Abstract

Considering a large number of vulnerabilities reported in the news and the importance of elections and referendums, the general public as well as a number of security researchers consider paper ballot voting with its fully verifiable paper trail as more secure than current e-voting alternatives. In this paper, we add to this discussion and explore the security of paper voting. Although individual examples of vulnerabilities of the software used for paper voting were already reported, this work looks at the cyber-risks in paper voting in a more systematic manner by reviewing procedures in several countries and through a case study of Switzerland. We show that paper voting, as it is implemented today is surprisingly vulnerable to cyber-attacks. In particular, we show that in different countries the aggregation of preliminary voting results relies on insecure communication channels like telephone, fax or non-secure e-mail. Furthermore, we observe that regulations typically do not mandate the use of secure channels. We further introduce two new attacks: vote report delay and front-running, both of which can lead to different compromise of election results. Even if preliminary results are later corrected through paper trail, this 3 to 30 day window during which incorrect results are perceived as final by the public has significant influence on financial and political decision making. An attacker exploiting this inconsistency can, e.g., benefit from stock market manipulation or call into question the legitimacy of the elections. Although our case study focuses on the example of Switzerland, the attacks and issues that we report appear to be wide spread. Given recent reports about easily modifiable preliminary results in Germany and the Netherlands, we conjecture similar weaknesses in other countries as well.

1 Introduction

In most modern nations, the process of electing representatives and deciding on critical matters directly through referendums, is essential. Historically, when implemented in stable democracies, ballot voting where the voters casts their ballots at voting stations is commonly perceived to be secure. The validity and integrity of ballot voting has been studied extensively [2, 21, 25, 49]. As the procedure from printing the ballots, to collecting and counting, and the transmission of results is slow, cumbersome and prone to errors [26], interest has shifted to voting machines and e-voting. However, the security of voting machines and e-voting systems has been continuously challenged [3, 23, 24]. Most effective attacks allowed modification of votes and compromise of the vote counting process. The classic paper ballot voting, while being much slower, is therefore still seen as a reliable alternative that is trusted more than its electronic counterparts.

Paper voting is conducted for multiple decades and robust systems have been established, mostly based on a decentralized vote casting and counting infrastructure. Usually, a local result is determined at a local (municipal, county, state) voting office, followed by a paper report containing the exact counts that is hand-signed by the responsible official(s). These local results are then sent to the central office where the final results are calculated. The communication of local results and/or ballots to the central office (typically via mail or dedicated transport), and subsequent counting and result validation can be slow and can take, depending on the country between 3 to 30 days. This is considered slow and therefore most countries also allow preliminary result to be published, in which case local results are typically transmitted using faster communication channels (e.g., telephone, fax, email).

Recent reports in Germany [33] and the Netherlands [31] highlight negligent security engineering in widely used vote counting and aggregation software. We add to this discussion by systematically reviewing the paper voting process across several countries and investigating the problems that arise at the intersection of paper voting and digital transmission of its result. We show that, in several countries, the aggregation of preliminary results heavily depend on common computer technologies and is therefore exposed to a wide range of cyber attacks, possibly as much as e-voting.

Interestingly, the regulations in the countries considered in
this work actually do not require that authenticity or integrity of preliminary voting results is protected. In particular, in our study we focus on Switzerland, a country that is considered a stable democracy [50], and where the citizens decide directly about constitutional changes and controversial laws. This is an interesting case since referendums are frequent in Switzerland and official preliminary results are published the same day the polls close, whereas the final results follow around 10 days later. Our study shows that the binary outcome of national referendums in Switzerland can be flipped by changing the outcome of only a few municipalities.

In addition to simply tampering with the preliminary reports sent by voting stations, we introduce two new attacks: delaying reports and front-running real reports with fraudulent ones. The impact of these attack vectors may be smaller than report modification, but they are harder to mitigate.

It might seem that attacks on preliminary results are not so severe since these modifications will be corrected when the final results are published (i.e., when the correct results arrive via dedicated physical channels). We show, however, that this integrity time-gap between incorrect preliminary and correct final results can be damaging. It can be used for stock market manipulation, fraud, reduce the confidence in the government and democratic processes, or can be used to delegitimize elected governments and referendum results. Most people are not aware of the official but much slower paper-trail and perceive the preliminary results as the final ones.

The immediate decay of the British Pound after the first interim result of the Brexit referendum or the risky German federal election in 2016 (see Section 5.2) highlights the severe impact that preliminary results have on trade markets and political decisions. Our work therefore shows that the popular argument that only the final results are important to protect no longer holds in today’s fast-paced world.

**Outline.** We review typical paper voting mechanisms focusing on the aggregation of votes. We investigate the provisions concerning the transmission of voting reports, followed by a description of two new attack vectors. Our case study of Switzerland highlights the (insecure) transmission mechanisms used in paper voting. We further discuss the real-world impact of fraudulent preliminary results. Finally, we provide recommendations to improve the security of paper voting.

## 2 Understanding Paper Voting

Paper voting is the dominant voting mechanism used throughout most democratic countries. As its name indicates, paper voting relies on paper ballots, submitted by the voters either at the polling station or via mail. The counting and the transmission of results is then entirely performed on paper. The advantages are apparent: the results can be confirmed by verifying the physical paper trail.

There are usually four stages of a vote that result in the final decision of the voters: the voting (ballot casting), counting, transmission, and accumulation. In the following, we will elaborate on these steps in a typical democracy.

**Voting.** Voting in a paper-based voting scheme is usually conducted by filling out a paper ballot. Some ballots provide only simple options, e.g., yes and no, while others offer many choices and even write-ins to specify the name of the preferred candidate. The procedure of handing in ballots can widely differ between voting schemes. There are countries like France where any voter needs to physically go to a voting station, fill out the voting card, and drop it into a ballot box [32], while other countries like the United Kingdom [46], Germany [11], and some states in the US additionally also allow postal voting. Recently some nations have started to use machine voting, where the vote is entered into a machine that produces a count in the end. Some variants of machine voting do not provide any paper trail, and therefore, do not allow for a manual recount. However, most voting machines produce a paper trail as well as a receipt to the voter to verify their vote was cast correctly. Nevertheless, these machines have been continuously proven to be insecure [3, 23, 24], allowing the attackers to modify the vote counts.

**Counting.** In a paper ballot system, the votes must be manually counted by officials. Before opening the ballot boxes, unused ballots must usually be removed from the premise to reduce possible mistakes. Only then the ballot boxes are opened. Typically, the ballots are first ordered to the respective decision and then counted manually (in some cases more than once). In the end, there are some validation checks to verify correct counting, e.g., verifying the total number of ballots in a ballot box. Finally, all counts of the various ballot boxes of one voting station are accumulated, and a report with the results is compiled. The report, with all irregularities attached, is hand-signed by the supervising official(s).

**Transmission.** After the counting, the report must be transmitted to the superior instance as shown in Figure 1. Every office waits until it has received all results from its subordinates until it will issue another report summarizing all the results. This procedure continues until the highest office is reached – national in some cases, regional in others. Note that this is a lengthy process since a single straggler can cause significant delays. In today’s interconnected world, however, people want much faster results, which are transmitted electronically (cf. Section 2.2).

**Final Result** Once all the reports have reached the final office, the signatures are verified, and the results are accumulated. After that, the results are published, but they are not official yet; some time is typically allowed for objections and requests for recounts before the decision is final.
2.1 Elections vs. Referendums

Most countries support two kinds of popular votes: elections to select representatives and referendums to decide on critical issues. Elections usually have multiple candidates to choose from and sometimes also allow write-ins, to vote for a person that does not appear on the ballot. A referendum, on the other hand, usually only allows two answers: yes and no. There are some countries where additional choices are also available, but mostly referendums require clear binary decisions for critical issues (e.g., Brexit [47]).

Referendums and elections can be held for all levels of the hierarchy shown in Figure 1, e.g., for the election of the city council, the national parliament, or a referendum on joining the European Union [9]. Depending on the hierarchy level, more votes must be transmitted and accumulated over more levels, leading to larger delays before the result is final. As representatives are usually elected for and within a district, there is no need for the federal office to accumulate all counts, while for a referendum it is – indicated by the dashed lines in Figure 1. An exception is, for example, the nation-wide elected president of France, who is elected by popular majority across all eligible voters in France.

2.2 Cyber in Paper Voting

Paper voting promises purely paper-based procedures. Historically, the paper voting systems fulfilled the promises, but recent demand for faster notification has led to several electronic component-replacements. In most countries, the results from voting stations are transmitted not only via postal mail but also using electronic communication channels (e.g., E-Mail, telephone, or specialized software). The results from such an electronic channel are not regarded as final; nevertheless, they are forwarded and accumulated to form official preliminary results. Compared to official final results, counting officials do not await all results of their subordinates before sending them on to the next office. After only basic feasibility checks, preliminary results are immediately forwarded and published by the highest offices (e.g., by the voting commission). News agencies use this information just hours after the polls close.

Exit polls are for earlier projections: voters are asked for their decision after they have cast their vote. Exit polls cannot provide accurate estimations of the outcome since voters can refuse to participate in the survey leading to statistical uncertainty. However, the results of exit polls can be used for forecasts before the polls close. Similarly to preliminary results, exit polling data is usually transmitted electronically to a central entity that accumulates the results and publishes projections. Exit polls are typically conducted by private companies, compared to official preliminary results.

Unlike exit polls, which have recently shown to be unreliable, preliminary (complete) results are typically accepted and used as final by the public. Adversarial modification of the preliminary results can therefore have a much more substantial impact.

3 Attacks on Preliminary Results

In this section, we investigate the regulations on the transmission of preliminary results in paper voting and highlight various attack vectors on the insecure communication channels. We stress that once the paper trail arrives, the fraudulent preliminary results will be corrected. Nevertheless, preliminary results can exhibit a lot of influence on the world. While countries have strong regulations on the paper-trail of an election to prevent tampering with the final result, they are not as concerned about the preliminary results. However, the preliminary results are becoming increasingly significant, often regarded as final by the public, and they lead to extensive political and economic consequences. We stress that the prob-
lem at hand has been mitigated for many years with secure channels \([15, 27]\), but in practice, many countries are still vulnerable to attacks on their digital communication of election results. Recently, some agencies have started publishing guidelines for electronic communication in paper voting systems, e.g., in the United States of America \([48]\). However, our inquiries to various election offices indicate that said recommendations are far from being implemented.

### 3.1 Regulations and Recent Incidents

The regulations on the transmission of (preliminary) results vary widely across countries. In Germany, Switzerland, and Austria, the election laws stipulate how preliminary results must be collected and transmitted as fast as possible \([11, 17]\). However, they do not require any integrity or authenticity guarantee for the transmitted report. France, Estonia, and the United Kingdom do not define preliminary results in their laws at all. There, the local results must be publicly proclaimed in the voting station after the count is finished \([30, 32, 46]\), where private companies collect the results and provide the public with preliminary results and projections. In the United States, the individual states deploy different mechanisms; some specify the transmission of preliminary results while others rely on private companies. In general, no election law (that we studied) requires any guarantee regarding the integrity or authenticity of electronically transmitted results. Some countries have published recommendations for voting systems where various security properties are required. To the best of our knowledge, however, none of these recommendations are currently implemented in practice.

Recent reports in Germany \([33]\) and the Netherlands \([31]\) highlight the vulnerable systems in place today. In the Netherlands, the results were transmitted entirely electronically without a paper trail unless someone objects the result. In Germany, only the preliminary results could be manipulated since the paper trail is always sent via paper mail. However, the Chaos Computer Club demonstrated how preliminary results for roughly half of the electors of Germany could have been manipulated due to grossly negligent software practices \([33]\).

### 3.2 Attack Vectors

We consider counting officials that count perfectly and transmit the correct preliminary and final results. Bribes and extortion aimed at counting officials are out of scope. The final result based on the paper trail is always guaranteed to be correct. Exit polls and preliminary results, however, are transmitted over electronic channels (e.g., VoIP or email) that can be manipulated. There are various types of communication channels used around the world, and we will discuss several attack vectors that might or might not apply the respectively chosen channel. In certain cases, only a single municipality that still relies on insecure communication, if altered, can change close preliminary results of a national election or referendum (cf. Section 5).

**Tampering with Reports.** Modifying the in-flight preliminary results is the most naive attack vector. Converting a few percents of votes in the report of a single municipality can easily lead to a swing in the national preliminary result. For example, swapping the yes and no vote-counts in the preliminary report will lead to an incorrect total preliminary result. The modification will be discovered as soon as the paper trail is processed (or an official notices the mistakes), but until then, the public will accept the fraudulent result. The adoption of an authenticated and integrity protected communication channel would prevent any modification. However, our case study in Section 4 shows that many constituencies use traditional communication means, such as telephone and email, and do not employ appropriate security mechanisms.

**Delaying Reports.** Any attacker that controls any critical part of the communication channel (e.g., mail server, internet router, etc.) can delay any transmission of a preliminary report. The delaying attack becomes even stronger if the adversary is able to learn the delayed results and abuses this knowledge for individual profit. Even without knowing the result, one can delay results from a constituency where there is a strong expectation for a specific outcome. As an example, an adversary learns from polls that cities are strongly against a specific proposal while rural areas support it. Delaying the results from cities change the preliminary totals to dip temporarily in a chosen direction. Analysts will potentially warn that the results from cities did not arrive yet, but the public perception might already be affected.

We stress that the delaying attack works for various communication channels, and even secure channels are vulnerable.

**Front-Running with Fake Reports.** While a specific voting office is still counting, a real-looking but maliciously forged preliminary report could be sent to the accumulating office before the actual report. If it is accepted as valid, the central accumulating office will take the fraudulent preliminary results and forward them to the next higher instance. When the real preliminary results arrive, the error will most likely be detected and corrected, but the damage is already inflicted. The time during which the fraudulent results are considered as correct might be minimal, but the attacker knows that these results are fake, and can, therefore, adjust his strategy to profit from the incident (cf. Section 5). Note that the communication channel must allow arbitrarily forged messages for the front-running attack to work.

### 4 Case Study: Switzerland

We have chosen Switzerland for our case study, a direct democracy where the people decide on policies directly with
| Canton               | Eligible Voters [40] | Transmission                  |
|----------------------|----------------------|-------------------------------|
|                      |                      | Election | Referendum         |
| Aargau               | 414,745              | Sitrox [39] | Sitrox [39] |
| Appenzell Ausserrhoden | 38,498               | ☑️ and ☐️ | ☑️ and ☐️ |
| Appenzell Innerrhoden | 11,565               | ☑️ or ☐️ | ☑️ or ☐️ |
| Basel-Landschaft     | 187,863              | ☑️       | ☐️           |
| Basel-Stadt          | 113,717              | ☐️       | ☐️           |
| Bern                 | 729,203              | Bewas [4] | Bewas [4] |
| Freiburg             | 196,027              | SyGEV [45] | SyGEV [45] |
| Genf                 | 248,915              | ☑️       | ☐️           |
| Glarus               | 26,268               | Sesam [38] | ☑️ and ☐️ |
| Graubünden           | 137,126              | Sesam [38] | Sesam [38] |
| Jura                 | 51,936               | ☑️       | ☐️           |
| Luzern               | 271,143              | ☑️       | Sesam [38] |
| Neuenburg            | 111,304              | SyGEV [45] | SyGEV [45] |
| Nidwalden            | 30,810               | Sesam [38] | Sesam [38] |
| Obwalden             | 26,244               | Sesam [38] | Sesam [38] |
| Schaffhausen         | 51,036               | ☑️ or ☐️ or ☑️ | ☑️ or ☐️ or ☑️ |
| Schwyz               | 102,145              | Wabsti [1] | Wabsti [1] |
| Solothurn            | 177,292              | Wabsti [1] | Wabsti [1] |
| St. Gallen           | 317,969              | Wabsti [1] | Wabsti [1] |
| Tessin               | 218,580              | Votel [29] | Votel [29] |
| Thurgau              | 206,118              | Wabsti [1] | Wabsti [1] |
| Uri                  | 31,928               | ☑️ and Sesam [38] | ☑️ and Sesam [38] |
| Waadt                | 428,569              | Votel [8] | Votel [8] |
| Wallis               | 216,041              | adminVotel [16] | adminVotel [16] |
| Zug                  | 74,803               | Wabsti [1] | ☑️ |
| Zürich               | 907,623              | Wabsti [1] | Wabsti [1] |
| Switzerland          | 5,283,556            | sedex [20] | sedex [20] |

Fax. Email. Telephone. or Either one required. and Both simultaneously required.

5.3M citizens eligible to vote [40], as it has a flexible election and referendum mechanism with around ten distinct referendums per year. The constitution can only be changed if the majority of the eligible people accept the change in a nationwide referendum. Similar mechanisms are in place to object laws passed by the two legislative chambers of Switzerland.

Politically, the Swiss federation consists out of 26 states, so-called cantons. These are politically autonomous, and the organization of elections and referendums lies within their sovereignty. Each canton has its own way of conducting and transmitting voting results, and there is no significant effort to unify these systems. Table 1 summarizes the cantons of Switzerland, including the number of eligible voters.

In federal elections, voters elect representatives for every canton individually. As there is no need for an accumulation of votes on a federal level, the impact of manipulated preliminary results of elections is limited to the canton’s representatives. Nation-wide referendums, however, are aggregated on the federal level, and a very little change in the outcome of one canton can flip the result of close referendums completely. For a change in the federal constitution, a referendum initiated by the people, called popular initiative, has to win two majorities to pass: the popular majority of all votes of every participating citizen (German: V olksmehr), and the majority of the cantons (German: Ständemehr) where the majority of each (full) canton casts a single vote, 23 votes in total. A referendum may win the popular majority due to an advantage in the highly populated cantons but fail to reach cantonal majority as many smaller cantons rejected the referendum. With country-side cantons usually having fewer inhabitants, this leads to a balance between the densely populated urban cantons and more sparsely populated rural areas.

The final results of the vote are obtained by written paper-protocols that are signed by multiple members of each voting station, usually members of several political parties, and then sent by postal services to the state chancellery. The first accumulation of the paper report results usually takes 3-5 days, maximal 13 days, followed by an objection period of 3 days [13]. Simultaneous to these final results, there is an official accumulation of preliminary results, which are usually

\(^{1}\)Due to historic reasons, there are 6 cantons with only half a vote, casting together 3 of these 23 votes.
published on the day the vote takes place.

Every canton provides its own solution to transmit the preliminary vote-counts quickly after the finished counting. These results are often transmitted using several known-to-be-weak transmission methods like email, telephone, and fax, which in their common form do not provide message authentication or integrity mechanisms. An overview of the technologies involved is given in Table 1. Many cantons apply individual dedicated software for voting results transmission, which have not passed a public security review. Given that 8 different dedicated software solutions are in use throughout Switzerland, the potential attack surface is rather large.

While there are severe security risks in the transmission infrastructure, we do not consider the system in Switzerland to be at imminent risk of large result deviations. Significant deviations are likely to be discovered, and the risk of detection increases with every modification of preliminary results. For close referendums, however, attacks stay feasible. It is interesting to note that the security in transmission of voting results in Switzerland is comparable to most other countries (cf. Section 3). As we show in the next subsection, manipulating the result from a few municipalities by a few negligible percentage points might be sufficient to flip the result of nation-wide referendums.

4.1 Attack on Popular Majority

This attack takes place during the vote "Volksentscheid gegen Asylmissbrauch" (referendum on abuse of the asylum system) from 24th November 2002 [35]. It was rejected by the popular majority with 1’119’342 to 1’123’550 votes. In contrast, the majority of the cantons of the vote was won. To flip the vote to acceptance, an attacker would need to change only 2104 votes.

We change those votes in the canton Basel-Landschaft (BL) since it is the largest that uses e-mail to transmit preliminary voting results. Without an attacker's action, the referendum in BL was won with 50.3%. In the case of manipulation, the vote would have been won as well, but now with 52.7%. With these minor shifts, the outcome of the federal vote would have been flipped.

4.2 Attack on Cantonal Majority

The second attack aims to flip the majority of the cantons. We target the decision on joining the United Nations from 3rd March 2002 [34]. On the federal level, the decision was won with 54.6% regarding the popular majority, and 12 cantonal votes opposed by 11 cantonal votes regarding the majority of the cantons. If the two majorities do not agree, the vote is rejected. So the attack only must change a single full cantonal vote.

We choose to attack the canton of Zug because it is the closest canton that uses email or other non-authenticated methods.

5 Impact of Preliminary Results

While most state-officials claim that a modification attack on preliminary voting results does not matter – arguing that only the official accumulation of the hand-signed paper reports count – the public perceives this differently. In many cases, the preliminary results are regarded as the final ones, usually due to ignorance or out of experience that there was never any significant difference. While from a formal-law viewpoint negligible, there are extensive decisions taken based on these preliminary results – for example, reacting stock markets or foreign currency exchange rates, induced long-term political decisions that are taken before the results are final, or high-frequency trading that reacts immediately on very recent information. In the case of tampered preliminary results, significant harm may already have occurred, even if the fraud will be detected one or two days later. The confidence in the voting process might suffer, which can lead to lowered trust in the democracy in general. Financial decisions based on false knowledge may bring significant loss, and far-reaching decisions might require a revocation. We will highlight three examples where the knowledge of preliminary results already had significant impact hours or days before the final results were published.

5.1 Market Insecurity after Brexit

Our first example is the decay of the exchange rate of British pounds to US-Dollar around the Brexit-referendum vote.

Originally, the cantonal vote was won with 55.2%. To flip the vote to a negative outcome, i.e. a result below 50%, we need to change only 2’438 of a total of 44’708 votes.

![British Pound Exchange Rate after Brexit](source: dukascopy)
process ending with UK’s exit from the European Union [47] – commonly referred to as Brexit. The referendum was finally accepted with a majority of 51.9% [43].

While the impact of the referendum on the British Pound was discussed the days before the Brexit referendum, in the night the votes were counted and the preliminary results were piece-wise published, the GBP/USD exchange rate fell to a historic low. Figure 2 illustrates the development. The polls closed at 22:00 followed by a slight raise of the exchange rate. After the first election office (Sunderland) announced its result (EU leave), the exchange rate fell immediately, eventually reaching the lowest point since 1985. The next morning, 8:15am at 24th June 2016, the prime minister of the United Kingdom spoke to the public announcing the final results [44]. The exchange rate improved again little bit, but still was over 8% lower than the day before. If the first result would have rejected the referendum (EU remain), Figure 2 might look quite differently.

5.2 Federal Elections in Germany 2017

In Germany, there exist official preliminary results that are publicly announced usually the day the polls close. The final results are provided 10 to 30 days later by the Bundeswahlleiter (federal election director). Our example, the 2017 federal parliament election took place on the 24th September 2017, a few weeks after the discovery of severe vulnerabilities in the vote transmission software (cf. Section 3.1). Preliminary results were available the same day, and the identical final result was approved 19 days later, on the 12th October 2017.

According to the preliminary results, the social democratic party of Germany (SPD) lost a significant number of seats to the new right-wing party Alternative für Deutschland. The SPD lost its previous ability to participate in the parliament’s major governing alliance. Therefore, they announced party-internal changes and stated to go into opposition already on the 24th September [36], not a day after the preliminary results were published. The next day, insecurities in the stock markets followed due to the recent change in the country’s power structure [37]. Four days after the preliminary results, the then current president of the United States of America, Donald J. Trump, congratulates the German Chancellor Angela Merkel for her reelection [7]. Finally, on the 9th October 2017, still several days before the results were final, the newly formed government coalition fixed the date they planed to start the negotiations about their future corporation [42].

While none of these actions were irreversible, they were all taken before the election results were final, and during the ongoing public discussion about insecure voting result transmission software (cf. Section 3.1). If, and this was not unlikely at that time, the preliminary result would have been tampered with, this could have left a lasting negative impression among the people of Germany.

5.3 Vote on Gold Reserves in Switzerland

In 2014, Switzerland held a referendum whether the Swiss National Bank (SNB) is obligated to store 20% of its foreign-exchange reserves in gold. At that time, the SNB retained only 7.5% of its foreign-exchange reserves in gold and, in case of acceptance of the referendum, would have been forced to buy around 1500 metric tons of Gold (worth around 60 Billion US-Dollar) within the next three years [41]. The referendum was rejected on 30th November 2014 by a large majority; the final result followed several days later.

This referendum became a major talking point internationally. Several News outlets discussed the referendum and showed its impact on the international gold price [5]. Figure 3 pictures the exchange rate of a troy ounce of gold against

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Figure 3: The price of a troy ounce of gold in US-Dollar. The market is closed on weekends (grey underlays). Quite surprisingly, the price has fallen significantly over the weekend where the gold referendum of Switzerland took place, indicated by the red line. The preliminary outcome was approved by the final result several days later.
US-Dollar. The exchange is closed on the weekends, hinted by the grey underlays in the figure. Usually, the exchange market opens on Mondays with roughly at the same price as it has closed the Friday before. This is indicated by the horizontal green lines. In the weekend where the referendum took place, however, the markets opened with a significantly lower price, indicated by the red line. Experts attribute this decrease to the rejection of the referendum [12] whose preliminary result was published Sunday evening, days before the final one. In the case of adversarial tampering of the preliminary outcome, false investments would have followed, the gold market would have seen increased insecurity and instability, and the trust into the Swiss democracy would have suffered.

6 Recommendations

The primary issue in all attacks on preliminary voting reports is the missing authenticity and integrity of the reports transmitted; the broadly used email or telephone do not provide these properties in their common form. For the transmission of preliminary voting results, signing the report to allow for subsequent verification must be mandatory. Moreover, each preliminary report needs to be uniquely attributed to a specific election and, in the case of intermediate result publications, contain a monotonic counted number to avoid ambiguities-leveraging attacks. Existing systems such as PGP [19] or TLS [14] already satisfy these requirements and are widely adopted.

Such technologies rely on asymmetric encryption to verify the origin of messages based on a public key. If every vote-counting and aggregation entity holds an individual private key to sign its voting-reports, then the validity of any report can be verified using the corresponding public certificate. However, the distribution of such trusted certificates is not trivial. As a possible solution, public Key Infrastructure (PKI) [10] is a perfect fit for the hierarchical structures in a typical country: The federal office could provide the root certificate and sign the certificates of the subordinate districts, who would then, in turn, sign the certificates of their municipalities. As long as the report is signed by a key belonging to the correct certificate, its authenticity can be validated via the chain of certificates eventually reaching the trusted root certificate of the federal office. Actually, many countries have already rolled out a PKI to secure their internal communication [6, 18].

The private keys belonging to the certificates are critical, as they allow an adversary to forge signatures on fraudulent reports. Additionally, any lost or compromised key must be revoked as soon as possible, which is non-trivial and requires significant effort. In order to protect the private keys from leaking, a country could make use of technologies such as smartcards [28], which encapsulate a private key in a creditcard like physical device and thereby making key extraction difficult [22]. The adversary needs to steal the smartcard to sign fraudulent reports, and a missing smartcard is detected quickly. Moreover, manipulating an election or referendum on a large scale would require several cards.

7 Conclusion

This work examines the non-negligible time-gap between preliminary and final results of paper-based voting mechanisms across several countries. In most countries, the final result of elections and referendums are determined based on written down and hand-signed paper-reports of the local results of each individual voting office, which are sent (by postal services) to the next higher aggregation office up to the topmost level that publishes the final result. As this process usually takes several days, faster aggregation systems for preliminary results have emerged, which use insufficiently secured digital transmission of preliminary voting results. As a result, the preliminary outcome of elections and referendums can be modified by an adversary. While this is unlikely for one-sided referendums or elections, very close decisions can be flipped by a small distortion of a regional intermediate result. We have shown this through a case-study of Switzerland, and given the reports about the software vulnerabilities of aggregation systems in Germany and the Netherlands, we conjecture similar issues in many other countries as well.

While tampering with preliminary results should be discovered at the latest when aggregating the final results, we have discussed the substantial impact of modified preliminary results with several examples. In the case of the marginal Brexit referendum – 51.9% voted for leaving the EU – the value of the British Pound crashed after the publication of the first preliminary result. In contrast, the market might have reacted differently if the first result would have proclaimed "EU stay."

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