware	17%
Not at all aware	13%

WhatsApp, Viber, Telegram, and Signal for the purpose of this study.

	Installs on	Rating on		Code	Code	Proximity Code	Remote Code
	Google Play	Google Play	Votes	Presentation	Length	Verification	Verification
WhatsApp	1,000,000,000 - 5,000,000,000	4.4	45,751,306	QR, Numeric	60 digit	QR code scanning, Manual number compare	OOB code exchange on messaging apps
Viber	500,000,000 - 1,000,000,000	4.3	9,339,793	Numeric	48 digit	Voice call	Voice call
Telegram	100,000,000 - 500,000,000	4.3	2,090,485	Image, Hexadecimal	64 characters	Manual number, and image comparison	Not available directly from the app screen, Any OOB code exchange
Google Duo	10,000,000 - 50,000,000	4.3	179,340	N/A	N/A	N/A	N/A
Google Allo	5,000,000 - 10,000,000	4.2	146,507	N/A	N/A	N/A	N/A
Signal	1,000,000 - 5,000,000	4.6	86,316	QR, Numeric	60 digit code	QR Code Scanning, Manual number compare	Not available directly from the app screen, Any OOB code exchange
Threema	1,000,000 - 5,000,000	4.5	44,160	QR, Hexadecima	32 characters	QR Code Scanning, Manual number compare	OOB code exchange on messaging apps
Wickr Me	1,000,000 - 5,000,000	4.2	9,011	N/A	N/A	Video	Video
ChatSecure	500,000 - 1,000,000	4	5,211	QR, Hexadecima	40 characters	QR Code Scanning, Manual number compare	OOB code exchange on messaging apps
Silent Phone	100,000 - 500,000	3.6	1,028	Words	Two words	Voice call	Voice call

Table 4: End-to-End Encrypted Messaging Apps Rating and Reviews

Table 5: The result of the Friedman and Wilcoxon Signed Rank tests to compare the code verification methods in the remote vs. proximity settings

						Friedman Test					
						p-values	Chi-squar	e			
				FAF	۱.	0.000	40.385	1			
				FRR SUS Comfort		0.003	18.333	1			
						0.000	9.579				
						0.150	14.090	1			
				Sati	sfaction	0.034	12.072	1			
				Ado	ptability	0.007	15.938				
					p-valu	es of Wilco	con Signed F	ank 7	ſest		
	R1-Audio	R1-Audio	R1-A	ıdio	R2-Imag	e R2-Ima	age R2-Imag		R3-Numeric	R3-Numeric	R3-Numeric
	vs.	vs.	vs		vs.	vs.	v	i.	vs.	vs.	vs.
	P1-QR	P2-Image	P3-Nui	neric	P1-Q1	P2-Ima	ge P3-Nu	meric	P1-QR	P2-Image	P3-Numeric
FAR	0.007	0.011	0.01	0.010		0.081	0.066		0.001	0.001	0.001
FRR	0.000	0.010	0.01	0.010		0.046	046 0.046		0.025	0.025	0.025
SUS	0.085	0.614	0.63	0.637		0.099	0.033		0.008	0.551	0.150
Comfort	0.380	1.000	0.17	0.177		0.048	0.048 0.0		0.013	0.0191	0.018
Satisfaction	0.133	0.874	0.15	0.156		0.027	0.008		0.070	0.902	0.233

# A.4 Statistical Analysis of Remote vs. Proximity Setting

The non-parametric Friedman test followed by the Wilcoxon signedrank test with Bonferroni correction was conducted to compare the error rates and the user perception among different code verification methods in remote and proximity setting. The results are summarized in Table 5.