# Attacks on RFID-Based Electronic Voting Systems

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**Abstract.** Many secure systems, such as contactless credit cards and secure entrance systems, are built with contactless smartcard RFID technologies. In many cases these systems are claimed to be secure based on the assumption that readers and tags need to be in close proximity (about 5cm) in order to communicate. However, it is known that this proximity assumption is false: Relay attacks are a class of hardware-based attacks which compromise the safety of such systems by dramatically extending the interrogation range of the contactless system. Interestingly, the proposed Israeli e-voting scheme is based on contactless smartcards. In this work we show how the proposed system can be completely compromised using low-cost relay attacks. Our attacks allow an adversary to read out all votes already cast into the ballot box, supress the votes of one or several voters, rewrite votes at will and even completely disqualify all votes in a single voting station. Our attacks are easy to mount, very difficult to detect, and compromise both the confidentiality and the integrity of the election system.

## 1 Introduction

### 1.1 A Typical Contactless RFID System

An RFID environment in general consists of a **reader**, a device connected to an external power source, communicating via a **wireless medium** with a multiple inexpensive **tags**. While there are several classes of such tags, this discussion specifically deals with **passively powered, magnetically coupled** RFID tags (also referred to as **tokens**, **prox-cards** or **contactless smartcards**).These tags are used in new e-passports[7], credit cards[8], public transportation[16] and secure entrance systems. Most passively powered, magnetically coupled RFID tags conform to the ISO/IEC 14443[12] standard family. Passive tags contain no power source and rely on the reader to provide them with operating power. Due to the physical principles behind magnetic coupling, the reader is only capable of delivering power to the tag if the tag is near the reader's antenna (Standard ISO/IEC 14443 readers and tags are designed for a 5cm operating range). This property, which imposes a severe limit on the usable range of the system, is sometimes considered erroneously as a security feature.

To provide for the case of multiple tags sharing the same air space (such as communication with one out of several contactless smartcards which are all

located in the same wallet), the ISO/IEC 14443 standard specifies an **anticollision** protocol which allows each tag to be interrogated in turn without corrupting the communications with other tags. An in depth introduction to RFID can be found in [9].

### 1.2 The Theory Behind Relay Attacks

As stated in [9], most contactless smart card systems (and specifically the ISO 14443 [12] family) operate on the physical principle of **magnetic coupling**. This choice of **air interface**, which is used both to provide power to the smartcard and to communicate with it wirelessly, is supposed to impose a very severe limit on the distance between the reader and the tag, as illustrated in figure 1. This leads to the (mistaken) implicit assumption that whenever a reader can communicate with a tag one can assume that the tag is physically very close to the reader.

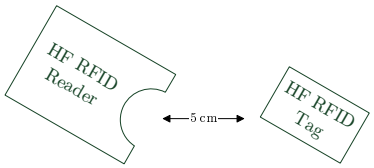


**Fig. 1.** A simple magnetically-coupled RFID channel

As described in [14], relay attacks challenge this underlying assumption and allow a nearly unlimited distance between tag and reader. The attack achieves this ability by placing a **relay**, consisting of custom-designed tag and reader hardware connected by a high-range communication link, between the victim's tag and reader.

As illustrated in figure 2, the **leech** device (or proxy-reader) presents itself to the **victim tag** as a legitimate reader, while the **ghost** device (or proxy-token), presents itself to the **victim reader** as a legitimate tag. When the victim tag and reader wish to exchange data, their messages are captured by the relay devices and sent across the fast high-range communication link. Thus, any data exchange between the victim's tag and reader can be carried out over the relay channel, even if it is strongly encrypted and authenticated. Such a relay attack on a credit card system, for instance, would allow the attacker to make a purchase and pay using an unsuspecting victim's credit card. The attacker will present the ghost device to the point of sale system, while the leech would be placed near the victim's wallet – perhaps in a totally different location.

Since the attacker' ghost and leech hardware are custom manufactured and do not need to comply with any regulatory standard, the adversary has a large degree of freedom when designing his system. The adversary can specifically

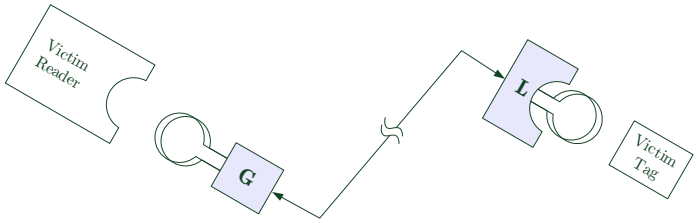


**Fig. 2.** An RFID channel under a relay attack. Device "L" is the leech, while device "G" is the ghost.

design his ghost and leech so that they have an internal power supply, a different form factor or (most importantly) a higher operating range.

Thus, there are three ways in which relay systems increase the distance between the victim tag and victim reader:

1. Increasing the range between the **victim tag** and the **leech (leech range)**
2. Increasing the range of the communications link between the **leech** and the **ghost (relay range)**
3. Increasing the range between the **ghost** and the **victim reader (ghost range)**

### 1.3 Previous work on Relay Attacks

An excellent survey on the history and state of the art on relay attacks has recently been written by Hancke et al.[10]. As stated in the survey, the first published discussion of a relay attack is arguably the "chess grandmaster" attack, which Conway writes about in his famous book "On Numbers and Games"[3]. In the chess grandmaster attack, the adversary successfully plays simultaneously against two chess grandmasters by relaying their moves – even though he has no knowledge or understanding of chess. In 1987 Desmedt et al. [4] wrote of the "mafia fraud" attack, the first discussion of a full-fledged relay attack used to compromise a security protocol (specifically, the Fiat-Shamir authentication protocol).

In 2005 Kfir and Wool[14] first noted that applying a relay attack to a near-field contactless system will cause the security of such a system to "collapse". They also used a detailed physical model of the physical layer to evaluate how the ghost and leech distances can be significantly improved beyond the nominal 10cm at a reasonable cost. They predicted that the leech range can be increased to 40 to 50cm and that the ghost range can be made as large as 50m. In that same year Hancke[11] demonstrated a working relay attack on an NFC system using a high-speed radio link, using standard equipment for the ghost and leech radio interfaces and a low-cost radio transciever for the relay link. This setup provided a relay range of about 50 meters. In 2006 Kirschenbum and Wool[15]

actually built a functioning leech element of the relay by demonstrating a low-cost RFID skimmer that provides a range of 25cm, thus validating the model-based prediction of [14]. The article also explained how the leech distance can be improved even further while staying within a very low budget. A possible way to protect against a relay attack would be through the use of Faraday cage shielding, or by employing a hardware based distance-bounding protocol which strongly proves physical proximity (see [6]), but even these protocols cannot reliably detect a short-range relay attack.

In 2007 Drimer et al.[6] applied a relay attack to a contact-based smart card system implementing the high-security UK EMV payment system[8]. One original aspect of this system was the design of the attacker's ghost and leech devices. Since the tag under attack was contact-based and designed to be used in a point-of-sale setting, the authors took special care to make the ghost look as much as possible like a standard EMV credit card. They achieved this feat by taking a genuine card and connecting a long cable to the gold pads interfacing the smardcard with the reader, with the other end of the cable wired to a hardware device implementing the relay functionality. This resulted in a card that looked authentic when viewed from the top side, but was actually connected to external hardware on the back side (see figure 2 in [6]). To make this attack undetectable in the field, the relay device and connecting cable could presumably be hidden up an attacker's sleeve. The leech device (which is supposed to receive communications from the victim's tag) was placed inside the box of a standard Chip & PIN terminal, resulting in a device that looks perfectly genuine to the victim.

## 2 The Israeli e-Voting Scheme

The scheme discussed in this report is based on the e-voting system currently undergoing a process of legal ratification and widespread pilot testing in Israel. Our information on the scheme comes from its official description in a patent application, currently under submission to the World International Property Organization by the Government of Israel[19,5], and from discussions with Yoram Oren, one of the co-developers of the scheme[18].

The novelty of the system is that instead of using paper ballots, the votes in the proposed system are cast on contactless smartcards. To cast their votes, the voters use a computer terminal to write their choice into a contactless smartcard, and then physically deposit this smartcard into a ballot box. A more detailed description of the voting process follows.

### 2.1 Components of the Scheme

The components of a voting station are illustrated in figure 3. Each voting station consists of the following elements:

– A **voting terminal** (a portable computer with a contactless smartcard reader). The voter uses this terminal to cast his vote. The vote is recorded

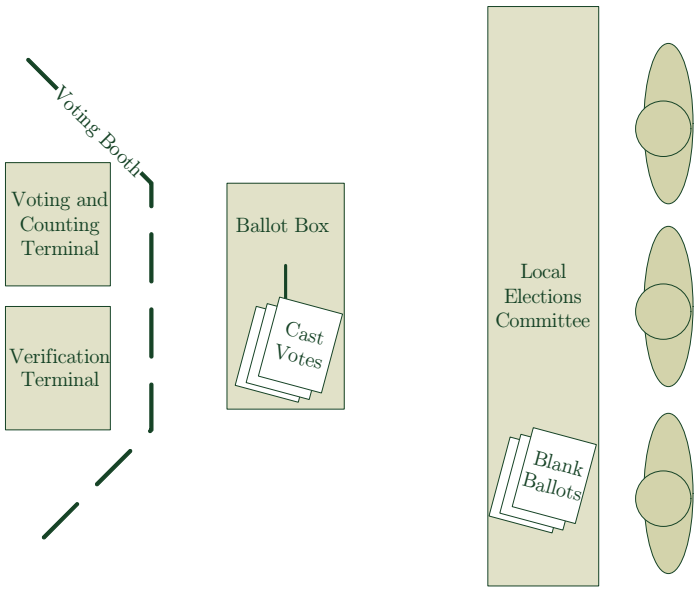


**Fig. 3.** Physical layout of the proposed Israeli e-voting scheme. Illustrated from left to right are the voting booth, the cast ballot box and the local election commitee's desk area.

twice: First, the individual vote is written onto the blank ballot (a contactless RFID smart card). Second, the total vote count is immediately tallied and this total is written to a regular contact-based smart card plugged into the voting terminal.

- A **verification terminal** (another portable computer with a contactless smartcard reader). This terminal is only capable of reading (and not writing) ballots. The voter can optionally place his written ballot on this terminal to make sure his vote was correctly cast.
- A set of **blank ballots**, taking the form of secure contactless smart cards which are cryptographically paired with this specific instance of voting and verification terminals (see subsection 2.3).
- A **voting booth**, formed by folding a cardboard divider, that hides the voting and verification terminal from the elections committee and allows the voter to vote in privacy.
- A **ballot box,** where cast ballots (written contactless smartcards) are physically collected. The ballot boxes are typically made out of cardboard sheets, which are delivered flat and folded into shape on election day.
- The **local elections committee**, which typically consists of three mutually distrustful (and technologically inexperienced) members nominated by the parties participating in the elections. These local commitees in turn report to a central elections committee which oversees the election process.

– A **population register terminal**, used by the local elections committee to verify that each voter accessing the voting station is eligible to vote and has not voted before.

### 2.2 The Proposed Voting Process

The actual voting process is illustrated in figure 4, and is carried out in the following way:

1. The **voter** approaches the **elections committee**, which verifies his eligibility to vote using the **population register terminal**, takes his ID card (which is mandatory in Israel) and provides him with a **blank ballot** (contactless smartcard).
2. The voter enters the **voting booth**, where his actions cannot be seen by the committee. He next places his blank ballot on the reader connected to the **voting terminal**. He selects the vote he would like to cast via a touchscreen interface. Once the voter is satisfied with his vote it is written electronically to his ballot. The running total count of votes is also written to a (non-contactless) smart card embedded in the voting machine. The voter is allowed to change his mind and update his vote multiple times, with both the voting terminal's internal smart card and the ballot tracking the latest choice in real time.
3. If the voter wishes to convince himself that the vote he has selected was correctly recorded on his ballot, he may place the ballot on a reader connected to the **verification terminal**, which simply displays his selected vote. As noted in subsection 2.3, the verification terminal is only capable of reading votes cast in this particular voting station. The ballot is supposed to be cryptographically secured and its contents cannot be read back by any other way.
4. The voter, now satisfied with his vote, drops his written contactless smartcard into the ballot box, in plain sight of the voting committee.
5. After witnessing the voting process, the elections committee returns the voter's ID card to the voter.
6. At the end of the day, the local elections committee retrieves the contact-based smart card from the voting terminal and delivers it to the central elections committee, where the cards collected countrywide are tallied to calculate the nationwide preliminary election results. These results are formed by adding together the running totals stored on the voting terminal's smart card forms.
7. After the preliminary results are announced, the elections committee manually counts all votes found inside the ballot box by passing them one by one through the verification terminal. Importantly, the final manual count takes precendence over the preliminary computer-counted results. If the "hand-counted" votes and the computer-counted votes mismatch by a certain percentage ([5] suggests 30%), all votes in this voting station are ruled invalid. Any subsequent vote recounts, if desired, will also be performed against the smartcards inside the ballot box.

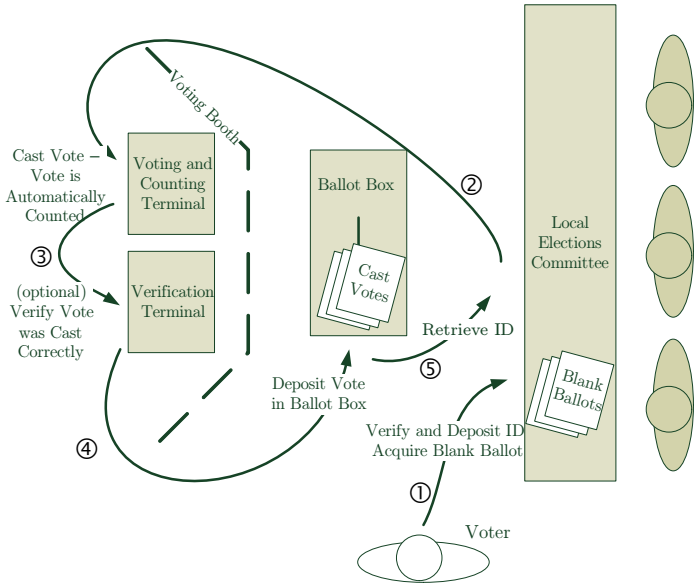


**Fig. 4.** The proposed Israeli e-voting scheme in action. The arrows show the path followed by a voter through the three areas of the voting station.

Note that the security properties of population register terminal are not covered in this report.

### 2.3 Security Features of the Scheme

The Israeli e-Voting Scheme was designed with a certain emphasis on security. The voting and verification terminals are cryptographically paired with the blank ballots used in each specific station, meaning that (at least as designed) a ballot cannot be read from or written to outside its specific voting terminal[1]. This means an attacker cannot steal a voting terminal from one voting station and use it to his advantage in another station. The voting terminals have no online connection either – the identity of the voter is only verified using by the population register terminal used by the voting committee. We have not reviewed these security features in any way.

The redundancy in the vote counting process offers another degree of security, since the voting tallies which are written to the secure smart card inside the voting terminal must match the count of votes in the ballot box. Thus, an attacker would theoretically need to subvert both locations before compromising the election results.

[1] Even the government's "master key" is incapable of rewriting a ballot. It can only format the contactless smart card to a blank state

The designers of the Israeli e-voting scheme chose near-field contactless readers instead of traditional smartcards for non-security-related reasons. First and most important is the issue of cost and reliability – since a contactless smartcard reader has no mechanical interface and no moving parts (in contrast to a traditional smart card or magnetic-stripe reader), it can survive many more repeated uses with a reduced opportunity for damage or deliberate vandalism. In addition, as observed in [10], contactless smartcards are easier to use than magnetic stripe cards or traditional smart cards since they work regardless of the way the card is oriented with respect to the reader. Cost saving is also reportedly the reason why the system has absolutely no paper trail – the designers wished to save on the cost of maintaining and supplying paper to thousands of printers on election day.

Note that this system has been criticized by many (cf. [20,21]), specifically for its lack of a paper trail, but also for its cost and possible discriminatory nature against the technologically challenged such as the poor, uneducated or elderly voters. In this work our goal is to provide a purely technical critique that is based on the suspectibility of the system to physical layer attacks and to relay attacks in particular.

## 3 Relay Attacks on the e-Voting Scheme

As mentioned before, the fact that legitimate contactless smartcards have a limited read range should not be considered a security feature. Specifically, the fact that a certain tag is communicating with a certain reader does not imply with any certainty that the tag and reader are in proximity. In our attacks, we use this flaw to create a communications link from the voting and verification terminals inside the voting booth to the RFID-based ballots inside the ballot box that carry votes which were already cast.

One specific aspect of the voting process makes relay attacks even more effective in this context. As stated in the previous subsection, in conventional relay attacks the attacker's tag (or ghost device) is generally used in a legitimate point-of-sale or conditional entry scenario, and as such must look very similar to an authentic tag to avoid suspicion. Fortunately for our attacker, this limitation on the physical form of the ghost does not exist when attacking the Israeli voting system – when performing relay attacks on the election terminals, the attacker is hidden inside the booth and is promised a high degree of privacy by the very nature of the voting process itself. This means that the ghost end of the attacker's relay setup can take any arbitrary form. The attacker may even use his time in the voting booth to replace the entire ensemble of voting and verification terminals with hacked machines running his own code (as the authors of [6] did when attacking EMV systems). The reader end (or leech device) can likewise be given an arbitrary shape, if we make the reasonable assumption that the voter can approach the voting commitee carrying a backpack or bag and ask them to mind his bag while he votes, or even consider the possibility that one of the three members of the elections committee is collaborating with the adversary.

The following subsections outline several relay attack scenarios that are possible against the proposed Israeli voting system. This is not an exhaustive list: there may be other scenarios which we did not consider.

### 3.1 The Ballot Sniffing Attack

This attack, as illustrated in figure 5, allows an adversary to learn the complete contents of all votes already cast into the ballot box.

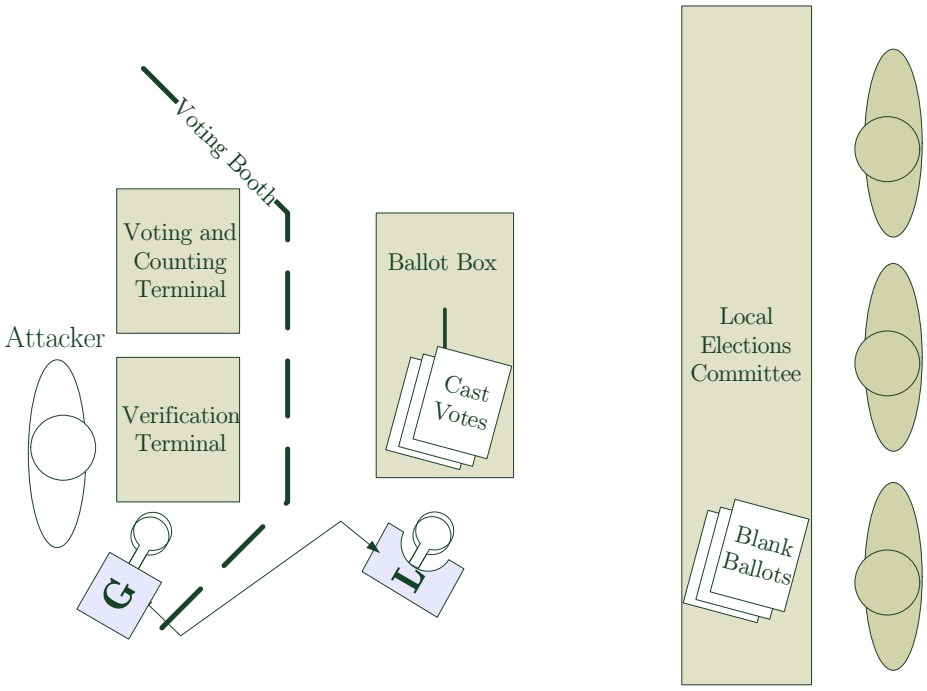


**Fig. 5.** Ballot Sniffing Attack

**Attack Description** To carry this attack, a relay is set up between the votes inside the ballot box and the verification terminal inside the voting booth. Next, the adversary repeatedly activates the verification terminal, each time with a different ballot. Since the verification terminal is paired with all cast votes in the ballot box, the adversary can now enumerate all votes inside the ballot box and display the votes recorded on them. This process can be carried out reliably and efficiently even if there are many votes already in the ballot box, as long

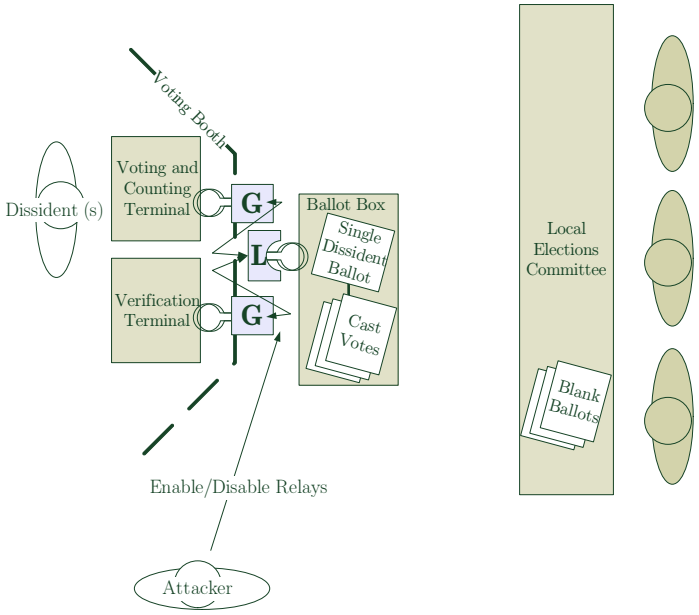


**Fig. 6.** Single Dissident Attack

as the "leech" component of the relay uses the RFID anticollision protocol to activate the tags one at a time[2].

**Implications** Using this attack, an adversary can determine the partial results of the vote before the voting day is over. If the votes in a certain ballot do not fit the outcome expected by the adversary, he may use this data to decide to disqualify the entire voting terminal using other methods described below. More importantly, if this attack is carried out twice in one day on the same ballot box it will teach the adversary about the votes cast in the interval between the two attacks. Thus, this attack can be used to verify that a voter had voted a certain way, violating voter privacy and allowing coercion to be inroduced into the voting process.

### 3.2 The Single Dissident Attack

This attack, as illustrated in figure 6, lets the adversary suppress nearly all undesirable votes in a certain voting station while remaining virtually undetectable.

[2] According to [18], even though the ISO 14443 anticollision protocol was officially designed to discriminate between up to $2^{32}$ tags, it has problems in practice when dealing with more than 3 tags at the same time. If indeed this is the case, this may limit the effectiveness of the ballot sniffing attack.

**Attack Description** To carry out this attack, the adversary needs to be present near the voting terminal while another voter is voting (for example, the adversary may volunteer to serve on this specific election committee or simply stand outside). As a prerequisite to this attack, the adversary sets up a relay between the voting and verification terminals and a single previously cast vote located inside the ballot box, hereby called the "single dissident vote". This relay can be turned on and off as desired by the adversary. The adversary then selects a certain group of voters whose voice he wishes to suppress[3]. In general, the relays will operate only when one of these "dissidents" is inside the voting booth. As stated previously, an attacker can easily obtain such fine-grained control over the voting and verification systems if he replaces both terminals inside the voting booth with similar-looking computers running his own code (see [6]).

When the relay attack is active, all of the dissenting voter's actions (voting, verifying, etc.) are not performed against the blank ballot he is holding, but rather shunted to the single dissident vote already in the ballot box. Since this single ballot is properly authenticated, both the voting and the verification terminals happily register the vote and display its correct value. Thus, the voter has no idea that the attack is taking place, but his personal ballot always stays blank. After the voter exits the booth, he casts his blank vote into the ballot box and his vote is effectively disqualified and ignored.

**Implications** If the adversary manages to correctly guess the disposition of the voter, this attack makes sure the ballot box contains no more than one dissenting vote for each undesirable party. Because of the relay attack all other dissenting voters will register as blank, or invalid, votes, and have no effect on the outcome of the elections. Since the votes inside the ballot box correlate directly with the values written to the smart card inside the voting terminal, the recount at the end of the voting day will find no discrepancy between the two. However, there is only one vote left to represent any amount of dissenting voters.

While this attack seems at first difficult to set up and carry out, it has the advantage of being virtually undetectable. If one of the dissenting voters gets suspicious and tries to find traces of this attack, even manual examination of the per-box vote counts will not reveal the subterfuge in this case, since each voter can be certain only of his personal vote, and at least one dissenting vote has been registered in this ballot. Thus, each dissident will be forced to conclude that his accomplices had a change of heart at the ballot, and that he is indeed the only one to have placed a dissenting vote in this specific ballot box.

If the attacker is somewhat uncertain of his ability to guess how a voter will behave inside the booth, he can use not one but several dissident votes and map the dissenting voters at random into one of this small set whenever one of them enters the booth. Since only a single vote for each party needs to be registered at

[3] The attack builds on the assumption that the the adversary can guess the vote of a some voters based on their external characteristics or some other auxiliary information. This is very reasonable in general, and even more so in Israel given the highly heterogenous nature of the Israeli voting body.

the voting terminal for the attack to be undetectable, the probability of failure can be significantly reduced by choosing an appropriate size for this group.

Note that according to [18] the voting terminal can somehow keep track of which ballots it wrote to, and refuse to connect to previously written tags as soon as it encounters a new tag. We cannot comment on this mechanism since the documentation given in [19] does not specify exacly what identifier is recorded and how the mechanism should work. Indeed, it seems difficult to provide this functionality without exposing the system to voter privacy violation or to denial of service attacks. Nontheless, such a mechanism may limit the effectiveness of the single dissident attack.

### 3.3 The Ballot Stuffing Attack

This attack, as illustrated in figure 6, gives an adversary complete control over previously cast votes, using a relay attack to rewrite them to the candidate of his choice.

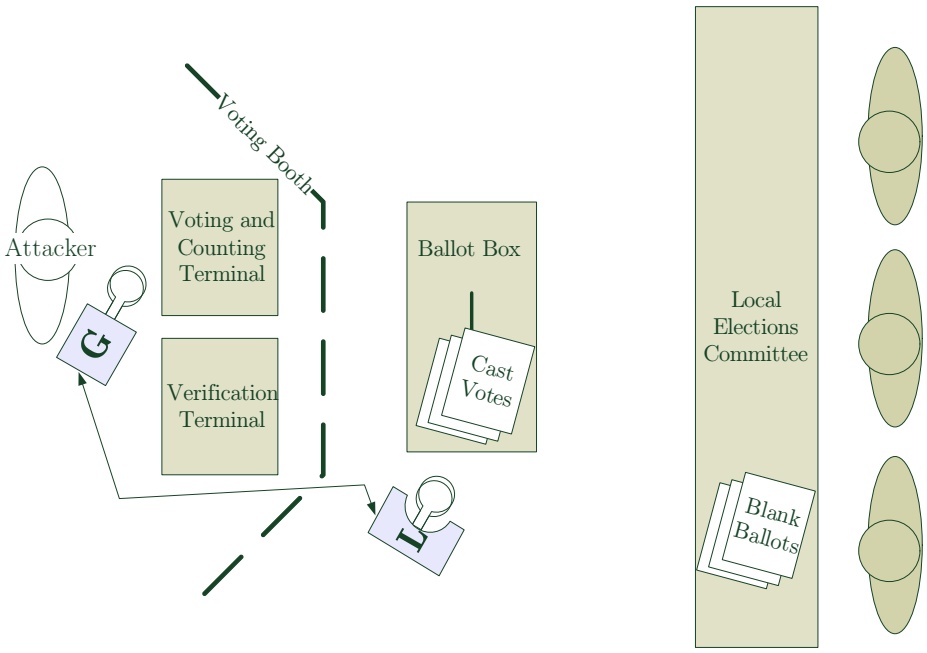


**Fig. 7.** Ballot Stuffing Attack

**Attack Description** To carry out this attack, a relay is set up between the ballot box and the voting terminal. Next, the adversary enters the voting booth

and repeatedly votes for the candidate of his choice, each time with a different ballot selected from the ballots already inside the ballot box. Since the voting terminal is paired with the previously cast votes, it has no reason to prevent the votes from being modified. Since the voting terminal itself is used to perform the attack, it constantly updates its running vote counts and thus remains in perfect sync with the cast votes instead the ballot box[4]. This means that this attack causes no discrepancy which can be detected during a recount. The RFID anticollision protocol allows this process to be carried out reliably and efficiently even if there are many votes already in the ballot box. The ability to rewrite ballots multiple times is a **confirmed feature**[**18**] of the system.

**Implications** This attack is the most conspicouous of all attacks presented here, but it is the most powerful, since it allows the entire set of ballots to be rewritten arbitrarily. As noted in the previous subsection, the only sort of fraud that is detectable by mutually distrustful voters would be the case when a party the voter had personally voted for ends up with zero votes in this ballot. If the adversary had previously applied the ballot sniffing attack to read all votes in the ballot, he can avoid this form of detection by registering one vote for each party originally represented in the ballot under attack and giving all other votes to his candidate of choice. The lack of paper trail means that this attack is undetectable and unprovable, even though it has the potential to arouse voter suspicion if used crudely. Note that the countermeasures sketched in the two previous subsections affect this attack as well.

## 4 Non-Relay Attacks

The relay attacks described in the previous section require some sophistication and a minor budget from the attacker. In addition to these attacks, the RFID technology used in the proposed voting system is also susceptible to simpler hardware-based attacks.

### 4.1 The Zapper Attack

This relatively low-tech attack, illustrated in figure 8, can quickly and easily disqualify a certain ballot box, allowing an adversary coarse-grained control over the results of the election.

**Attack Description** This attack assumes that the adversary had decided (based on apriori demographic knowledge or on information gained by the ballot sniffing attack described in subsection 3.1) that the votes cast by the entire

[4] We assume that the voting terminal handles multiple votes using the same card by subtracting one vote from the old choice and adding one vote to the new choice, and that there is no "finalizing" step which locks the card from subsequent edits. This interpretation was validated by [18].

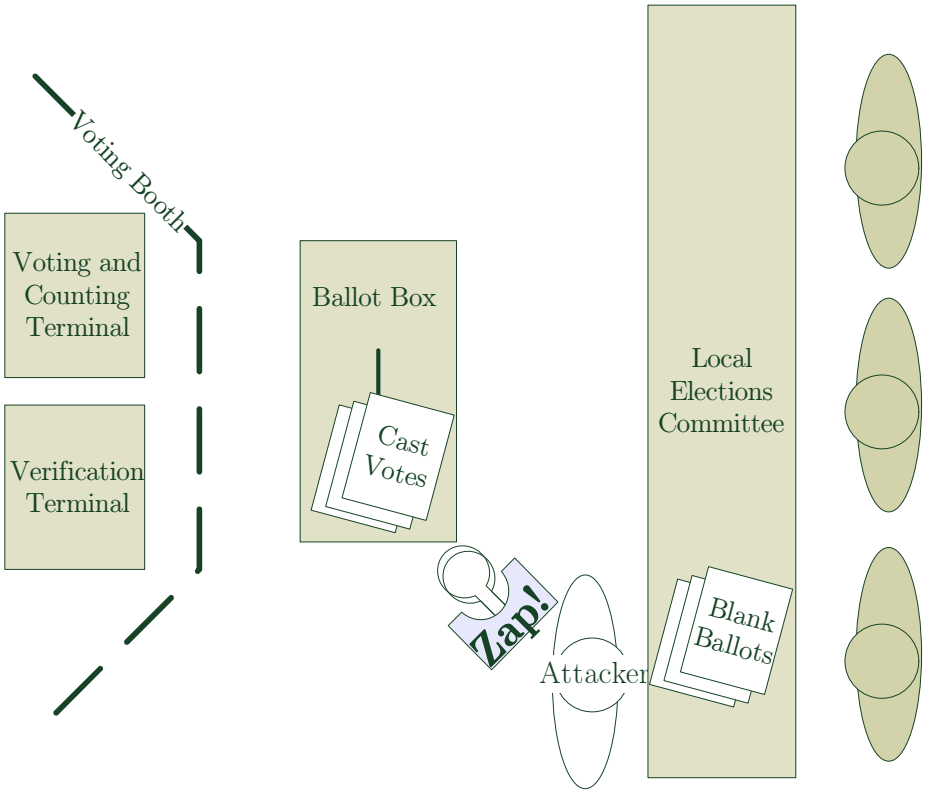


**Fig. 8.** Zapper Attack

population of a single ballot box are not to his liking. The adversary can make use of a low-cost "RFID Zapper" device[17], consisting of a pulsed power source (most conveniently, the flash circuit from a disposable camera) connected to a properly shaped reader antenna. When the pulsed power source (e.g. flash camera) is activated, a powerful electromagnetic pulse flows through the antenna and "zaps" any RFID tag close enough to couple magnetically with this antenna with a powerful surge of current which overwhelms its input circuits and generally renders it unusable. A live video demonstration of such a device being used to disable an ISO/IEC 14443 tag can be found in [2, starting at 19:00]. Once 30% of the tags inside the ballot box are "zapped", this will cause a discrepancy between the count of ballots held by the smartcard located inside the voting terminal and those counted manually by the elections committee, causing the entire ballot to be legally disqualified.

We were told [18] that the high-end Java cards selected for the Israeli elections contain circuitry to protect them against static electricity shocks, which may offer some protection against zapping. It is unclear how well these defenses work against a high-power burst of energy produced by a dedicated zapper device, as opposed to a high-voltage DC electric shock.

**Implications** This attack allows anybody with access to a ballot box to quickly and undetectably disqualify its contents and remove it from the election process. The ballot box can be zapped during the election process or later, while the ballots are kept pending the manual recount. This attack is so easy and inexpensive to carry out that it may be even done for reasons of malice or protest, and not just for changing the election results.

### 4.2 Jamming, Blocking and Selective Denial of Service

The jamming attacks illustrated in figure 9 can disrupt the operation of the RFID reader at a distance. They can be turned on and off on demand.

**Attack Description** While the physical interface used by the tag is based on magnetic coupling, most RFID readers actually use a standard radio decoding technique called single side-band (SSB) demodulation to decode the tag responses. As noted in [14], this property allows the ghost component of a relay to work at distances of up to 50 meters, but it also means that the reader's standard operation can be disrupted by SSB modulated signals sent to it from a distant radio antenna. To carry out this attack the attacker uses a directed antenna to broadcast a random SSB-modulated bit pattern toward the reader at the tag's upper side-band frequency of 14.4075 MHz. The reader connected to the voting terminal will not be able to distinguish between this disruptive signal and the tag's response, rendering the reader inoperative and creating an effective denial of service attack.

A similar attack can be performed by hiding a "Blocker Tag"[13] somewhere within the voting booth (for example, between the voting terminal and the table

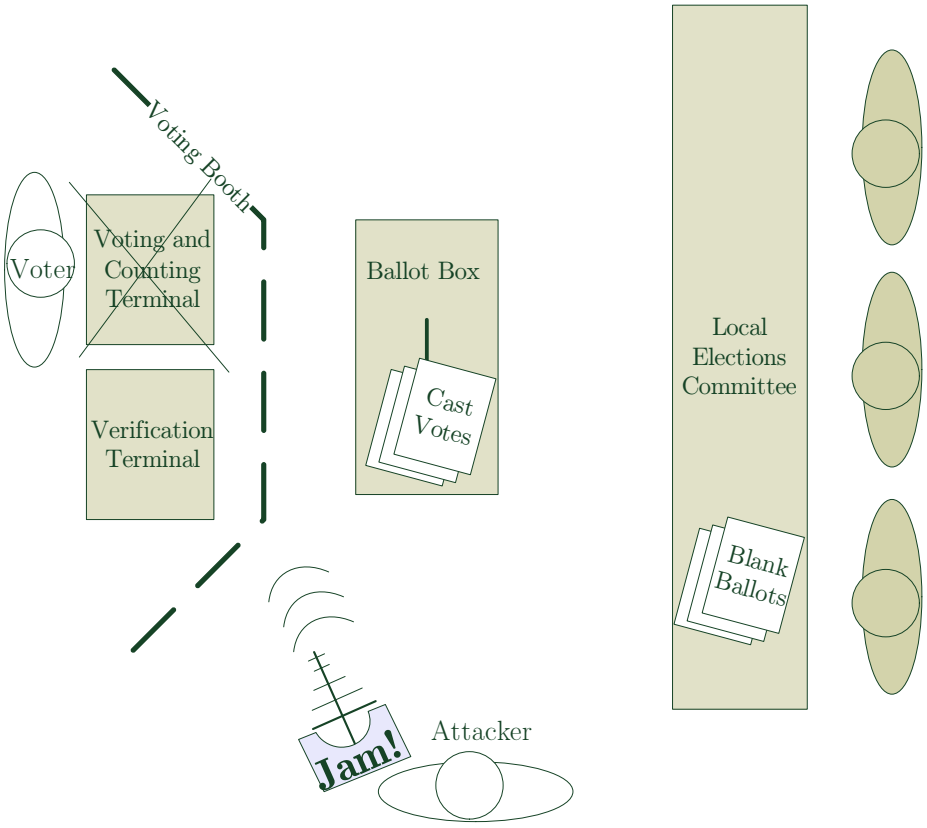


**Fig. 9.** Jamming Attack

on which it is set). This tag is a special hardware device which conforms only partially to the RFID specification – specifically, it ignores the tag anti-collision protocol under certain conditions, disrupting tag and reader communications. The blocker tag presented in [13] prevents RFID readers from communicating with tags whose ID matches certain criteria while allowing all other communications. The design can be modified to support a high-range remote control interface allowing blocking to be turned on and off on demand, creating another hard to detect denial of service system.

**Implications** The jamming attack is a **selective denial of service attack**, since it is easy to apply selectively only to a certain subset of voters at the discretion of the attacker. This attack is also unique in its very high operating range. It cannot be prevented unless electromagnetic shielding is applied to the walls, doors and windows of every voting station (and not just the ballot box itself).

### 4.3 Faulty Implementation Attacks

As stated in subsection 2.3, the Israeli voting scheme has certain security properties built in by design, most significantly the cryptographic pairing of blank ballots and voting terminals. This pairing means that a compromised terminal stolen from one voting station cannot be used to attack another station. Throughout this article we assumed that this security feature was properly implemented. A proper implementation would mean that both terminals and blank ballot authenticate each other via public key, they execute a properly randomized key exchange protocol resulting in the generation of a random session key, and all messages sent under this session key are properly randomized, padded, encrypted and MACed to prevent replay or message modification attacks. However, implementation flaws in any part of the cryptographic pairing process immediately make the system even more vulnerable. Here are some examples:

1. If the authentication process consists of a highly secure and authenticated "unlocking" phase followed by a less secured exchange of commands with the "unlocked" tag, the attacker can wait until a tag is legitimately unlocked and then take control of the conversation and send his own commands to the unlocked tag, allowing him to influence the voting results or disqualify an entire voting terminal. This mode of operation is actually common in several low-security RFID protocols, such as the EPC Gen-2 memory write command[1].
2. If encryption is not randomized, then there would only be as many possible encrypted messages as the number of parties in the elections – well under 100 values in Israel.
3. If the messages are not padded to a fixed length and the plaintext includes the full name of the selected party, then the encrypted message length divulges information about the encrypted content.

## 5 Countermeasures

This section lists several countermeasures which can be applied to increase the security of the proposed system. Even with all of these countermeasures applied, the system as proposed seems "too broken" to be used in a high-stakes democratic process. However, it would make good sense to apply them if a future variant of the scheme is used for a less important purpose than a democratic election.

### 5.1 Physical Layer Security

The most crucial protection mechanism against relay attacks is that the voting station and its environment should be protected from all forms of electromagnetic radiation. Most importantly, the ballot box should be made into a Faraday cage by constructing it from a sufficiently thick sheet of conducting material such as aluminum. Ferric materials such as iron are probably less suitable since they may not block magnetic coupling between reader and tag. Electromagnetic shielding should also be applied to the walls, windows and doors of the voting station itself, to prevent jamming and selective denial of service attacks from being carried out from a distance. A handy indicator of proper shielding would be the total lack of cellphone reception inside the voting station. Furthermore, when outside the ballot box, the individual ballots (used or not) should be carried inside envelopes made of conducting metal.

The ballot box should also be kept away from any object large enough to hide a leech device. To be on the safe side, no object should be allowed to come within a 1m radius of the ballot box. In particular, the ballot box should **not** be on or near the committee table. One open question is how to allow an untrusted voter to approach the ballot box and deposit his vote.

### 5.2 Audio Feedback and Cooldown

The voting and verification terminals should be programmed to emit a loud beep each time they read or write a tag. In addition, the terminals should have a "cooldown" period of at least 30 seconds between each use, or at least before switching from one tag to another. Any attempts at wholesale vote sniffing or rewriting will now take a long time and result in many conspicuous beeps, a fact that should arouse the suspicion of the voting commitee. Note that these countermeasures have no effect on the single dissident attack (which registers a single vote per voter), nor do they prevent a single voter from modifying a small but constant amount of votes.

### 5.3 Single-Write Ballots

The voting station should include some sort of irreversible "commitment" or ballot cancellation process (similar to the one performed on paper stamps) which

will finalize the vote so the RFID smartcard can be read from but not written to again. In the best case this can be accompanied by a visible mark on the ballot itself. The single dissident attack described in subsection 3.2 will still work in this case if the adversary belongs to the elections committee, since he can keep one uncommitted smart card especially for this purpose and perform the relay attacks against this dedicated card. Note that this countermeasure makes the e-voting scheme less cost effective, since it makes the ballots one-use-only and precludes them from being used over multiple elections. According to [18], the proposed implementation is supposed to include an (as yet undocumented) mechanism along these lines.

### 5.4 Strong Probabilistic Encryption

To protect against implementation attacks, the data exchanged between the ballot and the reader should use well-established security best practices. All conversations between the tag and the reader should be authenticated by the private keys of both tag and reader and encrypted by a per-session key. The voting data, which probably consists of a very short payload indicating the selected party, should be padded with random bytes to a constant length and contain a sequence number (to prevent replay attacks on voters who change their minds).

## 6 Conclusion

In this work we have shown how any party with moderate technical expertise and a fairly small budget can completely compromise the proposed Israeli e-voting system. Our attacks are aided by the fact that the voter's actions in the voting booth are unmonitored, by the design choice of making the tags rewritable, and by the additional fact that the local elections commitee are typically technologically inexperienced.

Despite the threat of relay attacks, contactless RFID smardcards are in use in sensitive applications such as credit cards, e-passports and secure entrance systems, so one may think that they are good enough for e-voting as well. Unfortunately, in these other applications there are always additional security mechanisms: audit trails, credit card statements, insurance, security cameras, human guards, store clerks or border officials. In a voting application, voter privacy **by design** eliminates the possibility for all of these additional safeguards. Unless the attacker is caught "red handed" during the attack, a relay attack on an election may well be a perfect crime.

The designers of the voting system most probably chose contactless technology for cost and reliability reasons. However, this choice led to a devastating side effect in the form of the relay attack. In its current form, the proposed system cannot guarantee the privacy of voters, and it cannot promise that cast votes were not manipulated after the fact. We have offered a few suggestions that, if properly implemented, can mitigate some of the attacks. Nevertheless,

viewed together with the substantial non-technical flaws with the system (as discussed in subsection 2.3), we believe the proposed system is strictly inferior to, and completely unacceptable as a replacement for, the plain-paper ballot system currently used in Israel.

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