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On the Estonian Internet Voting System (IVXV) – SoK, New Attacks and New Suggestions

Abstract. The Estonian i-voting experience, since 2005, is probably the richest to analyze; yet it still holds a collection of noteworthy threats as stated in the 2025 Estonian Academy of Science (Cyber Security Committee) report. This paper first gathers vulnerabilities discovered and improvements/fixes introduced to the Estonian i-voting system, IVXV, in the years 2023-2025; then presents a thorough analysis of its status, as of October 2025 version, with exploits pointed out and solutions suggested. In our review, we shade some light on automated formal verification research attempts that went unnoticed by the Estonian research community; we also notice that, since 2024, forcing a time gap between multiple votes could prevent Perreira revoting attack for verifying voters. Although the problem of not authenticating the Voting Application (VA) is not new and was discussed in the Estonian report, we warn of possible threats that have been missed. We show how new technologies like **anonymous online auctions** between candidates and **hardware execution attests** for conditional payment can be used to orchestrate an automated large-scale attack where an encrypted vote is generated online without the vote sellers even knowing who they're voting for; adding fresh randomness to each ballot enables the attack to pass duplicate ballots anomaly check if existed. We agree that compromised voters' credentials is a known threat to all i-voting systems; however, it only gets severe in the Estonian case where any application can cast a vote. Finally, we discuss the approaching quantum threat and recommend protecting election data from the possible **HNDL (Harvest Now Decrypt Later)** privacy threat by encrypting ballots, while residing on the system servers, using a quantum secure symmetric key algorithm (AES).

Keywords: IVXV, El-Gamal Encryption, universal verifiability, vote buying/coercion, HNDL.

1 Introduction

When analyzing systems security, the term "*Computationally Secure*" is usually used where we consider the system secure if attacking the system was computationally in-feasible with overwhelming probability. Specifically, in nation level e-voting systems, the power and incentives of possible attackers have an impact on the probability of an attack to succeed; the amount of resources (money and computing power) an adversary may dedicate to an attack depends on whether it is just a party competing to win, or a powerful country that has farsighted interests in the elections result. Therefore, we start our introduction with a whole picture brief on the Estonian geo-political environment and the involved players in the election game before we move on to the technical details.

Estonia is a small 1.35 million population country located in east Europe who gained independence from the Soviet Union in 1991 and joined the European union in 2004 [P. Ehin et al 2019].[1] Most Estonian citizens

[1] Total population in 2026 is 1,362,954 (https://www.worldometers.info/world-population/estonia-population/). Detailed statistics from 2025 (https://www.stat.ee/en/find-statistics/statistics-theme/population/population-figure#) shows only **1,123,385 "citizens"** , of which 285,819 **~ 25.44% are ethnic Russians**

welcomed the earlier *digital transition*; however, when it came to e-voting in 2005 there were some kind of "*notable divisions within the society between those who fully trust and those who fully distrust internet voting*" as quoted from the ***OSCE-ODIHR*** (*Organization for Security and Cooperation in Europe- Democratic Institutions and Human Rights*) **2023** report [2]. This is reflected clearly in the i-voting statistics; although the Estonian experience could be viewed as the earliest and most advanced [3], the official site [4] shows the ratio of i-votes reaching its maximum of 51% in 2023 (local Parliament), down to 41.7% in 2024 (European Parliament), then little up again to 45.8% in the just ended 2025 local elections. One can trace a long history of objection incidences mostly from right wing parties in [1] and [2/(page 8, footnotes 16&17)]; the situation was emphasized in 2023 when internet votes flipped the results for one of those parties (***EKRE***). Analysts view it as a natural echo of the society division mentioned above; i.e., it is expected for curves, [5], showing the distribution of internet votes to be completely different from paper votes curves according to each party's preference. Still, there were some complaining activities that continued persisting to the 2024 European elections [6] and the current 2025 local elections [7]; the party even called for a parliament vote to urgently suspend e-voting in 10th Nov 2025 that gained 25 approving votes and only 1 refusing vote, while the rest of 87 present members chose not to vote as shown in Fig.1. In fact, we believe the distribution of members attitude reflects even more society division that the statistics in [4]; even if the majority (61 out of 87 attending members and 101 total members) did not support "*urgent*" suspension, they cannot be classified as pro e-voting in any sense.



Fig.1. the Estonian parliament voting on a proposal to "*urgently*" suspend e-voting as taken from (https://www.facebook.com/share/p/16cvJgpr9y/, https://www.riigikogu.ee/tegevus/tooulevaade/haaletused/haaletustulemused-kohalolekukontroll/42bf2e09-0c16-4e1c-b227-478fdb5ad4b9/)

To complete the picture, it is appropriate to note that Estonia shares a border with Russia (recall from footnote 1 that ~25.4% citizens are ethnic Russians); according to [8] the ongoing war has put extra pressure on the country. The i-voting[2] system faced Russian attacks that authorities say were properly defended. Since most security metrics are probabilistic [9/sec. 4], the power and incentives of possible attackers have an impact on the probability of an attack to succeed; the amount of resources (money and computing power) an adversary may dedicate to an attack depends on whether it is just a party competing for a win, or a powerful country that has

[2] The term *"i-voting"* refers to voting through the internet (online) which is a subset from the more general term *"e-voting"* that refers to all kinds of electronic voting that may include using Ballot Marking Devices (BMDs) at poll stations; hence, both terms can be used to describe the Estonian voting system.

farsighted interests[3]. We believe the Estonian problem is further complicated by a dilemma of opposing factors; the parties against i-voting could be classified ideologically as nearer to Russia and the bright image of a perfect high tech election system is what Europe prefers, on the other hand overlooking the exploits raised against the system or diminishing their impact is what Russia (or any other adversary) benefits from. However, we here just notify of a possible impact and leave the analysis of measuring/estimating it to political science researchers.

After this brief preface on the Estonian election environment and the involved players, we proceed into the technical and cryptographic details. We believe **the main contributions of this paper** are time chronological Review of past versions, thorough analysis of the present version, a simple system barrier that could prevent Perreira revoting attack, new attacks for the voting application (with their mitigations), and finally a suggested solution for the HNDL quantum threat. The contributions could be detailed as follows:

1. Reviewing the progress of the Estonian i-voting system, IVXV, through the last three versions showing when and how each vulnerability was fixed or improvement was made and the academic research behind the solution; also surveying all research discussing it. To our knowledge the last existing survey covers till the year 2019; even the official English documentation stopped on the 2022 version, where newer files are only available in the Estonian language. Table A1 in Appendix A summarizes the presented review.
2. Through the review we discovered that, since the 2024 version, a simple system barrier of enforcing a time gap between multiple votes could prevent the famous Olivier Pereira revoting attack better than the voter dependent mechanism in [9] (sec.4); a time gap that exceeds the session ID interval will prevent receiving more than one encrypted ballot for each session ID.
3. A thorough analysis of the current 2025 version that consolidates all remaining vulnerabilities and issues discussed in the academic literature and different kinds of reports (OSCE/ODIHR, observation reports, Cyber Security Committee report, …etc.) along with the suggested solutions for each. Table A2 in Appendix A summarizes it.
4. Discovering new possible attacks/threats associated with the fact that the Voter Application (VA) is not authenticated; the possibility of largescale encrypted vote broadcasting and online anonymous vote auctions with execution attests. We are aware that risks from malware and compromised voter credentials were heavily discussed on a much older 2014 version, before IVXV, but researchers limited their effect for newer version as will be discussed further in the following sections. Besides, our attack does not assume any malware residing in the voter's device; it only assumes a malicious voting application and some AI and/or social engineering to target non-verifying voters. The severity of this family of attacks comes from the automated online triggering of all compromised voters at once. We introduced other possible solutions and/or recommendations to handle those threats, in addition to the obvious solution of authenticating the voting application by the system.
5. A suggested, we believe fast and easy to apply, solution for the current HNDL (harvest Now Decrypt Later) threat, where adversaries store available encrypted data that are computationally secure with current technologies to decrypt them when quantum computers exist; to re-encrypt the encrypted votes list when received using a quantum secure symmetric key encryption (ex. AES with

[3] We say that attacking a system is computationally infeasible if the cost of computation power needed to complete the attack is more than the gain from the attack; for example, if it is an object, then it is computationally secure as long as the cost to steal it is larger than its money worth value. Mapping to elections, a rational candidate/party will not spend on hacking the elections system to forge a win more than he/she will gain from winning; however, political science researchers can measure better than the author the cost-benefit analysis for other countries (Russai as an example) towards the Estonian elections (probably differs from local elections to European Parliament elections)

longer 256 bit key), then decrypt before counting. The solution does not disrupt the system's main steps in any way, or the user experience since it happens at the server side, and with cryptographic commitments added during encryption the system trust guarantees remain the same.

The rest of the paper is organized as follows. Section 2 reports some recent important activities by the i-voting opposing community that have technical merit, while section 3 marks briefly the milestone steps through the evolution of the Estonian i-voting system[4]. Then section 4 explains in detail the current version of IVXV ending with an important attack that was fixed before the 2023 elections, while section 5 goes through recent improvements that were made in IVXV before the European elections and section 6 scans briefly the updates we recognized in the version just released on the 3rd of October. Section 7 discusses the remaining vulnerabilities of the system along with the existing research suggestions and ends with a holistic view of the system status quo that raises some general questions. Finally, in section 8 we summarize the paper with concluding remarks and in section 9 we introduce possible research threads to the cryptographic research community that we found through our work; Appendices contain extra details and summarizing tables.

2 Recent Opposition Activities with Technical Merit

Discussing the Estonian environment and exploring possible players in its political game with their variant power resources, is an illustrative example of how digital democracy enforced security researchers to investigate the geo-political prospective. Vice versa, this section illustrates how electronic voting partially turned the opposition-system classical debates about election results[5] into technical ones. We find observers who read papers and acquire programming skills (part of their job is to trace the election code which must be open sourced early enough for them to do so), while political parties are suspicious of what they do not know and must learn; finally, courts are cautious and sometimes confused by experts. As a general attitude, we preferred to cite social media or blog posts, not just the official statements, to give the interested reader the chance to explore the variety of comments by the Estonian citizens. Section 2.1 presents activities and complaints that accompanied the 2023 local elections, while section 2.2 covers 2024 European elections, then section 2.3 goes through the currently ongoing activities of the 2025 elections that just finished while writing this version of the paper and section 2.4 is closes with concluding remarks.

2.1 The 2023 Local Elections

A technical incident that gained some publicity in 2023 elections [10] was done by the same computer scientist observer[6] in [5]; Mart Poder ***voted using his own Python code*** [11,12]. This highlighted the known fact that the

[4] Since there were many previous studies discussing earlier years of the Estonian i-voting, like [1] till 2019, this paper is more concerned about the vulnerabilities and improvements of the recent years. Our title says IVXV; a design that took place in 2017.

[5] Everywhere all the time, losers always complain and winners always defend; one of the hardest jobs is to extract the facts and the objective arguments from the equally motivated sides of the story.

[6] The word "***observer***" is used by IVXV to acquire certain access rights during election, as opposed to "*auditors*", [18]. The term "***Computer Scientist***" (taken from [10]) is rejected by IVXV representatives who describe Märt Põder as "***A hobby hacker activist***", while the OSCE report referred to who codes another voting application as "***someone with sufficient programming skills***".

voting application, which voters should download to deliver their vote, is not authenticated by the system; the OSCE/ODIHR report [2/page 8] believes the incident "*could present a cyber security risk*".

The report also mentioned *some wrong district votes*; the incident was magnified by the opposition [13,14], while described by IVXV representatives [9/ sec. 5] as a population registry problem that would have taken much longer to detect and resolve without i-voting.

Even if some exploits and/or problems were magnified, it is the authors' impression that most complaints get rejected without objective investigation based on a submission deadline (*3-days from election*); [15] is a very recent (20/6/2025) example. The OSCE/ODIHR 2025 report commented on this issue by saying [16/sec. 3.3/68 & Recom. J] "*the legislator should also address the specific complexities of internet voting when determining appropriate deadlines"*. To be fair we noticed that in many cases, as will be illustrated throughout the paper, the vulnerability gets handled and fixed silently before the following election.

Should also be mentioned in this context that Mart Poder published a poster, [17], at a scientific conference E-Vote-ID (in Oct 2023, while the elections was in March 2023); the poster questioned multiple voting as a vote coercion/buying mitigation mechanism by demonstrating it is possible to get a hard proof of the last vote through some existing system services. This will be discussed in detail with some follow-up research in sections 5.3 & 7.2.

2.2 The 2024 European Parliament Elections

We start with another rejected complaint about ***the decryption of invalid votes*** (after the elections), where the rejection was done objectively this time [14]. Among the three listed reasons, being an *observer* not an *auditor* seems to be the dominant one, where auditing is organized by the State Electoral Office in all elections [18]. According to [19/Conclusion], generating proofs of correct decryption of invalid votes was remediated in code before June 2024, but *the file containing the decryption of invalid votes is only accessible to auditors* [19/page 22]; the reasons will be further discussed in section 5.1. The version released in October 2025 for the local elections prevents invalid votes from entering the system; however, this does not apply to other unofficial voting applications voters may use as will be discussed further in section 6.

In addition to the complaint in [15,18], and the rejecting voices [20], the European parliament elections were accompanied by some activities from the i-voting opposing community. The same observer mentioned above has developed some kind of ***shadow e-voting*** site called *virtual threshold survey* [21] encouraging citizens to vote again on it as a check (although there is no evidence of considerable participation ratio).

2.3 The 2025 Local Elections

In the current 2025 local elections, observers have prepared a voting & verification application (reveals the vote decryption), [22], and they are broadcasting a tutorial video to show voters how to use it, although we couldn't trace an effective participation ratio. In the course of doing so, they had to update their 2023 voter application[7] code to handle the new ballot format in the new version; hence, they filed a complaint to the National Electoral Committee, on October the 3rd, for the delay in publishing the system code, only at 30th of September, which does not give them enough time to study and analyze the updates. The complaint was first rejected, while the appeal to the supreme court upheld the complaint [23,24] and declared that it is "*unlawful that the State*

[7] The terms "Voting Application" and "Voter Application" both abbreviated as VA, are used interchangeably in available literature, documentation and news coverage to refer to the application that runs on the voter's device to receive the voter's choice, turn it to an encrypted digitally signed ballot, and sends it to the system.

Electoral Office (RVT) failed to disclose the source code of the electronic voting system and the verification application prior to the test vote".

Other circulating issues in 2025 elections include not publishing the voters' list [25] which could affect the tracing of wrong district votes mentioned above or the total number of eligible voters in general; the handling of the parts of the election secret key during the setup phase [26] was the subject of another rejected complaint by the supreme court [27]; also, some incidents, [28], that happened during the re-reading and integrity checking phase. The EKRE party [29], also *The Representative Association of Election Observers*[8], submitted several complaints that were rejected by the Electoral Commission then pursued to the supreme court; [30] is an observers' preliminary report that captures many details which we will discuss as we go in this section.

2.3.1 The test vote reading

The election act [31/§48[3]/(4)] states that a public test voting is organized before the election starts; during which, the State Electoral Office tests the casting of electronic votes, the use of the access tools set up and the determination of the results of the electronic voting and checks the integrity of the electronic voting system.[9] During the reading and integrity checking of the 2025 election, [32/mins 00:45, 15:50] and Fig.2, two issues were reported by observers [29, 33]. The first is the system failing to read the checksum of a vote, and the second is an integrity alarm declaring a duplicate vote; the voter's information was disclosed due to the errors. This was included in the rejected EKRE complaint mentioned above, [27], as one of the reasons to doubt the whole process. The election authority on the other hand released a statement, [34], described the circulating video as "*misleading*" and clarifying that the system reading error was due to a vote coming from a different voting application which did not accurately comply with the new ballot format, while the alarm came from a voter's error in repeating the same vote twice which does not reflect a problem in the system. The EKRE complaint about the whole process was dismissed by the Electoral Commission [35].

Analysis & recommendations:

We, the authors of this paper, are convinced by the official justification of the first issue; the complaint in [24,25] partially reflects the tedious format update issue discussed by the same person in [22,23]. However, the EKRE posts, [27], comments on the fact that the voter (his identity was revealed) unfairly lost his vote; the system did not send him any feedback error message[10] to revote. Hence, **we recommend applying the invalidity checks to all votes even those coming through private voter applications.**

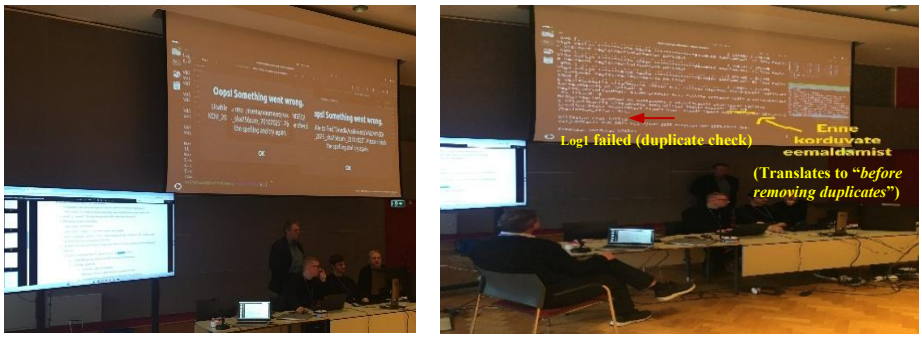
We disagree though with the argument explaining the duplicate vote alarm; it should not be a problem if the same voter revoted with the same exact choice again, the added randomness (see section 4) makes the two votes encrypt to completely different cipher texts. We believe if the system here detected two duplicate ciphers, this *could possibly reflect a malicious voting application that submits the same ballot no matter what the voter chooses.* **We recommend adding a general check of duplicate ciphers exactly after removing voters' signatures and while they are still available to trace**; this will be further discussed in section. Also, since the

[8] The post (http://x.com/trtram/status/1989257971663360040), just appeared while we were finalizing this manuscript, gathers the index numbers of 11 other complaints rejected by the supreme court if an interested reader wanted to trace them all at the supreme court site.

[9] It states also that "*After the test voting, the electronic voting system is brought to the condition which existed prior to the test voting*" and this is where the key parts problem came from; the security stickers had to be removed to use the key then sealed back again.

[10] Apparently, their voting application delivered the ballot directly to the vote collector application, while the official one has a server-side part (https://github.com/valimised/ivxv/blob/published/voting/service/voting/main.go) that performs some checks and sends error messages.

voter's ID was already revealed during the process, we suggest checking his side of the story on the exact details of what he did; in general, **we recommend tracing individual errors even if they were not to change the election results** as part of the system debugging phase to discover any unnoticed vulnerabilities.



(2-a) min 00:45 not able to read checksum **(2-b)** min 15:51 log1 check failed due to duplicate

Fig.2. Snapshots taken from [32] before blurred as shown in [29] (the red arrow and the English caption are added by the authors of this paper)

2.3.2 The key parts

Since the impact of key leakage will be better understood after discussing the system architecture and its underlying cryptography, we will defer it to Appendix A; we will suffice here with the incidents and the activities in response to them.

The test vote reading process described above in section 2.3.1 uses the same secret election key. Hence, the chips containing the key parts must be brought to the event to be read and naturally their secrecy must be handled with great caution; security stickers are removed then put back again under the monitoring of auditors [31,36]. According to EKRE submitted complaint [26] and a supporting observer [27], the chips were kept with the key shareholders inside the meeting room, before putting the security stickers back[11], with them swearing they did not misuse it. The complaint was rejected on the basis that "*it is technically impossible to read and/or copy isolated chip cards from a distance"*; the observers report on the other hand, [30/point 5], stresses that the auditor ordered the key holders to put the stickers immediately, which they did not, and the auditors were mind occupied observing other simultaneous events at those 10-15 mins. In fact, the report cites a master thesis from University of Tartu, which discusses many problems associated with the auditing process in general, states as translated in [36/chapter 9] *"it may happen that the auditor may miss something important, for example being busy checking and opening security stickers at the same time"*; naturally, the argument stands valid the other way around.

It is worth mentioning in this context that there was also an older complaint about the desktop used in keys creation not being completely isolated and having some extra software downloaded onto it. A first earlier complaint granted an observer (23/2/2023) permission to see the content of the backup copy of the boot hard disk used in key creation to have full confidence there is no malware in the computer memory during key creation [37]. The observer took the photo shown in Fig.3 when the disk inspection took place (28/11/2023),

[11] The EKRE party statement used the expression "*pin codes protection was removed this year*"; however, reading the full details of the incident as summarized in [30/point 5], it could be that EKRE mixed up what happened with Estonia's future plans of deploying eID chips that do not use pin codes. According to public statements, that transition (see footnotes 15,16 in section 3.1) took place on 16th Nov, i.e. after election.

then pursued the matter further to the supreme court. The supreme court responded that this could not have affected the voting results; quoting their exact words "*voting results cannot be compromised with malware, because with the help of the reading certificate issued when determining the voting results, the compromise would be revealed immediately*".[12] On Aug 2024, a commentator from IVXV team stated (in an earlier reviewers' report of an earlier version of this paper) that they admit the risk and "*it has been taken care of*". Published in the same month, the thesis in [36/chapter 9/sugg.1] recommended auditors should audit the software used to generate the key parts and must seal the system disk and its back up copy with security stickers signed by the auditors; the Estonian election act was updated in 24 May 2024 to necessitates the presence of an auditor at the generation and destruction of secret keys [31/§ 48^7/(4)], but we have no evidence that the specific mentioned recommendations were met.



Fig.3. An image taken from [37]. According to the observer, this is the computer used in key creation which was supposed to have only an authentic Windows10 operating system, but he detected other software installed on it; DigiDoc4, Notepad++ and RamDisk.

2.3.3 The published code vs the used one

Commenting on the doubts raised by EKRE in [29,35] about "*how can be sure the published code is the one they actually run?*"; this can be achieved through file digests(fingerprints)[13]. The cryptographic hash of the published code that is claimed to run can be calculated ahead of the meeting, then calculated again during the meeting before they start the run. Again, this was part of the first suggestion in [36/chapter 9] explaining that "*it is not guaranteed that authentic software is installed on the hard drive*" and recommending an amendment should be made to make software and application installation an auditable procedure; the thesis was mainly talking in this part about the generation of the election key, but the argument applies to all used software even to the voting application code if it became open-source.

2.3.4 Absent e-voting

Election participation ratio between the Estonian voters (whatever through the internet or in poll stations) usually ranges between 50-60% except for the European elections 2024 was down to 37.6% participation ratio. When gathering information about the 2025 elections, we found that some voters, [38], say that when voting at poll stations, they were told that this is not their first vote; the system records an earlier electronic vote for them.

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[12] For the verdict statement and official progress of events, see (https://www.riigiteataja.ee/akt/328022023004, https://www.riigikohus.ee/et/lahendid/?asjaNr=5-23-40/2).

[13] Another approach of using *Repeatable/Reproducible software builds* (https://reproducible-builds.org, https://en.wikipedia.org/wiki/Reproducible_builds) has been mentioned in many places of the 2025 Estonian Cyber security reports to enable auditors from checking the authenticity of the election software and specifically the voting application; its complexity is the problem.

In Estonia, a poll station vote cancels the electronic vote, so in this specific case, the voter's choice was recorded correctly. However, accumulating with the previous incident, we believe this deserves an investigation; i.e., we repeat our previous recommendation of tracing the error. As a broad safeguard, **we recommend to check and alarm if the timing of poll station vote precedes the time of an e-vote for the same person**; also, **to check a random sample of e-votes using statistical techniques** (for example to contact the sampled voters and assert they actually voted in the given time). Absent e-voting and/or contradiction with poll station data will be further discussed in section 7.

2.4 Closure/Concluding Remarks

Finally, after navigating through the opposition' and observers' activities, and auditing tools provided by the election commission and the Estonian government in general, we present some concluding remarks.

2.4.1 Improvements

First, we acknowledge the improvements in the governmental attitude especially in this last election in Oct 2025.

- Updating the election act, since the European elections in 2024, to ensure the presence of auditors in most steps [31/§ 48].
- Publishing more parts of the code, the server-side part of the voting application.
- Although there was a complaint about the delay, the code was published earlier this time (2 weeks before the election) than during the European election last year (nearly 4 days)
- We see a lot of complaints investigated objectively compared to previous years; i.e., following the OSCE/ODIHR 2025 regulation recommendation, [16/J], of loosening the 3-days deadline.

2.4.2 Regulative Recommendation

In the regulation perspective, transparency and observation necessitates publishing the source code of the client-side voting application (VA); otherwise, there is a possibility that it could be malicious. In fact, tracing the law regulating e-voting in Estonia shows a contradiction regarding the voter application; in [31/§48^3/(7)] it states: "*Prior to the start of electronic voting, **the State Electoral Office publishes the voter application**, the vote verification application and the data necessary for ensuring the authenticity and integrity of the website on the election website*"; while in [31/§48^8/(7)] it states "***The source code for the voter application is not published***." The election authority kind of twisted around this contradiction by publishing the server-side part and hiding the client-side part; what we, the authors of this paper, believe was not the optimal decision in this case.

2.4.3 Technical Recommendations

Trying to stand in a middle spot between [9] and the long list of complaints, we believe e-voting provides more tools to detect errors or frauds, they are just not properly used.

- A general recommendation for all kinds of errors is to trace individual errors, even if they are not to alter the election result, to find out the vulnerability behind them and whether it was invoked in other undetected cases.
- Also, a general idea is to apply statistical auditing techniques, *Risk Limiting Audits (RLAs)*, to check a random sample of votes whenever there is uncertainty about a certain risk.
- From the vote in Fig.(2-a), voters should be alarmed when submitting invalid votes; although this was part of a test procedure, the Estonian language statistical site shows 3 invalid votes in the election final results. Technically, completely preventing invalid votes could be achieved if the checks to reject

invalid votes (whether in content or format) were applied to every vote entering the system even through a private voting application; this will be discussed further in section 6.2.

- Take a random sample
- Check and alarm the existence of duplicate vote ciphers, even if from different voters, as a safeguard from replay or copying attacks. This will be further illustrated in the following sections, but we mention it here since it came out from a real incident in the replay.
- Check and alarm if the timing of poll station vote precedes the time of the last e-vote. In this case, and the case above, the election authority should retrieve all available details of the problematic votes to know how this exactly happened and whether there is a non-negligible probability it was repeated; extreme possibilities like those in [39] will be further discussed in section 7 along with some suggested solution.
- A general note is the somewhat careless handling of election sensitive/crucial components or events; handling the key parts in 2023 & 2025 is an example. Also, not choosing representatives with enough knowledge of IVXV to attend the re-reading; otherwise, they would have a better understanding and handling of the errors in Fig.2 explaining the reasons behind them and that it is a good quality to have a strong error flagging mechanism even if it has some false positives (although we are not sure they are just false positives yet).
- Auditing software installation: we acknowledge the improvements in law and the presence of auditors, but there seems to be some issues in reality; the report, [30], says there were only one auditor and that the key holder asked the auditor in clear words to delay putting the security stickers for one round. Also, we are not sure whether the security stickers were signed by auditors to exclude the probability of having two sets of security stickers; whether the software authentic installation was properly audited or not since it is repeatedly doubted in EKRE complaints and opposition posts.

2.4.4 An Academic Trusted Third Party?

Finally, we end this section by pointing out to a scientific report from ***the Cyber Security Committee of the Academy of Sciences*** that was handed to the election organizers. The complete June 2024 report was not published, but in October 2024, [40], they clarified that they *have identified* ***6 medium threats***[14] *and* ***25 low risks***. We chose to mention the 2024 report here (all reports will be further discussed in section 7) although it is not an opposition activity, since it discusses the software installation audit problems mentioned above; also, to illustrate that even academics from Estonia who could be viewed as a trusted third party admit some problems, In fact, the committee cannot be accurately considered a third party since it is led by the scientific director of the e-voting company Cybernetica; However, Cybernetica has in total only 3 out of 12 members. Hence, as a general conclusion, not all opposition complaints are exaggerated, and the authors are not just taking their side or diminishing the hard work of the IVXV team through the years. To be fair, we should stress that this report was before the improvements and/or fixes made in 2025.

[14] The 6 risks (not published, https://x.com/danbogdanov/status/1802998209649762582) were first classified as "higher than small" in a meeting on 3rd of June (https://www.akadeemia.ee/akadeemia/noukogud-ja-komisjonid/kuberturvalisuse-komisjon), then a system representative commented on a review of an earlier version of this paper (14/8/2024) that all the 6 threats are of risk class medium (11-13); finally, this was confirmed publicly in October 2024.

3 Earlier System Evolution

As mentioned earlier, digitization has been in Estonia for more than 20 years, even before 2001, and was extended to include the private sector hand in hand with the e-government; e-ID cards existed since 2002, and electronic transactions is the casual behavior of the Estonian citizen. While details on digital system architecture and components like *Xroad*, *KSI* private blockchain seem irrelevant here, we find the e-ID key generation relevant since it is used in internet voting from its beginning in 2005. Hence, we will dedicate section 3.1 to one major event that changed a core cryptographic component of the e-ID system, **RSA;** then we will follow with a brief overview of i-voting earlier evolution till it reached its main design as IVXV in 2017.

3.1 Electronic Identity Card 2018 problem

In May 2018, Estonian authorities officially declared a persisting problem that started to appear in some rare incidences of duplicate RSA keys since 2011/2012. Citizens with problematic keys were asked to re-install the Java Applet on their cards at PPA (Police and Border Guard Board = *Politsei-ja Piirivalveamet* in Estonian language) stations. When reinstallation became more frequent, researchers started to analyze the accumulating data for the root problem. Then, it was proven that the ID card manufacturing company, ***Gemalto***, generated the RSA keys outside the chip, which violates the agreement rules and gives a chance to copy and/or repeat key pairs. A lot of interesting details on how the analysis was done can be found in [41]; more faulty keys issues[15] can be found in the same researcher's, Arnis Parsovs, PhD [42], and independently in [43]. Also, other RSA vulnerabilities were discovered in [44] which justified aborting RSA as an algorithm, not just the company.

According to [1], this was a global crisis for the company which was sued in many other countries. Spain and Slovakia [45] replaced all the physical cards, while Estonia fixed them remotely; then changed the company to ***IDEMIA*** [46] and, as recommended in [41], moved to threshold cryptography and homomorphic encryption. Currently, the Estonian i-voting system IVXV, [47], also uses ***384-bit Elliptic Curve*** Cryptography ECC with El-Gamal Encryption (section 4); yet the list of authorized votes is still signed using 2048-bit RSA key. Although [48] nullifies the effect of eID problems[16] on IVXV, we preferred to bring up those old problems to stress on the importance of studying all security issues involved with the transition to the new cards company *Thales*; a transition that the Estonian government wisely chose to make it after the election ends.[17]

[15] Including codes printed too dark that they were readable using torch, without opening envelope (happened in 2002 with the old company then again in 2018: https://news.err.ee/886313/new-id-card-issue-codes-can-be-read-using-torch-without-opening-envelope), duplicate email addresses in certificates, issuing certificates with incorrectly encoded public keys, failing to revoke certificates of deceased persons.

[16] Despite that, we chose to include this subsection in the paper to enlighten the reader that digital identity problems are part of the issues involved in the more general process of i-voting and hence digital democracy. A demonstration of this fact is that when *IDEMIA* started a transition into a new chip platform, Cosmo X, on July 2025 (http://www.id.ee/en/article/important-changes-with-the-current-estonian-card-issuer-idemia/) this necessitated some updates in IVXV 2025 version as will be discussed in section 6.

[17] *IDEMIA* contract with Estonia will end on 16th Nov 2025; *Thales* is scheduled to take over as the manufacturer of Estonian ID cards (https://www.id.ee/en/article/thales-id-card/).

3.2 Estonian i-voting before IVXV

As a preface, this section gives a condensed brief on how the Estonian i-voting system has evolved from 2005 to its final form as IVXV.
The main design theme since 2005 is a *double envelope protocol* sending voter signed ballot after first encrypted by the election public key[18] to the vote collector. Then, we mark 2 milestone step transitions [sec.1 of 49,50.51]:

In 2011, a student named *Paavo Pihelgas*[19] demonstrated a proof-of concept ballot-manipulating software that relied on the absence of an acknowledgement to the voter that his/her vote was received. Hence, [52], *the ability for voters to verify their votes* was first introduced in 2013. However, several flaws were discovered in 2014-2016, [53], that could maliciously alter the vote or the QR code.

Then, in 2015, *Cybernetica* partnered with *Smartmatic* to produce a new design that was first launched in October 2017 elections, IVXV [54], with the QR verification code in its current form. A lot of improvements were included on IVXV: a *vote-registration* service to guarantee no vote dropping, a *shuffling re-encryption mix-net* that cryptographically shuffle anonymized vote ballots to guarantee vote privacy, and a *Schnor based non-interactive zero-knowledge proofs (NIZKPs)* to prove the shuffled mix-net output decrypts to the same value as its original input; all of this will be detailed in the next section.

4 IVXV

In this section, we explain the design and structure of the Estonian internet voting system, IVXV, as described in the official documents [55]. Then we detail an important cryptographic attack along with its fix before the 2023 elections.

4.1 Brief Factsheet

The developing companies are ***Cybernetica-Smartmatic*** [3,55]; the voting device had to be a desktop PC, smartphone voting is about to become possible [56]; voting can be done using *mobile-ID*, *Smart-ID*, or any digital identity integrated in the *web-eID*[20]; *multiple voting* is allowed to avoid coercion or vote buying (only last vote is counted and a poll station vote overrides all i-votes); ***El-Gamal Homomorphic*** Encryption scheme is used to encrypt votes then the encrypted vote is digitally signed by the voter (double envelope); optional vote verification can be done by voters (through *QR codes* using a second mobile device) within 30 mins of voting with a max of 3 times; a ***single re-Encryption Mixnet server*** is used to scramble votes before decryption to preserve ballot secrecy. The setup phase, before the election starts, constructs the *election secret key* from 9

[18] That's why it is called "*double envelope*"; the vote is embraced with 2 cryptographic keys: the voter key and the election key.

[19] The student filed a complaint, [50], to the Estonian Supreme court requesting to nullify internet votes in 2011 elections. The complaint was dismissed for passing the 3 days limit (https://www.riigikohus.ee/en/constitutional-judgment-3-4-1-4-11); an older example that accumulated to our impression on frequently rejecting complains based on deadline. We stress that the authors of this paper have never visited Estonia and do not have any connections with Estonian people except those we contacted as part of the Systemization of knowledge process.

[20] The IVXV version for EP-2024 included extra ***web-eID assistance service***, ***Smart-ID assistance service***,…to scale horizontally enabling the usage of different digital identities (section 2 of the architecture, sections 8.5-8.6 of the protocols in [59]). The web-eID solution (https://www.id.ee/en/article/web-eid/, https://github.com/web-eid/web-eid-system-architecture-doc) is part of the European Union web-eID project for all public key cryptography digital identities across Europe.

parts issued by the members of *the Election Commission of the Republic*, such that decryption requires *5 out of 9 parts*[21]. Finally, after the election, there is ***an auditor application*** (could be run by anyone) that verifies the cryptographic NIZKP proofs provided by IVXV on the election published output data.

4.2 System Architecture & Voting Steps

The system architecture and voting steps are depicted in Fig.4, which could be summarized as follows

1. The voter installs the voting application, sometimes abbreviated as **VA**, on his/her PC; as of 2024, the voter can authenticate the downloaded VA before usage.
2. After submitting the digital identity ID, the voting application sends to *the vote collector*, **VC**, which in turn sends to *the registration service*, **RS**, to check the eligibility of the voter to vote; if eligible replies with the candidate choices for that voter (according to district) to be displayed to the voter.
3. The voting application encrypts the voter choice using the election public key (El-Gamal encryption), adds the user signature on the encrypted vote (with the voting application running on the voter's PC and after the voter's approval, *the voting application has the right to sign a message with the voter signature*), adds also the signed *timestamp certificate*[22] received from the registration application through the vote collector *after verifying the signatures of both*, and then sends the double envelope ballot to the vote collector. Note that the voting application VA is not assigned a digital signature key pair; the system can receive ballots from non-official VAs.
4. The vote collector application validates the voter's signature; after validation, the signature is removed, and the encrypted vote is added to the list of votes stored in the *Ballot Processor*. After voting is closed, and before sending ballots to the mix-nets, the ballot processor performs some integrity checks, removes multiple votes and votes overridden by poll station voting. Finally, the remaining list of "to be counted votes" goes through shuffling mix-nets (one *Verificatum* server)[23] to hide their original order (in local elections each district votes must be mixed separately as they will be counted separately), then verifiably decrypted at the counting phase.
5. The voting application sends a verifying ***QR code***[24] to the voter for optional vote verifying (through verification application) using a second smart device.
6. In the newest October 2025 version, the encrypted ballot in step 4 is first received by a server-side part of VA, which first checks that the vote is valid using Range Proofs (section 6.2); another ballot validity check is also added to the verification code.

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[21] Hence comes the term "***threshold cryptography***" in the end of section 3.1, because a threshold is agreed upon from the beginning (here 5 out of 9). Relating to the key parts concerns mentioned in section 2, cryptographically, as long as malicious committee members (or leaked key parts) are ≤ 4, they cannot collude to leak the key. A reader interested in election key management of different e-voting systems can check this recent, EVoteID25, SoK (https://link.springer.com/chapter/10.1007/978-3-032-05036-6_2)

[22] When [1] was written, the timestamp certificate was used only to distinguish the last vote and to check the 30 mins verify duration. In 2024 version, we will see why in section 5.3, *the certificate* sent by RS to VC *is* a ***signed CONFIRMATION*** that contains the original request (***ORDER***) sent and signed by the VC, along with the *timestamp*.

[23] IVXV uses *Douglas Wikström's Verificatum* (https://www.verificatum.org/); the package provides a verification application, and IVXV too (and several other projects [49]).

[24] According to [11], there was a revealing incident of *the president vote* through his QR code: he showed it in front of cameras to encourage citizens, and someone took a snapshot. As mentioned in [9], this is not considered a privacy exploit since the President voluntarily revealed his QR-code.

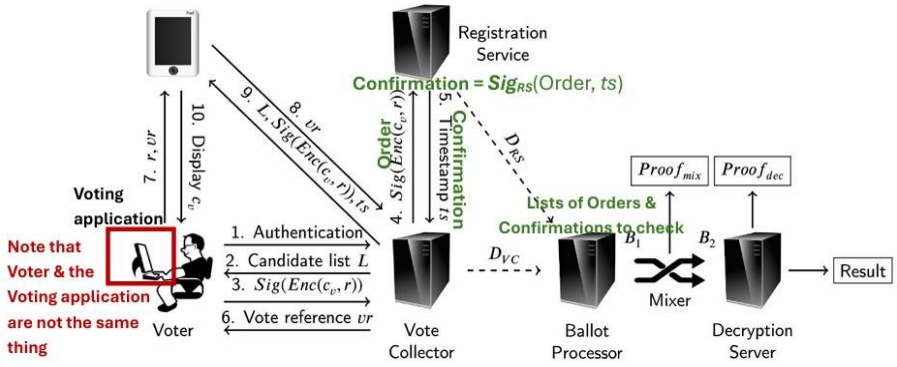

Fig.4. A diagram describing the architecture & the steps of the Estonian voting system; adopted from [1] with adding some remarks in red, and new updates in IVXV 2024 in green

4.3 Cryptographic Details of Last Fixed Attack

The exploit introduced in 2022 by [50], and fixed in 2023 by IVXV, give us a closer look into the cryptographic details of El-Gamal encryption algorithm; especially since we will mostly treat it as a black box in the rest of the paper.

-Let the election public key be "**y**" with corresponding secret key "$\mathbf{S_k}$", and "**g**" be the generator for El-Gamal encryption over the finite field **G**; hence, the equation « $\mathbf{y = g^{Sk}}$ »[25] holds.
-To encrypt a vote "**v**" the voting application generates a random number "**r**", so that the encrypted vote is $\mathbf{(C_1, C_2) = (g^r, y^r v)}$[26]
-The verification application, working instantly within 30 mins, receives "**r**" from the voting application (hidden in the QR code) and calculates $\mathbf{v = C_2 / y^r}$ where the voter is assured when the displayed "**v**" is the same "**v**" he/she voted for.
-When counting votes, the election authority uses the election secret key ($\mathbf{S_k}$) and El-Gamal encryption known equation « $\mathbf{y= g^{Sk}}$ » to calculate $\mathbf{v= C_2/((C_1)^{Sk})}$
-In the older design, the verification application only receives $\mathbf{C_2}$ from the vote collector. This gives a malicious voting application the chance to manipulate the encrypted cipher text by sending different values of $\mathbf{C_1}$ for the same $\mathbf{C_2}$. Without checking $\mathbf{C_1}$ value, the verification application will not detect a problem/error if the voting application sent a wrong "***r***" value to the vote collector; either to drop the vote from being counted (becomes invalid), or to craft a specific ***r'*** such that $\mathbf{y^r v = y^{r'} v'}$ to deceive the vote collector into recording ***v'*** as the voter's intended vote.

The authors found *three possible manipulations* all with *a simple fix (**only for verifying voters**):* making the vote collector send the whole encrypted pair (C_1,C_2) to the verification application which should also *verify that* $\mathbf{C_1 = g^r}$ as was finally done [57] on 23rd Feb 2023 just before March 2023 elections. The check methodology has changed in the 2025 version to checking that the pair (C1,C2) represents a valid point on the election elliptic

[25] All the presented equations are modular arithmetic over the finite field G, and in the IVXV used elliptic curve **SecP384bR1**

[26] Now it is clear why a voter revoting with the same choice should lead to a different ballot (and the voter will sign a different cipher leading to a different signature value also); hence, we believe the duplicate vote problem in Fig.3-b reflects more than that.

curve[27]; in the designated attack example; this will echo the invalidity error to the QR code if the adversary tried to drop the vote, or inform the voter that his/her vote was recorded differently (***v′*** instead of ***v***).

In 2022, the authors found it concerning [50/sec. 3.6] that such a straightforward vulnerability wasn't noticed earlier; they also criticized IVXV in general [50/sec. 4] especially in keeping the source code of the voting application secret. It turned out that the Estonian e-voting regulation law [31/§ 48^8/(7)] clearly states that "*The source code for the voter application is not published*", despite the contradiction we pointed out to in section 2.4.2; what was promoted recently (30th Sep 2025) as publishing the voter application refers to publishing only the new server-side code [58] that receives the already encrypted and signed ballot (step 3 in Fig.4) instead of communicating directly with the vote collector. The PhD in [48] says it is generally considered a national security matter; hence, we add ***an honest official voting application as a trust assumption in IVXV***, otherwise all risks associated with using a malicious voting application remain possible for the official one as long as it is not open sourced; see section 7.6 for how the Estonian report describes it.

5 Updates and Fixes in the 2024 version

In addition to extending IVXV to support voting with more kinds of digital identities like web-id and mobile-id, [59], the IVXV version 1.9.10-EP2024 included many other improvements. This section discusses three important fixes that were committed to the official code site on 30th May 2024 before the European Parliamentary elections on 3rd of June 2024[28] and the research efforts that led to them; it also discusses providing a fingerprint authentication check (section 5.4) for the voting application. See Table.1 in Appendix B for a summary.

5.1 Decryption of Invalid Votes

Invalid votes are now thrown in a separate file and ***ZKPs (Zero Knowledge proofs) are generated for correct decryption of invalid votes as well***. However, election observers are not allowed to access this file or verify those proofs and there were a lot of debating and complaints about that (section 2); the issue of observers' rights persists in OSCE/ODIHR 2025 report [16/sec. 3.3/65].

Why not reveal invalid votes?

The reason is better explained scientifically as T. Kraavi did in his master thesis, [19], than by the state election service as recorded in the supreme court decision [14].

-Reasons 1&2 in [14] talk about the technical infeasibility of decrypting invalid votes after the election and how this needs parts of the secret election key. The fact is, this was already done; meaning it is feasible, and the statement was kind of *misleading the court*. The interested reader can find the scientific details in [19] and/or trace the code in ***DecryptTool.java*** file [60].

-While the 3rd reason in [14] of "*not knowing in advance what the invalid ballot contains and it may be an attack*" seems vague and not convincing, the argument is rationalized in [19]; it is the possible reveal of some

[27] The files in [57] now, since 30/90/2025, contains only a RPC (Remote Procedure Call) *RPC.Verify*; the real check is now done in (https://github.com/valimised/ivxv/blob/published/common/java/src/main/java/ee/ivxv/common/crypto/CorrectnessUtil.java) and if an error is detected (not a valid point) it will be seen by all verification applications.

[28] Note that the time difference here is 3 days, while it was nearly 3 weeks in 2025; this is related to the delay complaint in [24,25].

information about the voter of the invalid vote, or more severe the threat of ***encoding attacks*** described in [61/ sec. 3.3 & 4.1] where an adversary can know the votes of say "k" voters choosing from n possible options in $O(n^k)$, if able to submit a carefully crafted invalid vote (composite from their encrypted ballots) and view its decryption. Hence, the rational is to shrink the circle of trust into auditors only, which is almost not needed if invalid votes were rejected earlier by the system (done in 2025 as will be discussed in section 6.). Note, however, that voters can make their own voting application that allows invalid votes, and accompany it with a verification tool that enables them to view the vote decryption [22,23]; this can defeat both cautionary steps and make the system vulnerable to encoding attacks if done by an insider. Tracing the *number of* ***invalid votes*** in the official statistical site [4] to be ***exactly 1*** in three local elections since 2021, increased to 2 in 2024 and to 3 in the test vote reading of 2025, but became 0 in the actual 2025 elections[29] with the issue being further discussed.

5.2 Integrity Checks

Another problem that was mentioned in *OSCE* 2023 report [2] is that the authorities are assumed trusted regarding *the deletion of multiple votes or ill-formed vote ballots*. Quoting their own words "*The critical step of removing the votes overwritten by another vote cast on the internet or in a polling station was not audited*", "*An insider with sufficient resources to alter the system, if able to do so undetected, could manage to control which votes are removed and therefore partially impact the results*". This was viewed by [62] as trusting the vote collector (VC) and registration applications (RS) to not collude, otherwise it would be possible to drop ballots; the *Ballot Processor* in Fig.4 could also manipulate the ballots (assumed trusted by the system). To elaborate more, yes there are decryption proofs that what goes into the *mix-nets* is exactly what gets out of it to be finally decrypted, and yes there is the possibility to design a public independent decryption proof verifier [49], but there was no cryptographic proof for the transition from the total list of votes to the "to be counted" list of votes; what is called the *processing stage* and we believe is part of *universal verifiability*.

IVXV Adopted Solution

What we believe is partial protection from this vulnerability (see section 7.1), was integrated into the audit application of IVXV through the files, [63], ***Integritytool.java & Intcheck.py*** in May 2024; the details of the solution were published academically in [64] as of 23/12/2024. The authors state that they have contacted IVXV team with their proposed checks to detect insider risks at the processing stage, and that it was successfully deployed.

The proposed checks are applied to the Ballot Processor data which is an offline computer [64/sec. 3.A] that performs some processing on this data (step 4 in section 4.2) to then input the list of anonymized votes to the mix-nets as shown in Fig.5.

[29] 2025 statistics are not added to [3] yet, but zero can be calculated from the numbers in (https://kov2025.valimised.ee/en/detailed-voting-result). However, in Q.29 of (https://www.valimised.ee/en/internet-voting/frequently-asked-questions/questions-about-reliability-i-voting); "*The person has to actively fight against the verification mechanisms of the voting server in order to submit invalid votes*".

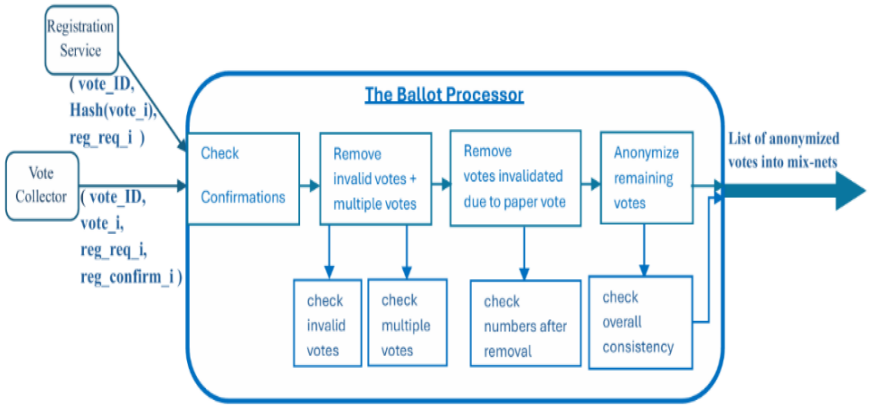

Fig.5. The (modified) processing stage after adding the *integritytool.java* file

Since the votes file (along with the necessary checksums) is cryptographically signed after each step, most examinations depend on comparing SHA256 hashes of subtotals, totals, and individual votes before and after each step. Also, *count-based validation* was needed to detect certain types of manipulations like adding the removed older multiple votes to the list of anonymized votes; i.e.,

Count (original votes file) - Count (anonymous valid votes) =
Count (multiple votes) + Count (replaced by paper) + Count (invalid votes) …Eq(1)

Note that the Ballot Processor receives the list of all votes along with any necessary confirmation checks [59/protocols.pdf/Fig.6.3]; i.e., the integrity of those cryptographic checks (like the *Count (original votes file)*) depends on trusting the vote collector and the registration application to not collude [62]. Hence, what was ***mitigated*** by [63,64] is ***the risk of a colluding Ballot Processor***; recall that it also helped in discovering other technical errors like those in Fig.3 of section 2.3.

5.3 Session ID & Time Checks

A possible attack by a malicious voting application that could deceive even verifying voters was discovered by Olivier Pereira in [51]; a malicious voting application could fake a system crash to deceive the voter to vote again. By doing so, the application can take the voter signature twice (generate another "***r***" value to construct and sign a new encrypted vote in the background); hence while showing the voter the QR code of his/her choice, the system will consider it an old vote and will use the new vote.

Previous Suggestions

- Olivier Pereira suggested a few mitigations in his paper, K. Krist's PhD [48/sec. 5.3] suggested others; none was actually adopted, and we will mention them as we go.

1. One may also recommend advising voters to double check the number of voting transactions with other available e-government services available in Estonia like *myID* service [65], especially if their device has suffered a system crash while voting. However, some doubted the usability of this kind of consistency check, considering it to be technically sophisticated for the average voter.
2. Another simple safeguard from this specific problem, [66], would be *to force a time interval between votes;* the verification interval, *30 mins*, seems a suitable choice. However, this must be accompanied by heavily warning voters to shut down their PC then reopen it again; the author in [51] warned from

Ghost Click attack[30] [53] if a compromised voter eID (PIN code known to the adversary) remained available on the voter's PC more than 30 mins. Also, this safeguard alone cannot prevent the ***timing attack*** discovered by [67] through *automated formal verification* where the malicious VA stores the encrypted ballot gained through the fake crash (or any other way) to submit it much later slightly before the election ends.

3. Both Pereira [51] and [67] suggested allowing to verify the last vote only, we thought of adding a flag to the QR code on whether this is the last vote or not.
4. While adding a timestamp to the QR code won't help the voter[31], a voting attempt tracking number as suggested by [51,67] will change in the revoting screen after the faked crash. Specifically, [67], the voting application should generate a session tracking number that is shown on the voting screen, added to the ballot, and checked to be new each time; the number should be embedded in the QR-code for the voter to check that it equals the corresponding number on the voting screen. However, some may view asking the voter to trace numbers as decreased usability.
5. Olivier Pereira suggested in [51], also was previously suggested in [53] as a mitigation for ghost click attacks, the use of a feedback channel (like an email or a mobile SMS) to inform the voter of a new vote but was afraid the malicious VA could be capable of delaying such message to the end of elections. However, IVXV team excluded this solution since it involves knowing (tracking) the voter identity and hence violates vote privacy and could be used by coercers/vote buyers.

-Jan Willemson argues in [9/sec. 4] that all such solutions could be used by a coercer/vote buyer to find out if the voter voted again and believes that advising voters to report crashes is enough protection. For suggestion 1 such risk exists anyway [33,34], where coercers are expected to be more technically sophisticated; for suggestions 2 & 4 the risk does not exist; suggestion 3 puts a coerced voter at this risk for a duration of only 30 mins (the verify duration).

Formal Verification & Extended Pereira Attack

Published on June 2024, [67] introduced for the first time an automated formal verification of IVXV security (treating cryptographic functions as black boxes). Their tool rediscovered the Pereira attack and another *timing attack* where the adversary stores the fake vote to submit it as late as possible to guarantee its count. We believe IVXV deployed the time difference & session ID checks suggested in [67].

IVXV Adopted Solution

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[30] In general a **ghost click attack** refers to automated or undetected clicks, that are generated by a malware, to trick a system or a network into beleiving the interaction was done by the actual user (https://cyberpedia.reasonlabs.com/EN/ghostclicks.html); the origins of the name is rooted back to 2011 FBI's *Operation Ghost Click* which was a large cybercriminal takedown of an ad fraud infrastructure that unfairly earned $14m (https://dl.acm.org/doi/abs/10.1145/2420950.2420954). In the context of IVXV, Springer et. al [53] introduced the threat on an older 2013 version (exactly after adding QR codes, but before IVXV as discussed in section3.2) if the adversary was able to intercept the PIN code of the voter digital ID and remained available on the voter's PC long enough; Pereira [51/sec.5] considered his attack a more of a threat assuming if compromising the PIN code was more harder (PIN handled by browser extension) or detectable (through other regular eID uses [48/ref.166].

[31] Even if the voter noticed the small-time difference, could think "maybe the system records the time when I started, not when I finished"; a vote counter can't reveal following votes either.

A solution to the generalized attack in [67] was added on 30th May 2024. The code was updated to check the session-ID is still the same before generating the verifying QR; the code documentation [69/lines 22&105&167][32] highlights that this "***prevents reusing session ID until it is deleted from a database or expired***".

Tracing a little deeper, [59/protocols PDF/sec. 8], the ***PKIX*** *(Public Key Infrastructure X.509)*[33] timestamp protocol is used by the registration service to record the time of casting the vote, while the ***rsyslog*** service records the logging time in milliseconds which make it possible to use the *Guardtime* module to ensure the integrity of the logs.

5.4 Authenticating the Voter Application and the Pereira Attack

As [67] warns, the solution adopted in section 5.3 cannot handle the original attack in [51]. The Pereira attack depends on the fast sequencing of the fake crash-restart scenario, a ghost click attack can also do that; in both cases, the malicious VA can still use the same session ID twice and generate a legitimate time difference. That's why we believe **combining this solution with the simple suggestion in 2 of section 5.3 (enforcing a 30 min gap between multiple votes) could prevent the Pereira attack.**

According to our study of available resources, IVXV published in 2024 the fingerprint of the official voter application with a documentary, [70], guiding voters on how to check it after the download. Other than that, they sufficed with the session ID check up till now in 2025 version; they adopted the argument in [9/ sec 4] that diminishes the effect of the attack to $(1-p)^n$ for n voters where p is the probability of a voter reporting a crash when it happens.

However, we believe that the effectiveness of reporting the crash, and authenticating the official voter application to begin with, holds as an argument only **if it is assumed trusted**. Removing the trust assumption necessitates publishing the source code of the voter application (VA) for voters (and possibly observers) to review the code and then compares its digest to that of the downloaded one; otherwise, if the probability of a malicious official VA is not negligible, reporting a crash would be like reporting a crime to one of the suspects.

6 Improvements in the 2025 election

In addition to publishing the server-side part of the voting application, [58], and the earlier publishing of the election source code in general, IVXV 2025 version 1.10, [71], included many other updates that were committed to the official code site around 30th Sep 2025 before the local elections on 19th of Oct 2025. This section covers technical implementation updates like changing the ballot vote format and the way El-Gamal encryption is verified, then moves to discuss in detail the significant improvements of using Range Proofs to prevent invalid votes from entering the system. These improvements are also included in Table.1 of Appendix B.

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[32] The file has slightly changed in the new version released 30/9/2025; checking the session-ID and the time limit for a voting session is in the server-side of the voting application, [58], and almost every code that deals with the vote.

[33] ***PKIX*** is a timestamping protocol that enables a trusted third party (called *TMS* in [66]) to confirm the existence of a specific data at a specific point in time with its signature; can check 4 times *thisUpdate*, *nextUpdate*, *producedAt*, *revocationTime* (https://datatracker.ietf.org/doc/html/rfc6960, https//link.springer.com/referenceworkentry/10.1007/0-387-23483-7_302)

6.1 Technical Enhancements

The updates in include, as detected by the authors of this paper, but maybe not limited to:

- Changing the ballot format, [58], in a better way to include the checksums integrity checks needed in section 5.2 and dynamic qualifying services (like the voter eligibility to vote or any other future purposes); this was reflected in the extra effort [22] needed to adjust their private VA, and the first error in Fig. (3-a) also came from it.
- The dynamic qualifying services in [58] includes also a check of the voting duration time to enforce a tighter time limit on the session ID; i.e., further enhancement of the session ID tracking safeguard discussed in section 5.3.
- Some changes to handle the new eID chip platform discussed in footnote 15; one can also trace future plans (TODO parts of code) for the upcoming new *Thales* cards (footnote 16).
- Switching the regular check of El-Gamal encryption pair (the vote), which involves exponent raising, to the more efficient check of it constituting a valid point on ECC the Election Elliptic Curve *SecP384bR1*, [72], as discussed in section 4.3
- Enhancing the mix-net shuffling code, [73], to add support for the elliptic curve cryptography methodology introduced above. We could not accurately trace repeating the mixing into more extra rounds as previously criticized; however, the new protocol file [71/protocols.pdf/secs 7.1,10.1] explains that in this local election votes are first grouped according to district before mixing.

6.2 Range Proofs

To eliminate any complaints (like [14]) and/or risks (ex. [61]) accompanying invalid votes, it is much safer to prevent them from reaching the Ballot processor at all. The thesis in [19], followed by the scientific report [74], suggested the use of a Zero Knowledge Proof (***ZKP***) check by the Vote collector application to check the validity of the vote it receives from the voting application without revealing it and hence reject invalid votes before being added to the list of votes.

-The thesis preferred the use of ***Range Proofs*** as opposed to ***Set-Membership proofs*** for their simplicity and suggested some mitigations to the discontinuity of the set of vote choices. The authors proposed Range Proofs that are based on ***Bullet Proofs & Pedersen Commitments***, since they depend on the Discrete Logarithm problem like El-Gamal encryption used in IVXV. They considered general purpose SNARKs (Succinct Non-Interactive ARgument of Knowledge) based on polynomial commitments not suitable for El-Gamal based voting systems; the Range proofs presented above are what is implemented in the 2025 IVXV version (with TODO parts to optimize proof aggregation for larger ballots). The validity check can be clearly traced in the published server-side part of the voting application, [58], which performs different checks (including Range Proofs) on the vote before sending it to the vote collector; the Range Proof check was also added to the verification code. Tracing the number of invalid votes, [3], it was exactly 1 in three local elections since 2021, increased to 2 in 2024, then became 0 in 2025 elections. Only the 2025 pre-election trial test vote experiment we discussed in section 2.3.1 contained 3 invalid votes, but this was a ballot format matter not about the cipher itself[34]; voters can still send invalid votes through their own voting applications.

[34] 2025 statistics are not added to [3] yet, but zero can be calculated from the numbers in (https://kov2025.valimised.ee/en/detailed-voting-result). However, in Q.29 of (https://www.valimised.ee/en/internet-voting/frequently-asked-questions/questions-about-reliability-i-voting) "*The person has to actively fight against the verification mechanisms of the voting server in order to submit invalid votes*". We are not sure the word "fight" exactly

7 Remaining Issues & Further Research suggestions

This section collects existing research that either points to remaining vulnerabilities in the IVXV Estonian i-voting system or suggests further enhancements to strengths its security, then seals with a holistic view of the status quo. Table.2 in Appendix B summarizes the findings of this section.

7.1 Adding NIZKP (online) to remove trust assumptions

This was first suggested in 2022 by [61]; to add a *NIZKP of knowledge* to each encrypted vote as a protection from privacy attacks. The 2024 version of IVXV (1.9.10) partially responded; the Registration Service now sends *hash(vote)* to the Ballot Processor (Figs. 4&5) as explained in section 5.2. Tracing the code [63/line 239], vote hashes are stored in a *Treebag* which represents a binary search tree data structure in Java; i.e., even if it reflected a Merkle tree design, the number of nodes in a Merkle tree (votes) is not cryptographically verified. Also, Range proofs were added (online) in 2025 as explained in section 6.2; however, it is not just privacy attacks, and it is not just the Ballot Processor that we need to remove trust from.

In 2022, [48/sec.5.1.2, 44] discussed IVXV trust assumptions including software components and key holders; in 2023, [62] acknowledged the risk if the Vote Collector (VC) and the Registration Service (RS) colluded together. The 2024 [67] usage of automated formal verification methods [76] asserted the same result; when analyzing IVXV End-to-End-Verifiability (EEV) and privacy under 9 different combinations of trust assumptions [67/Table1] for an adversary controlling more than "some voters' credentials", EEV^{+} (that maps to current IVXV status) fails if 2 of (VC, RS, timestamping service TMS) colluded. Also, both the OSCE/ODIHR 2023 [2] and 2025 [9/sec. 3.3/28] reports mentioned persisting political parties concerns regarding insiders' trust.

Hence, the 2025 E-Vote-ID conference contained two suggestions of using Vector Commitments (sometimes referred to as Verkle Trees); the first [77] is a poster that suggests the use of Verkle trees based on KZG commitments to cryptographically prove the number of ballots as well, and the second is a paper [78] suggesting those based on Pedersen commitments. Readers interested in deep cryptographic analysis of the differences can find it in [79]; however, we anticipate that the next version of IVXV will deploy Pedersen based vector commitments. The suggestion in [78] aligns with the system's previous choice in Range Proofs, the authors are from the IVXV team, and they claim faster simulation time of less than 1 second.

As a basis for comparison, note also that the trusted setup phase in [77] (KZG based vector commitments) involves an integrity risk, not just privacy like the current IVXV election secret key setup phase (see Appendix A). Another alternative suggestion in [77] is to use ZK consistency checks with other transaction activity logs existing in Estonia (like *myID* [31]), this could be combined with the use of *Risk Limiting Audits* (*RLA*s) where a random sample of votes is checked manually for consistency. Since [77] was originally part of this paper, Appendix C holds more details & discussions about those two suggestions.

7.2 Integrity-Coercion tradeoff and other existing sources of information

The PhD in [48] was the first resource we encountered, 2022, concerned with the tradeoff between integrity vs coercion resistance when discussing mitigations for handling a corrupted voter device. Also, [61] demonstrated

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reflects "computionally infeasible"; besides, if invalid votes ballots cannot enter the system at all, why an extra validity check is added to the verification application.

(through introducing the possible privacy attacks discussed in section 5.1) that *IVXV is vulnerable to attacks against vote privacy in those threat scenarios that were considered for it originally*. In addition, [67/ Fig.1.D] usage of automated formal verification methods discovered a new attack against privacy using some form of replay attacks.[35]

Getting back to the Estonian research, in 2023 M. Poder presented it clearly in a poster [17] how the *myID* service [65] can provide hard copy evidence of the last e-vote in Estonia which destroys the multiple voting defense against vote coercers/buyers (recall the discussion in section 5.3) and contradicts with the election act [31/§48^6/(9)]. Accordingly, in an earlier version of this paper, we raised the broader question of *to what limit can the information provided by general purpose activity logs of digital identities* (in any country that uses digital identities in online voting) *help vote buyers/coercers* in catching voters who try to deceive them. Or even broader question of **Integrity vs. Privacy** in any e-government: To what limit can duplicating information to facilitate consistency checks (like the information provide users' general purpose activity logs of digital identities) or duplicated meta-data that exists in large information systems, contribute to information leakage and hence violates users privacy (whether by vote buyers/coercers or for any other malicious phishing purpose). Then, in Oct 2025 [68] discussed the specific Estonian case and suggested different possible solutions like making election transactions secret or obfuscated or even using a special ID card for e-voting that doesn't allow such integrity checks on its transactions. The last suggestion does not seem to align with the system's main strategy of allowing the usage of different digital identities (see footnote 3); the first suggestion, on the other hand, does not prevent consistency checks as described in Appendix D and [43] as they use zero knowledge techniques and do not necessitate the revealing of transactions raw data.

A final remark on this context is that suggestions that involve applying aggregating queries as consistency checks on the election results numbers, like [77], can still be deployed with any of the suggestions in [68]. Those queries are assumed to use zero knowledge techniques; i.e., they do not necessitate revealing the raw transactions data.

7.3 Automated Formal Verification and Mix-net Servers

Although formal verification tools in general, like [76,80], treat cryptographic details as black boxes that one may diminish their value in testing IVXV, two independent attempts were introduced in June 2024 from Luxembourg and France; to our knowledge, the literature does not hold automated formal verification analysis of IVXV done by researcher from Estonia. We believe this useful security tool should be added as a casual routine check before the release of each new version of IVXV.

The first, [67], was discussed in sections 5.3 and 7.2; the second [81] was mainly concerned about mix-net servers. The authors used *ProVerif* , [80], to discover [81/ sec 4.3 & Table 5] the same privacy attacks in [61] showing that they can only be defeated using a strong NIZKP for each vote (section 7.1); the paper also contains a comparison analysis between exponentiation mix-nets and re-encryption (like IVXV) mix-nets for the interested reader.

[35] The attack copies b=(C,s) of an honest voter into b'=(C,s') where s,s' are the signatures of "C" the ballot as a whole C=**(g^r , y^r v)**=(C1,C2) in the terminology used in this paper. They say this strategy of minor biases in the outcome could be generalized leading to quantifiable privacy violation [67/ref.44]; as a straight forward step, if you can vote with an exact copy of another voter cipher, you can reveal his/her choice by verifying your vote.

It is also worth discussing that IVXV uses only one single mix-net server[36]. Although *Verificatum* uses in its documentation, [49/ref.1], an example of 3 mix-net servers, IVXV uses its own implementation of one single server; the argument is simplicity and that distributing the key into parts provides an additional security layer. As a basis of comparison, the Swiss-Post i-voting system used in Switzerland has 4 mix-net servers and [82] discovered that NIZK proofs must be verified after each server not just at the end of the whole shuffling process.

7.4 A Safety-Critical Audit Methodology

A recent research article, [83], suggested auditing the i-voting code as a structured software-testing task grounded in mission and safety-critical principles. Concentrating on the processing stage as an extension of the earlier work in [64] (section 5.2), the paper defined three-phase artefact-centric workflow combining DO-178C[37] structural coverage and mutation-testing principles. Phase A was instantiated by defining 19 requirements, 37 fault scenarios, 6 explicit oracles, and a GDPR-neutral corpus[38] to enable independent, reproducible, and evidence-based evaluation; however, Phase-B (execution) and Phase-C (Validation and Reporting) were conducted only on a test sample of 7 voters with 10 votes. Note that checking for anomalies, that we are going to recommend in different cases presented in the following sections, could fall under the fault scenarios discovered by [83] as "should be reported" by the code.

We have also encountered another article from Brazil, [84], that discusses AI usage in anomaly detection and the possible privacy risks associated with it; the article, which is mainly concerned about the Estonian i-voting case, mentions that AI is already used by the Estonian e-government in decision making process.

7.5 The Voting/Voter Application (VA)

We believe the voting application is the most persisting and/or serious integrity problem in the Estonian i-voting system. All risks associated by previous literature with a corrupted voter device, or a corrupted communication channel, are perfectly feasible with a malicious voting application and even more.

7.5.1 Associated Risks

In addition to the usability issues regarding the available authentication method added in 2024, [70], of the official VA; as long as the code is not published, it is based on a trust assumption of it not being malicious. Getting back to the student complaint in footnote 18 of section 3.2, the QR code verification was an enough solution for ***individual verifiability***[39], but with more than 90% non-verifying it is not enough evidence for

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[36] We thank a previous anonymous reviewer of an earlier version of this paper for pinpointing that weakness point.

[37] DO-178C (Software Considerations in Airborne Systems and Equipment Certification) is the primary international standard used by aviation authorities to ensure the airworthiness and safety-critical reliability of software used in commercial aircraft (https://en.wikipedia.org/wiki/DO-178C).

[38] ***GDPR*** refers to *General Data Protection Regulation* made for the European Union (https://en.wikipedia.org/wiki/General_Data_Protection_Regulation); hence, "*GDPR neutral corpus*" means that the data collection used has been anonymized so that they do not contain personally identifiable information. In fact, this is the reason this paper was put in section 5, since the trial vote experiment discussed in section 2.3.1 shows that a voter identity was revealed; i.e., we believe the paper idea remains in the category of "possible future improvements". However, some of the raised error flags do comply with the fault scenarios in the paper.

[39] The term "***individual verifiability***" refers to proving the correctness of each voter's vote with overwhelming probability; after the fix in sec. 3.3, IVXV had no detected problem in individual verifiability until the trojan horse pointed out by this

universal verifiability; the election result may be very well altered by a malicious voting application. In fact, anyone who has enough access rights to edit a few lines of the secret code, or upload a different file to the site, can do that. If non-verifying voters can be identified somehow, for example through social engineering or AI [84], traditional techniques for Public Bulletin Board (PBB) attacks can be used here.

In addition, *new technologies like online coding through blockchains and smart contracts*, [85], have introduced more capabilities to render automated large-scale attacks and/or execution attests for vote buyers/coercers, [39] and Fig.6, feasible. The attack in [39] could be viewed as an extension of the *copy attack* presented in [67] (which we discussed in section 7.2 and footnote 32); the adversary writes an encrypted ballot $\mathbf{(g^r, y^r v)}$ for the malicious VA (or the voting trojan horse) to copy with added randomness $\mathbf{(g^{r+rnew}, y^{r+new} v)}$. Note that, in this case it is possible that neither voters nor middlemen know the true vote; by middlemen we mean those who distribute the malicious VA, sell stolen credentials or negotiate vote price with voters. In addition, the attack shows that it is possible for the cloned vote to be determined by code (the path 3abc for step 3 instead of the direct path 3') through an **online auction** (and still be sent encrypted to voters); in this case, blockchains gives **anonymity** to both vote sellers (could be middlemen from the country or dark web) and bidders (possibly election candidates or anyone who wants to interfere with the election results). The payments could be also automated (step 6) through execution attests; for example, if the middleman claimed to control ***n*** voters during the auction, he only gets paid according to the execution attests counter. The attack intuition came from[40] the *DARK DAOs* idea in [85, 85/ref.33] for vote buying in ***DAO*** (*Decentralized Autonomous Organizations*) governance, and from *TEEvil* in [86] showing how ***TEE****s (Trusted Execution Environments*) can play an evil role in e-voting.

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paper. ***Universal verifiability*** on the other hand refers to the correctness of election results, whether it could have been altered or not; for example, many researchers do not consider tracing individual errors, which we suggested in sections 2.3&2.4, part of universal verifiability if those errors were not to alter the election result (the difference between the winner and the loser is more than the number of doubted vote). However, universal verifiability is considered part of ***end-to-end verifiability*** as can be deduced from [happy path/11, happy path/24]

[40] The author has also heard in the news that vote auctions on Iraq elections happened in Dubai, where UAE is the most famous of blockchains and DeFi experts in the middle east, however this was after the poster publishing and we do not even have an evidence that, if really happened, it happened through online auctions.

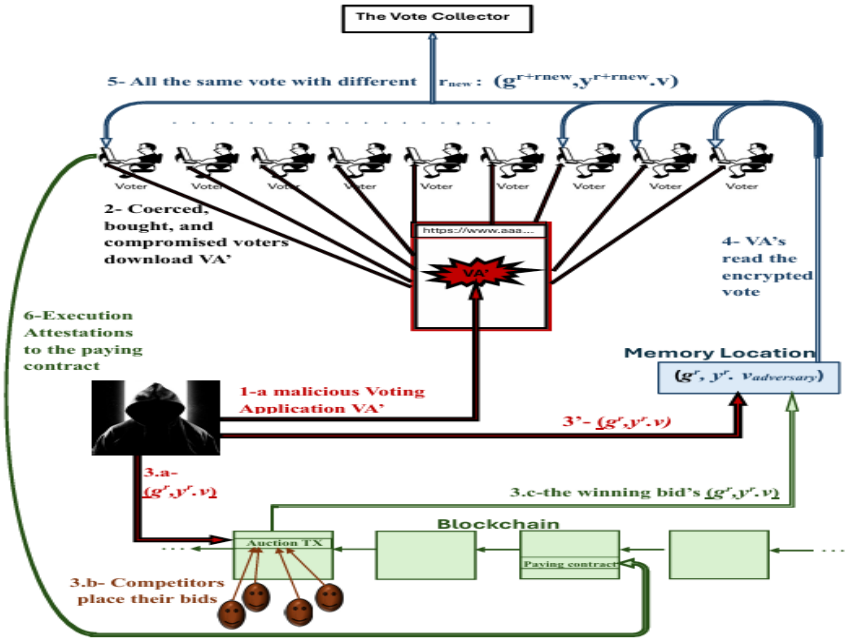

Fig.6. Automated Ballot Stuffing Attack, figure adopted from [39] with intuition from Dark DAOs idea in [84,84/ref.33].

On the Argument of Observable Anomalies and Comparison with attacks in [53]

Although risks from malware and compromised voter credentials, ghost click attack as an example, have been introduced since 2014, [53], researchers [51] have limited their effect for newer versions based on the newer 2015 design IVXV. Recalling the comparison of the attacks impact Perreira. [51], made and discussed in footnote 12; we believe PIN is handled now by the government-secured web browser extension for each digital ID.

Besides, the attacks introduced here are different; all variants of Fig.6 (step 3 or step 3', with or without step 5 or step 6) do not assume compromised voters' credentials, they only assume the ability to distribute a malicious VA on a large-scale. The attack also rings a bill on how automated execution can drastically change the equation; [49/ref.166] was written in 2014 before smart contracts provided online execution [85/sec.3&5], and TEEs (Trusted Execution Environments) provided execution attests. Those researchers warned from possible "evil" uses in e-voting ([86] since 2019, [85/ref.33] in 2018); however, it seems that their warnings have not reached the e-voting research community though. An important note here is that although those new technology threats are applicable to most i-voting system, their impact is amplified in the Estonian case due to the possibility of malicious voting applications.

Finally, like all other attacks, [51, 53, 67], the time and session ID checks deployed in 2024 (section 5.3) limit the risk to the time the attack is triggered; i.e., the generated ballot cannot be stored by the adversary to be submitted in the last minute.

7.5.2 Suggested Solutions

-The only defenses we find possible from the trojan horse case, without solving the voting application problems, is for the Estonian government to separate i-voting transactions. This could happen **by adding a meta data field that check the application category** so that IVXV does not accept transactions from applications registered as

gaming, buying,...etc; also, could be achieved through the suggestion in [68] of **using a separate ID card for e-voting transactions**. However, the first interferes with the whole e-government mechanism and the second does not comply with IVXV philosophy of integrating more digital IDs and we find no way out of authenticating VA.

-We suggest as safeguard to protect from the copy attack, and from situations like that in Fig. (2-b) whatever caused it, is **to check for equal values in the list of encrypted votes** and raise an alarm if found any. This could reflect an attack that repeats an adversarial encrypted choice through a set of compromised voters' credentials (whether bought, coerced, or hacked); note that this protects only from the simplest form of the attack in [39] if the adversary did not add a fresh randomness to each clone to be **(g^{r+rnew}, y^{r+new} v).**

-Other suggested solutions are mostly straight forward; change the law to **publish the official voting application** with a more **simplified batched authentication** [86] to check the published code is the used one; allow only **private VAs** that **are pre-registered** and hence **authenticated** and examined for malicious code before the election; encourage voters to verify; **alarm voters** if their vote was casted using a private VA and alarm voters of a new voting transaction in general.

Absent Voters
-All mentioned risks can be magnified for absent voters, as there is no QR code to check; recall the case in [38] mentioned in section 2.3.4 and see Appendix D for more details.
-Simple suggestions could be to encourage voters to vote in the first place (maybe by **adding a "reject all" or "boycott" option**) and/or encourage **nonvoters to check if someone forged a vote for them** using services like myID service. Also, observers could take ***a* random sample** from those who did not vote and those who voted (online or poll); the sample is to be **checked against the election results** using known statistical methods like different *Risk Limiting Audits (RLA)* techniques.

7.6 Cyber Security Committee 2025 Report

We appreciate the Cyber Security Committee step in Spring 2025, [88], to change its assessment methodology to include *risks that become more serious due to the combined effects of several hazards* which perfectly describes the attack in [39] and the trojan horse attack. Navigating the report, we find 5 out of 9 threats that were considered noteworthy threats are about the *voting application* (section 7.5.1). The other four noteworthy threats are the *quantum* threat we will discuss in section 8, the *developer dependence* threat of using a limited number of developers for the whole system code especially with the absence of bug bounties and the secrecy of some of its parts, and finally 2 risks associated with poll station voting canceling an e-vote (section 7.5.2).

7.6.1 Noteworthy threats concerning the Voter Application (VA)

- They admit that the distribution of mock voter apps undermines election integrity.
- They have also assessed the threat of both open and closed source code voter application (VA) and found that their impact is similar, but the possibility of a threat event is higher in the case of closed source code. They describe the trust problem as the threat of "*code written into the voter application that manipulates the voter's expression of intent*". The report also added the risk of not detecting programming errors, security vulnerabilities, back doors, covert channels, and side channels; the same old known argument behind publishing encryption algorithms to encourage cryptanalysis instead of keeping them secret to limit cryptanalysis. The report considered that publishing the VA code will make it easier to produce a malicious VA, what sometimes referred to as a *rogue application*,

even though non-official VAs have already existed since 2023 without publishing the official one; however, we acknowledge a recent research article, [89], that recommends hiding parts of the software.

- They examined added threats when allowing voting through smart phones; whether to download the VA from an official site or make private contracts with Google play and Apple store to prevent fake applications. As a less significant threat, the report also discussed whether smart phone voting is worth the effort or is it better to dedicate the effort to enhance the security of the current system. We believe that malware attacks may become more possible with smart phones voting; a questionable risk is whether any malicious application that takes the voter signature could embed a voting trojan horse. Maybe that's why the report recommended making private contracts to prevent fake applications.

7.6.2 Threats from the connection with poll station voting

Recall the absent e-voting incident in section 2.3.4, there are possible reverse risks; the thought of "*what if the voter is lying, or the poll station officer is lying*?" rings a bell on providing guarantees that poll station officers do not alter the election results by altering the names of poll station voters. Presumably, there are enough guarantees that the number of paper votes in a voting booth equals the number of names marked as voted there; what guarantees can prevent a malicious poll station worker from marking the wrong individuals.

A possible scenario is to mark some e-voters if they are known in the district of their support to a certain candidate who encourages e-voting, in place of another candidate supporters who can now double their votes through e-voting. Some may minimize such probability as unlikely, because in the Estonian case complainers are those who advise their candidates to vote in poll stations; however, politics are sometimes deceiving.

Protection suggested in the academy report

To use a notification channel (ex.: an email) to inform the voter of a poll station vote; this will work for wrongly canceled votes. Then we can use the same probability argument in [9/sec.4]; if a voter will report a forgery to the election authority with probability "*p*", a malicious poll worker who altered *n* votes will be detected with probability $(1- p)^n$. However, we remind that an adversary could have the power to delay or block the side channel messages; a risk [51] has warned from.

We suggest the following

1. Before deleting e-votes corresponding to poll station votes, check for anomalies like an e-vote with time stamp larger than the timing of the corresponding poll station vote; this involves accurate timing of poll station votes, which may hesitate malicious workers from conducting the attack as an added advantage. Another anomaly could be that a significant ratio of cancelled votes came from a certain poll station.
2. Take a random sample from cancelled votes and check that they had really voted in the corresponding poll station; *RLA* measures may be applied on the sample result.

7.7 Quantum Computing Risk

The report in [87], and earlier Estonian efforts [88] included in its new assessment methodology *future risks* and featured the quantum threat as *noteworthy* threat. Quantum Computing (QC) devices, whenever they exist, will

be able to solve most known hard problems (like *the discrete logarithm problem*[41] used in El-Gamal encryption) in faster polynomial time. This can break the cryptography used in IVXV which necessitates the migration to new post quantum cryptography (PQC); however, the transition is expected to take years for many reasons[42]. The report also shares our warnings in earlier versions of this paper from the privacy violation if old election data were leaked to be decrypted[43] when QC is available; a concept cryptographers call[44] ***Harvest Now Decrypt Later (HNDL).***

Protections suggested by the report include ways and/or measures to make sure of complete destruction of all existing copies of encrypted ballots after the election; in the current system, all election data is usually destroyed (deleted) after a month from the election.

While Appendix F is dedicated to the Estonian efforts toward the post quantum transition, we suggest here some quick solutions that could be applied on the current IVXV version prior transition; we build on the fact that Symmetric key encryption can tolerate by increasing key size and SH-2, SH-3 hash functions by increasing hash length. First, hash function parts like the voting application authentication (whether as it is in [] or batched as in []) and the 2024 integrity checksum of votes [] can easily be made quantum secure. Then, **for the HNDL as a current threat that needs fast mitigation, we propose the following solution**.

7.7.1 Idea & main theme

- The main idea is to reveal only data encrypted by a post quantum secure encryption algorithm; i.e., adding a 3rd envelope layer without disrupting the main system stages or violating its main guarantees. We chose a fast symmetric key encryption algorithm AES (Advanced Encryption Standard) with increased key length of 256 bits to be quantum secure.
- The obvious most secure option is to let the voting application (VA) encrypt each ballot online before sending it over the network; however, this is the core efficiency problem in the post-quantum transition. Hence, we will be concerned with the insider threat on the whole list of votes, not on individual ballots intercepted by adversaries over the network; we will do it offline, in a pipeline mode, at the vote collector (VC) to not affect the performance at the user side.
- The AES encryption step should also include adding verifiable cryptographic commitments to the original list. Possible other options range from a simple cascaded hash of already existing vote hashes and a vote counter, a Merkle tree root of vote hashes which allows verifying sample witnesses, to strong cryptographic NIZKPs like Pedersen commitments currently used in Range Proofs and suggested for other parts of the system. We suggest using AES in Galois Counter Mode (GCM) [89,90] to provide authentication and counter checks[45] on the encrypted data in the same solution package and leave further analysis of other alternatives as possible future work.

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[41] For example in the pair $(\mathbf{g}^{\mathbf{r}}, \mathbf{y}^{\mathbf{r}}\mathbf{v})$, it is computationally infeasible (takes exponentional time) to find $\boldsymbol{v}$ without knowning $\boldsymbol{r}$ or the election secret key $\boldsymbol{S_k}$ as explained in section 2.3; if a QC device exists, it can conduct a brute force attack (try all possible values for $\boldsymbol{r}$) in polynomial time.

[42] https://e-estonia.com/cybernetica-post-quantum-cryptography-joins-to-menu

[43] The report exact words as translated by Google "*Reorganizing the elections will not help, because people's preferences have become public. This would most likely mean the end of i-voting in Estonia*".

[44] https://a16zcrypto.com/posts/podcast/quantum-computing-what-when-where-how-facts-vs-fiction/; https://www.hashicorp.com/en/harvest-now-decrypt-later-why-today-encrypted-data-isn-t-safe-forever; last accessed 24/4/2025.

[45] Recall when we discussed in section 7.1 the cryptographic proof on the number of votes in the Verkle tree solution, verifying using AES-GCM would provide that check on the total number of votes entering the Ballot Processor.

7.7.2 Setup

The AES key, and initial vector (IV) if AES-GCM is used, should be generated during the setup phase with the election public-private key pair; ; note that this key will be internal to the system and need not to be exchanged with voters.

7.7.3 Solution details

We put the AES encryption module at the vote collector (VC) or the VA server side; the solution steps are demonstrated in Fig. 8 and can be detailed as follows:

1-After receiving the ballot from the voting application (VA), the system sends it to an offline post quantum symmetric key encryption algorithm (AES-256) before sending them to the ballot processor (BP). In our design, we use AES-GCM and expect it to include the meta data in its cryptographic commitments as explained in [90].
2-The ballot processor (BP) can perform its task of removing uncounted votes and consistency checks (Fig. 5 & section 5.2) as usual on the encrypted vote and its meta data; the only difference is that the AES-GCM authentication replaces the hash check.
3-The mix-nets also perform its task on an AES [anonymized El-gamal encrypted votes list]; the AES list gets shuffled with verifiable NIZKPs added as usual. The publicly verifiable data are now immune to HNDL.
4-An extra AES decryption step is done to get the original anonymized El-Gamal encrypted list of votes to be counted. The original SHA-256 vote hashes could be checked again at this step as a further integrity check.

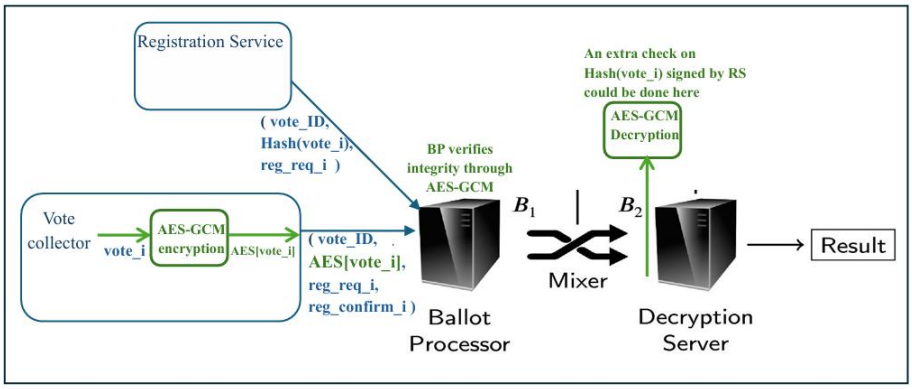

Fig. 7. a block diagram showing how the AES encryption could happen at the vote collector VC to provide protection from HNDL.

7.8 AI Risks

The previous report, [87], only mentioned as a less significant the possibility of an AI installed on the voter device could infer and leak the e-vote. Another independent research work in 2025, [84], discussed the pros of using AI for anomaly detection in the auditing phase and the data leakage risks that maybe associated with that; the paper also warned from the possible usage of AI residing in places that is not under the regulation of the European GDPR.

In light of the recent attacks conducted solely by AI[46], *we classify AI attacks as a* ***significant threat.*** In addition to the previously discussed risk of deceiving a voter to sign an unintended vote or identifying non verifying voters and non-voters as targets, the risks include identifying exploits for attackers or performing a general attack on the system.

7.9 Final thoughts on the status quo

In 2023, [62] analyzed IVXV *public information* as *satisfying* only *1 out of 9* (minimal restriction on disclosure of vulnerabilities) *quality metrics*[47] and warned from the possible existence of hidden vulnerabilities. In June 2024 mins of meeting [88] and secret report, the commission classified the 6 security risks found as "Higher than low"; in October 2024 they published in a conference [40,89] that all ***6 risks are medium*** and announced the existence of another ***25 low risks***. Their 3-5 (out of 6) focus of development areas supports our discussion about revealing and authenticating the voting application; this was assessed again in the new report released Sep 2025, [87], as discussed in section 7.4.3.

This proves that IVXV is continuously evolving and improving with time; we traced many improvements in IVXV 1.9.10-EP2024 and then in 1.10-E2025.[48] However, here comes another issue; if we have missed some updates, we believe it is because "***IVXV does not welcome strangers***" as a general attitude and favors researchers from Cybernetica team or the Estonian Universities as the most outer circle. The last English language PDF files are dated to the 2022 version which can be traced as the cited reference in all 2024 outsiders' research like [67,81]; we had to use browsers translators, trace GitHub commits, social media posts, use AI and contact involved personnel. This was also illustrated through the mix-nets available material; we could not find any document that states clearly the number of used mix-net servers, which turned out to be only one, especially that the cited documentation of *Verifactum* in [49] uses a 3-servers example for demonstration.

We seal this section by raising a question on ***whether e-voting systems are classified as a political national security matter countries ought to be discreet about, or a security research area and a cryptanalysis topic open for researchers?*** The authors of this paper are not against e-voting; we believe that although it introduces new risks, it still provides means to detect what cannot be detected using paper voting only. However, this necessitates open discussions as Estonian academics believe, [40,87,90], though real actions sometimes contradict and implies the national security matter convention mentioned in [48].

8 Summary & Conclusions

In this paper we gave a political and technological historical brief on the development and status quo of the Estonian internet voting system IVXV. We have also shed some light on the technical activities and complaints

[46] https://www.cybersecuritydive.com/news/anthropic-state-actor-ai-tool-espoinage/805550/, https://www.anthropic.com/news/disrupting-AI-espionage

[47] Used quality metrics were defined in an earlier paper by the same authors (FC'21, *New standards for e-voting systems: Reflections on source code examinations*)

[48] In 2024, GitHub showed 897 changed files with 34,059 additions & 10,830 deletions; in 2025, it shows 732 changed files with 11,532 added lines and 39,893 lines removed. Translating [59], dated 2024, a lot of work was done in integrating different kinds of IDs and in coordinating with XRoad service (X-tree). A whole section is dedicated to Registration Service, [59/protocols/sec.6]; the interaction between online (RIA), offline (RVT) and other IVXV services. The same applies for the 2025 version.

of the opposing community against e-voting in Estonia along with analyzing the incidents that triggered them and advising some recommendations. We explained the current system architecture and surveyed available material from academic literature and different other resources to cover reported attacks and/or vulnerabilities and how they were fixed by the system throughout the years, with extra focus on the 2024 and 2025 versions.

Then we discussed the remaining issues and the suggested research solutions; we addressed the concerns of opposing parties in their meeting with ODHIR [16/sec.3.3/28]; we warned about the feasibility of orchestrating large-scale attacks with the existence of new technologies like online coding and code attestation. Hence, we recommend dealing with published easily authenticated voting applications and adding strong NIZKP (not just checksums) to each vote. Finally, we did not neglect to mention the Estonian efforts towards the upcoming quantum computing threat, and to warn from new AI possible risks although we leave the exhaustive analysis to a future work.

The technical suggestions of this paper are summarized in Table 2 of Appendix B; however, general suggestions include tracing individual errors even if they are not to alter the election results and performing a reading process before closing the poll station voting to give a chance for error votes to express their opinion. Then, we strongly advise the Estonian government to publish the voting application code even if they had to change the regulation for that. Last but not least, for the electoral commission and the IVXV team to be more open to scientific discussions as stated in their own recommendations [40,88,90].

Finally, we hope also our reader has realized the so many steps and details involved in digitizing elections; from regulations to chip cards used for digital IDs to auditing from the setup phase and software installation up till the verification; from cryptography & cryptanalysis to software developments to political game theory sometimes; …etc. Yet the journey is worth the trip; for elections as it provides extra tools to detect and trace malicious behavior, and for researchers as it embraces a rich and diverse field material. While writing this paper, we navigated through, and gained knowledge from, a variety of different research areas; there is geopolitical factors and there effect on the security game, cryptography with cryptanalysis, zero knowledge proofs with their implementation details, automated formal verification methods, blockchains online smart contracts, hardware related details like execution attestation and informing users, repeatable software builds, code tracing for those many files, and finally the secrecy of the voting application retrieved an old read in Bruce Scheiener "*Applied Cryptography*" book of an old debate about the secrecy of cryptographic algorithms used by governments. We hope readers of this paper from those different research areas have found something useful they can build upon.

9 Possible Future Work

We have already stated that defense from AI attacks is a possible future research direction. In this section we go through possible research threads that could evolve from the gathered material, even if not necessarily pursued by the authors of this paper.

9.1 Range Proofs

First, the thesis in [22] and the scientific report in [24] contained a detailed argument for preferring Range Proofs based on Bullet Proofs Pedersen commitments over general SNARKs; since we started with proposing Verkle Trees based on KZG commitments we pursued some further research.

-The original paper for Microsoft *ElectionGuard*, [91], also assumed the existence of NIZK (Non-Interactive Zero Knowledge) Range Proof for ballot correctness in their system; the implementation of *ElectionGuard* v.2

used ***disjunctive Chaum-Pederson*** Range Proof[49]. We could add that whatever the underlying cryptography is, ZKPs that are based on the discrete logarithm problem (like *bullet proofs* and *Chaum-Pederson*) enjoy faster prover time than general purpose SNARKs. This is a desirable quality for ballot validity proof since the voting application is the prover (the vote collector is the verifier); the prover code must be executed online during the voting session and cannot be batched or pipelined even if the used ZKP allows it.
-We found a recent paper, [92], (a follow up to *Kryvos* referred to by [22] in the comparison) introduced benchmarks for an efficient implementation of *Groth16* over El-Gamal based voting systems. The authors used a 254-bit common elliptic curve BN254 in their implementation, while IVXV uses 384-bit curve; note that the circuit specific setup needed in Groth16 could be considered a drawback.
-Another 2024 paper, [93], introduces *Polymath* proving it can be more efficient than Groth16 and relates it to KZG commitments[50]. Here, the authors did compare KZG and Groth16 over a 381-bit curve (BLS12-381) which is closer to the one used in IVXV; their work also included mathematical proofs for batching reductions.

The work in [92] could be a starting point for researchers concerned with hardware acceleration of Zero Knowledge Proofs that goes in depth into circuit specific details, while [93] would be useful for researchers interested in theoretical cryptographic proofs. Also, research can be further pursued to conduct comparative analysis between possible zero knowledge proofs concerning implementation details along proof batching reductions over the exact 384-bit elliptic curve used in IVXV, or any other e-voting system for that matter.

9.2 Post Quantum Research

Even in validity proofs (Range Proofs for checking the validity of votes), a more far-sighted research direction is to seek post-quantum validity proofs; comparing different post quantum NIZKs and SNARKs that can be used in all places of the system where hashes can be easily transformed to post quantum ones.

The quantum cryptography research space is challenging, [94], on the efficiency-security tradeoff; demanding for new innovations [95], for cryptanalysis [96,97], and formal verification [98] of the new PQ protocols (how to prove correctness and security if it is not verifiable on existing hardware [99]). In addition, side channel attacks[51], [97], "*how information can be leaked from the implementation of a cryptographic component*" and maybe from quantum devices too.

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[49] https://github.com/microsoft/electionguard-rust/blob/main/TODO.txt#L1373

[50] Condensed summary and comparison between SNARKs are in the first 25 mins of (https://youtu.be/A3edAQDPnDY); KZG is a name abbreviation.

[51] Side-channel attacks, [97], discovered by Paul Kocher in 1996 as *Timing attacks* on implementations; they learn information from data disclosed while a device is functioning like electromagnetic radiation, sound waves, power use, or execution time.

the first is asserting thoughts as discussing with a colleague researcher, the second is repeatedly generating AI review reports to discover weakness points and prepare a revised version.

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Appendix A: Handling of the election secret Key

First, recall from section 4.3 that the election secret key ($\mathbf{S_k}$) is only used by IVXV when counting the votes (to allow the decryption of the votes without knowing the voter ID or the random number "r"); hence, the straightforward risk from key leakage concerns ***privacy***. However, let's investigate the possibility of integrity risks.

-When counting votes, the election authority uses the election secret key ($\mathbf{S_k}$) and El-Gamal encryption known equation « $\mathbf{y= g^{Sk}}$ » to calculate $\mathbf{v= C_2/((C_1)^{Sk})}$
-What prevents an adversary from stuffing ballot with any dummy pairs (C_1,C_2) such that $\mathbf{C_2/((C_1)^{Sk}) = v_{adversary}}$?

1. An outsider adversary cannot do that without compromising voters' credentials to add a valid signature; otherwise, the Vote Collector (VC) will detect it when contacting the Registration Service (RS) defining the voter as "not eligible to vote". Hence, these kinds of attacks do not really need the election secret key and fall into malicious voting applications and absent voting discussed in section.

2. An insider adversary can do that only, even in the newer versions, if he/she was able to compromise both VC & RS to fake the certificates and pass their integrity checks; however, if the Ballot Processor (BP) performs a cryptographic check on the online count of votes it can detect a change in that count.

Appendix B: Summarizing Tables

Table.1: Fixes/improvements done in IVXV 1.9.10 EP2024, 1.10 E2025

Risk	Deployed Solution	Remaining Issues	GiHub File	Corresponding Academic Research
Invalid votes	**2024:** Decrypted in a separate file with ZKPs of correct decryption	-Files are viewable by auditors only (complaints)	Embedded in [60] ***DecryptTool.java***	Tallinn Univ. Ms. thesis [19] (Jun 2024)
	2025: Deployed ***Range Proofs*** to prevent invalid votes from entering the votes list.	-Invalid votes (3 in 2025) can still enter the system through private voting applications (through the VC directly); hence, privacy attacks [61] remains.	Added in the server-side part of the voting application [58]	The thesis in [19] and the scientific report in [74]
The Voting/Voter Application (VA)	**2024:** Authenticated through a fingerprint [70]	-Complicated and involves many steps for regular users		Jan Willemson, E-Vote-ID 2025 paper [9]
	2025: Publishing the server-side code of the voting application [58]	Assumes trust in the official VA (client- side part) -Problems remains for non-verifying and absent voters (see Table.2)	[58] https://github.com/valimised/ivxv/blob/published/voting/service/voting/main.go	
Ballot Processor (BP) manipulation	**2024:** Consistency checks on SHA256 hashes of totals and subtotals.	***-Offline*** checks; i.e., count based validation depends on trusting the Vote Collector (VC) and Registration Service (RS) to not collude before the list enters the BP.	A new file [63] ***IntegrityTool.java***	Tallinn Univ. researchers [64] (Dec 2024)
Timing attacks	**2024:** Checking *Session ID* and *Timestamps* difference, which are generated by *PKIX* protocol	Cannot detect fast attacks that can manage to work in the duration of one session (like ***Pereira attack*** [51])	A new file [50] ***client.go***	An extension, [67], to a Luxemburg Univ. PhD on formal verification of i-voting systems, applied to IVXV (Jun 2024)

Table.2: Remaining vulnerabilities/risks in IVXV 1.10 E2025 and suggested solutions

nerability	**Risks/threats**	**Concerns/Complaints about the issue**	**Suggested Solutions**	**Proposed by**
Voting lication)	-Pereira attack [51] -Copy attack on Privacy [67] -Large-scale vote copying [39] -Variety of malicious VA risks -Extra risks for smart phone VA -Injecting votes through trojan horses embedded in apps that get the voter signature claiming other purposes; risky even for verifying voters.	-Cybernetica supervised PhD [48/sec.5-6] -Olivier Pereira [51] -OSCE/ODHIR 2023 report [2] -Many other researchers including the authors of this paper.	Using a ***microcontroller*** voting device	Tallinn Univ. PhD [47] (2022)
			-Publishing the VA code (change the law) -Batched easier checking of ***file hash***, [85] -Assigning a ***signature key*** for VA and allowing ***optional registering of other VAs*** but after scanning the code for malicious activities (more robust but require flexibility and cooperation from authorities to not reject unobjectively). -Activate an ***SMS ack*** with every election transaction on election days; could be delayed as discussed in [51] or discovered by vote coercers [9,17,68]. -Let the Ballot Processor, section 5.2, check and ***alarm the existence of equal encryptions*** even from different voters. -If the system insists on keeping the VA situation as is, using ***a separate ID card for elections*** (suggested in [68] for another reason) can protect from the possibility of casting votes through apps with *trojan horse* that take the voter's signature claiming other purposes. Another solution is to ***add a meta data field*** that allows IVXV to check ***the application category***.	Poster [39] in E-Vote-ID 2025, and this paper
lers' st	VC and RS are trusted to not collude; their collusion may result in: -privacy attacks [61,67] -different possible manipulations of the ballots list before entering the ballot processor	-Estonian parties and i-voting opposing communities in general [1,2, 16] -Detected by automated formal verification tools in [67,81].	-Adding a ***ZKP*** to each vote.	[61] (2022)
			-Performing different ***consistency check ZK queries***, and ***RLA***s, between ballots list and other services recording digital transactions in Estonia, like *myID* [65]. -Using ***Verkle Trees*** (***Vector commitments*** based on KZG polynomial commitments) to cryptographically prove votes integrity and counters.	E-Vote-ID 2025 poster [77]
			-Using ***Vector Commitments*** based on Pedersen commitments to cryptographically prove vote correctness.	E-Vote-ID 2025 paper [78]
grity vs. rcion	Double checking services like myID [65] can be used by vote' coercers to prove last vote.	-Observer's E-Vote-ID poster in 2023 [17]	-Making election transactions secret or obfuscated -Using a special ID card for e-voting that doesn't allow such integrity checks on its transactions.	E-Vote-ID 2025 paper [68]
ware iting	The risk of not detecting programming errors, security vulnerabilities, back doors, covert channels, side channels,… problems beyond the	-Supreme court complaint [23] -The Academy of Sciences report, [87], when weighing the pros & cons of open	-Publish the voting application (VA) as an open source.	The report in [87]
			-Publish the new version long enough to be analyzed before the election.	(complaine r + court [23]) + law [31]

	happy path of execution	sourcing the VA. -The paper in [83].	Auditing the code as a structured software-testing task grounded in mission & safety-critical principles (DO-178C)	Research article [83]
ent ers	-If their devices and credentials are compromised as *botnets* or through any dark web market, votes can be injected on their behalf. -This could happen through trojan horse apps too.	-Falls under "*unavoidable risks that can't be performed on large-scale"* by [48, 48/ref.166] as it will cause "*observable anomalies*" -Falls under (*corrupted voter device+ corrupted communication network*) category detected in [67]	Only safeguards, no complete protection (Appendix C): -Activate an ***SMS ack*** with every election transaction on election days; could be delayed as discussed in [51] or discovered by vote coercers [9,17,68]. -use a SNARK that supports ***Non-inclusion proofs***, and check RLA samples; voters could lie to falsify elections. -Allow a ***"reject all" choice*** to incentivize even boycotters to vote	This paper
Station ipulation	A malicious poll station worker could alter vote IDs (keeping the number consistent with the ballot box count) to delete the e-votes of some (by faking a booth vote) and double the votes of others (by giving them the chance to add another online vote)	To our knowledge, the Estonian Cyber Security Academy report, [87], was the first to identify the vulnerability as a "*noteworthy*" threat.	-Notify the voter through an email or any other notification channel of a poll station vote; could be deliberately delayed as [51] worries.	Cyber Security Academy report [87]
			-Check for anomalies like an e-vote with time stamp larger than the timing of the corresponding poll station vote. -Take a random sample of poll station cancelled votes and contact them to check the truth before deleting; then apply RLA techniques to decide on the result.	This paper
ntum puting	-Breaks existing cryptography -Privacy Risks (HNDL)	-The paper [102] (2024) -HNDL in earlier versions of this paper [75] (2025), and Cyber Security Committee report [87] (2025)	-Prevent data leakage -Defining measures and advising techniques to make sure of the complete destruction of all election data	Cyber Security Academy report [87]
			-First hardware chip enabling post quantum digital ID card -Prepare carefully, without rush, for the transition to post quantum cryptography (PQC)	Cybernetica
			-Lengthening hashes and message digests to be PQ -Adding another layer of PQ AES-GCM encryption	This paper
	-Leakage of voter's vote -Organize a sophisticated attack	-The leakage in the [87] report as a less significant threat. -The attack orchestrating threat is warned by this paper.	None yet	

Appendix C: The detailed steps of a complete Verkle Tree (VT) Solution

This Appendix details the Verkle Tree suggestion introduced in [77] (cited as [42] in the compact version) for cryptographically proving both ballot correctness and the total number of votes; i.e., ***End-to-End Verifiability***.

C.1 Setup:
The election authority picks a random secret $\mathcal{T}$ to be destroyed after the end of the setup procedure and calculates (offline) the following terms with a finite cyclic group G that is closed over the used finite field [100]; the calculated terms should be public to verifiers:
$H_0 = G$, $H_1 = \mathcal{T} \bullet G$, $H_2 = \mathcal{T}^2 \bullet G$, ..., $H_{p-1} = \mathcal{T}^{(p-1)} \bullet G$

C.2 Steps:
-When a new vote enters the system (through the vote collector and the registration applications), it goes through the following steps (Fig.8):

1. When a new vote record enters the vote collector, in addition to adding it to the votes list, the system cryptographically commits to the vote record by adding its hash to the first Verkle Tree; VT_1 = VT_1 + Hash(vote_i)*H_i
2. If this voter-ID hasn't appeared before, the new vote hash is aggregated into the second VT as well; VT_2 = VT_2 + Hash(vote_i)*H_i
3. If it's a repeated voter-ID, then before aggregating it to the second VT, the previous vote must be deleted from it first[52]. The deleted vote is then aggregated into the third VT (or the corresponding second le\vel VT if needed). Since [38] shows that multiple voters are sparse, O(10,000) multiple votes, second level VTs could be implemented as an array holding (voter-ID, VT value)
4. The fact that a voter has voted at the polling station, will not be available during this phase to separate them; if Range proofs were not deployed, then the separation of invalid votes will not be possible at this phase too. However, the Ballot Processor can commit to their values (after separating them as in Fig.6) by calculating VT_4 and VT_5 respectively.

-When i-voting time is closed, make all VT values publicly available in an immutable way; this could be done through the official election site or any trusted robust blockchain.

[52] We assume the index of the old multiple vote make it retrievable from the list of votes, otherwise step3 will be done by the Ballot Processor; also, this could be done in the background without delaying the interactive processing with voters.

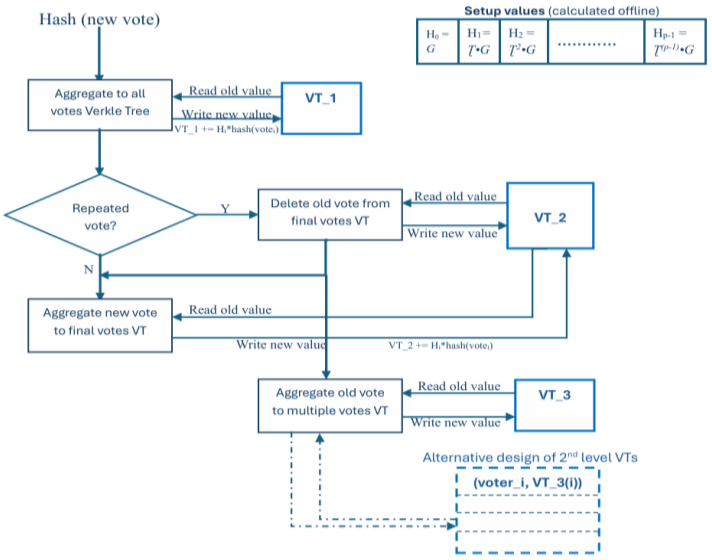

Fig.8. A schematic flowchart of the proposed Verkle Trees design

C.3 Results

The proposed Verkle Trees adds the following security values:

- The polynomial degree of each Verkle Tree proves the number of votes it holds (*n* of a Verkle Tree is cryptographically proved); i.e., two values from Eq.1 in section 5.2: *Count (original votes file)* and *Count (multiple votes)*. The Ballot Processor should check that ***VT_1=VT_2 + VT_3***[53].
- In addition to the above check, publishing all the VT commitments allows independent verifiers to write their own code to calculate VT_end of anonymized votes. Then, taking advantage of the Homomorphic property of KZG commitments, verify that ***VT_end = VT_2 – (VT_4 + VT_5)***.
- If RLAs were applied and samples were selected to verify manually, the calculated VT values can also provide separate succinct proof for every sampled value; this is possible whether samples were taken as ballots or as voters. The alternative design of 2nd level VT_3 (Fig.7) may facilitate individual voter verification in a more detailed way; VT_3(i) can prove the number and values of every deleted (multiple) vote for the sampled voters, even if they voted at a poll station afterwards.
- In the 2-levels VT_3 case, **QR codes can include the number of multiple votes** for each voter; this is an extra check against vote manipulation[54].
- **VT**_s could be kept after destroying election data to verify individual votes.

C.4 Discussion

Authenticated Data Structures (ADSs), [101], are proposed here as a mean to remove trust assumptions of voting modules by publishing SNARK values that were dynamically calculated using a publicly available code.

[53] Addition here means multiplying the two polynomials holding the data, where the resulting polynomial degree (number of committed elements) will be the sum of their degrees.

[54] There is a maximum of 3 QR code checks, but a voter could vote 10 times and check only the QR of the last vote; in this case our modified QR will reply that "*you voted 10 times, your last vote is…*".

In this paper, we chose Verkle Tree commitments as opposed to Merkle Trees or STARKs based on the following logic:

-More efficient (< 2 seconds) proof construction [65/A.5, 66]; Verkle Trees provide a constant order complexity *SNARK* (per node or per batch) using KZG vector polynomial commitments.
-Although Verkle Trees require a trusted setup procedure to generate a crs (*common reference string)*, we do not consider this a problem since it is a universal setup (not circuit specific as in Groth16) which aligns with IVXV setup & key generation phase. However, **we are aware that the leakage of the *crs* in this case constitutes an integrity attack that renders the Verkle Tree solution useless, while the key parts leakage in IVXV constitutes a threat to privacy only** (see Appendix A).
-This arrangement also allows the use of *Risk Limiting Audits (RLAs*) to verify the details of a selected sample of ballots. Merkle Trees can support checking RLA samples too (the logarithmic complexity is not an issue here since the checks are done offline). However, Merkle trees do not verify the total and subtotals numbers which is crucial in our case.
-Although the ***STARK*** (*Scalable Transparent ARguments of Knowledge*) option introduced in [101] is based on FRI commitments and hence provides post-quantum_security guarantee and does not require a trusted setup phase, we find those advantages useless in our case; IVXV involves a key setup phase anyway, and deploys EL-Gamal encryption which is not post-quantum to begin with. In their paper, the authors showed a projected performance analysis for applying their approach to EL-Gamal based e-voting systems, but it is not a performance issue; if quantum computing is feasible, an adversary can discover the private keys and produce correct values that will pass the verifier checks. Hence, we believe STARKs can only be a better solution if they were a suitable match with a post-quantum update of the underlying encryption.

C.5 Impact on Efficiency

It is worth mentioning that Verkle Trees are used by the Ethereum blockchain where a block of transactions is finalized every 10 seconds on average; i.e., no long delays are expected.

This result is further confirmed by this recent paper [102] that compared benchmark results for Verkle Trees (implementation from [102/ref.19]) versus Merkle Trees and an accompanying SNARK (Plonk [102/ref.6]); the paper found Verkle Trees to be faster and more efficient in proof generation, while the Merkle solution has a faster verification time. ***This exactly matches the needs of an online i-voting system where proof generation happens online, while verification happens offline after voting is closed***.

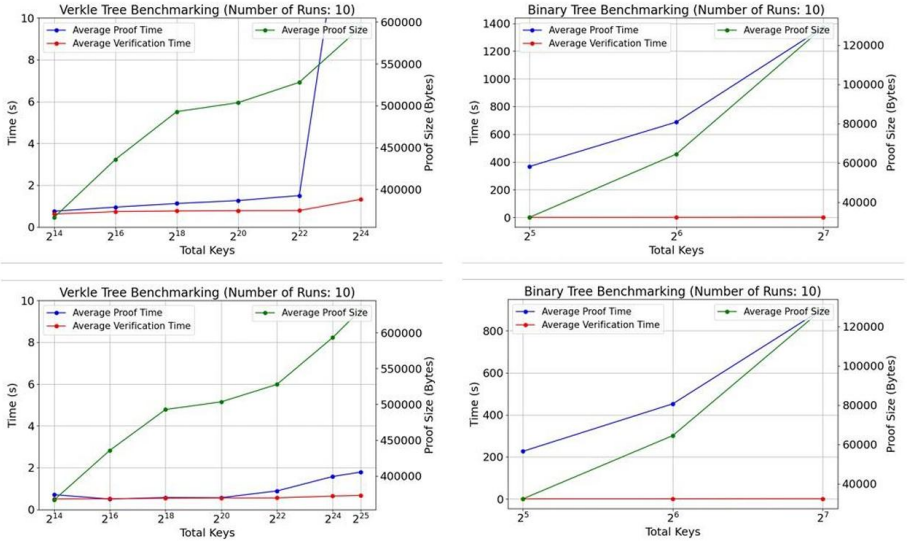

Fig. 1. Measured proving times, proof sizes, and verification times for Verkle trees on Machine 1 (top) and Machine 2 (bottom) averaged over ten runs.

Fig. 2. Measured proving times, proof sizes, and verification times for binary trees with SNARKs on Machine 1 (top) and Machine 2 (bottom) averaged over ten runs.

Fig.9. average proof generation and verification times on two different machines, adopted from [102]; the proof generation time is always less than 2 seconds on a regular windows machine even for more than double the Estonian population.

Fig.9 is taken from [102/sec V] where for regular Windows 10 22H2 operating system on an Intel i5-4690K machine with 22 GB ram, the proof size remains below 2 seconds as long as number of nodes $< 2^{22} \sim 4.19$ million. We believe this is a relieving upper bound, since the upper bound on the number of electronic votes is less than half this number and the calculating server machine will sure have more RAM; for an AMD Ryzen 32-core and 125 GB the proof generation is nearly 1 second and remains less than 2 even when the number of nodes reaches $2^{25} \sim 33$ million.

Appendix D: Risk Limiting Audits Consistency Checks

Since both use the same timing service, PKIX, generalize what voters using eID can currently do as a double check for individual verifiability using the existing *myID* service:

Verify:
Count (original votes file) =
Count_Transactions (source=all, destination=IVXV, time=election_interval)

-The same could be repeated for checking the integrity of all votes. The verification process could be a simple hash cascade, a sophisticated ZKP, or even a comparison between sorted versions of the common fields between the two lists:

Verify:
(original votes file) =
Transactions (source=all, destination=IVXV, time=election_interval)

-The first check could be instead accompanied by some kind of *Risk Limiting Audits (RLA)*s, where only a sample of random votes could be selected to check manually. Here, TXs stored in the Estonian information system will play the role of paper ballots to compare with IVXV data.

```
for all  i ∈ sample
 {   n= Count (original votes file, vote_ID=i);
Verify:
n = Count_Transactions (source=i, destination=IVXV, time=election_interval);
for all  j=1 to n              //in time order
Verify:
  Original votes file(vote_ID=i, order=j) = Transaction((source=i, destination=IVXV);
```

Appendix E: Absent Voting

The threat of online identity fraud through dark web markets [103,104] that sell compromised users' credentials [105], or devices to be used as botnets [106], has been widely acknowledged long ago, since 2019 [107], and continues to be [108]. While the stories published, like [109], talk mainly about affecting public opinion during elections, the technologies used do not exclude at all the possibility of online voting using stolen credentials.

The Swiss online voting system, SwissPost [82], guarantees integrity even with compromised voter device through using traditional paper mail as another channel; voters assert their personhood identity by entering codes they received by regular mail. In Estonia, IVXV depends on vote verification as the safeguard from such attacks which are kind of unavoidable risks on internet voting. Also, researchers like [48, 48/ref.166] counted on observable anomalies (like financial theft if the digital ID is compromised) as a guarantee that those kinds of attacks cannot go unnoticed if performed on a large-scale.

While we discussed how authenticating the voting application would provide more security guarantees even for nonverifying voters, we stopped to think that there are more risks associated with those who did not vote at all (no ballot to generate a QR-code or ZKP from). We believe counting on observable anomalies is not enough here; an adversary may buy compromised credentials only for political purposes, at least till the election ends and then uses them for stealing money. Also, equally likely, is the possibility of deceiving even verifying voters when using their eID in any other online activity (requiring a signature) after voting; a malicious application could contain a trojan horse that absently votes for whomever uses it.

With the current existing cyber security threats, there is no solid guarantee for those who chose not to vote that no one stole their voting credentials and voted instead of them. However, we suggest the following partial protections:

- Provide a "reject all" choice in every list of candidates to encourage boycotters to vote anyway and hence exclude this from this risk category.
- Educate voters about online identity fraud, [110], and check discovered criminal markets for Estonian victims.
- A separate election ID can only prevent absent voting through trojan horses.
- Activate an SMS acknowledgement for every digital ID transaction (like some banks provide for credit cards transactions) on election days. This way, an IVXV transaction SMS for someone who didn't vote will alarm the voter to take an action; for example, overwrite the vote whether electronically or in poll stations. Still, this solution is subject to deliberate message delays as discussed by Olivier Pereira in [51].
- If the used ZKP supports non-inclusion proofs, like Verkle Trees[55], a random sample from non-voters could be taken and checked for non-inclusion proofs in an *RLA* manner. This solution has a drawback of not being able to distinguish liars; i.e., if the *RLA* showed a large ratio of absent voting, how would a court know beyond reasonable doubt that those people are not deliberately lying (did vote by themselves) to falsify the election.

[55] Note that in this case, there should be another Verkle (or any ZKP) for voteIDs only; ie, not for the complete ballot as non-voters do not have ballots at all.

Appendix E: The Quantum Computing (QC) threat

Quantum computing depends on physics and quantum theory to perform computations much faster than current existing hardware in a way that can break most existing cryptographic systems, [94] especially those based on the discrete logarithm problem (El-Gamal encryption) or Elliptic Curve Cryptography[56]; hence, it is a threat to IVXV and the Cyber Security Committee Sep 2025 report, [87/noteworthy threats/quantum], acknowledges it.

Most digital information systems around the globe have started their research for alternatives that can defeat the quantum computing threat, what is known as ***Post Quantum Cryptography (PQC)***. Also, if the threat is not that approaching, there is an associated with another risk of storing encrypted data to decrypt them later when QC is possible [99]; the concept of ***Harvest Now Decrypt Later (HNDL)*** can jeopardize vote privacy[57] and necessitates a firm restriction on the leakage of election encrypted data before the usual timed destruction.

Estonian Quantum Efforts

All countries deploying e-voting/e-government systems should be motivated, without rushing unstudied, to provide post-quantum solutions. For our specific case of Estonia, the authors of [111] included 5 out of 24 experts from Estonia in their interviews, and covered steps taken by the Estonian government [111/ sec. 2.2.2] in different quantum related aspects.

-A European cooperation to deploy a quantum communication infrastructure in 2020 led to the NordIQuEst (*Nordic-Estonian Quantum Computing e-Infrastructure Quest*) in 2022 [112]

-A collaboration between *Cybernetica* and University of Tartu to create post quantum solutions has started in 2021 [113] including jointly supervised doctoral thesis from which we encountered a paper (2024) on PQC migration obstacles in Estonia [114].

-Finally, PQC is 1 of 6 challenge areas included the *Cyber Security hub* established in 2023 between Estonia and a major Czech ICT powerhouse both in industry and education [115].

Estonian I-Voting Related Efforts

Digital IDs are a crucial element in i-voting; the *ENISA* July 2024 report [116] on the unified European digital identity project *eIDAS*, though, did not specify the PQC transition details. Then on 19 Feb 2025, [117], *Cybernetica* announced that the first hardware chip enabling post-quantum ID card has been certified in Europe. When asked about post quantum i-voting, they answered "*there is more math to do*". In their 2024 paper [114/sec. 2.E], they considered the complexity of managing multiple layers a disadvantage in most existing Hybrid systems. For i-voting, [114/sec. 4.E], this would be a problem with the needed multiple layers to shuffle votes in *mix-nets.* As can be concluded from the latest available report, [87], the research work is predictably going to take years.

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[56] Note, however, that the NIST 2016 report stated that Symmetric key encryption can tolerate by increasing key size and SH-2, SH-3 hash functions by increasing hash length. This means that hash function parts like the voting application authentication (whether as it is in [70] or batched as in [86]) can easily be made post quantum; also the integrity checksum of votes [64] added in 2024.

[57] The report in [87] exact words about *HNDL* from Google translation "*Reorganizing the elections will not help, because people's preferences have become public. This would most likely mean the end of i-voting in Estonia*". Protections include ways/measures to make sure of the destruction of all copies of encrypted votes after the elections