Formal analysis of EMV

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Overview

- The EMV standard
- Known issues with EMV
- Formalisation of the EMV standard in F#
- Formal analysis using FS2PV and ProVerif

EMV

- Started 1993 by EuroPay, MasterCard, Visa
- Common standard for communication between
  1. smartcard chip in bank or credit card (aka ICC)
  2. terminal (POS or ATM)
  3. issuer back-end
- Specs controlled by EMVCo which is owned by
- Over 1 billion cards in use
- EMV-compliance required for Single Euro Payment Area

Why EMV?

- Goal: reducing fraud by
  1. skimming
  2. stolen credit cards used with forged signatures
  3. card-not-present fraud (EMV-CAP)

- And also some transfer of liability?

Does EMV reduce skimming?

- UK introduced EMV in 2006

Skimming fraud with UK cards, in millions£

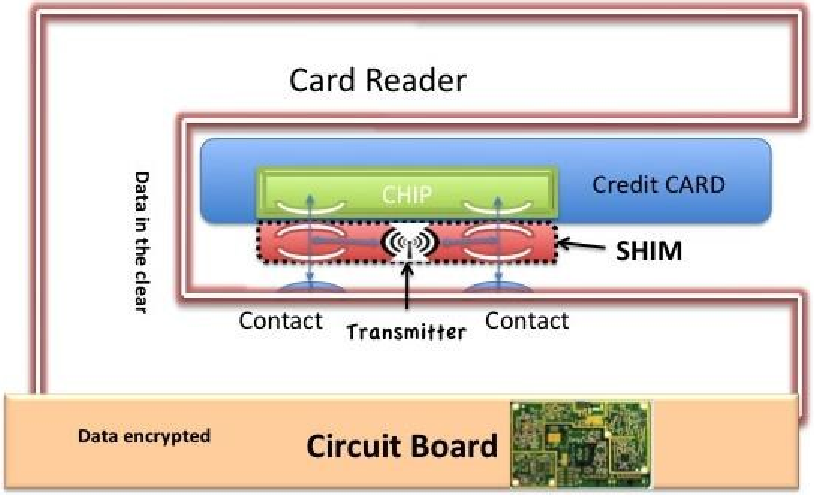
	2005	2006	2007	2008
domestic	**79**	**46**	**31**	**36**
foreign	**18**	**53**	**113**	**134**

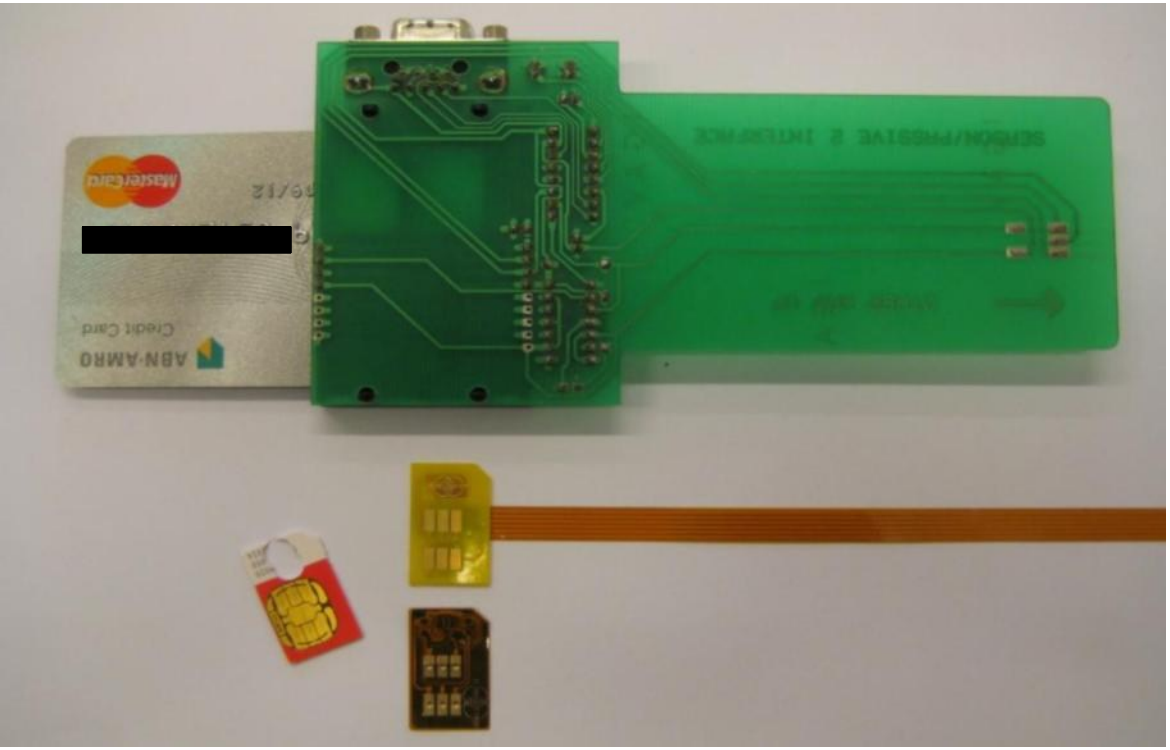
- Magstripe can still be cloned and used in countries that don't use the chip (notably USA)
  - Worse still: chip provides the Track 2 magstripe data
  - There are now moves to remove this `feature'

Man-in-the-Middle attacks

- using a shim

  possibly invisible inside terminal
- eavesdropping or modifying traffic





old-fashioned version
(mainly used for hacking pay TV)

newer, thin versions
(used for studying SIM locking)

The EMV protocol suite

- EMV is not a protocol, but a "protocol toolkit suite":

  many options and parameterisations (incl. proprietary ones)
  - 3 different card authentication mechanisms
    - SDA, DDA, CDA
  - 5 different cardholder verification mechanisms
    - online PIN, offline plaintext PIN, offline encrypted PIN, handwritten signature, no card holder verification
  - 2 types of transactions: offline, online

  All these mechanisms again parameterised by Data Object Lists (DOLs)
- Specification public but very complex (>750 pages)

EMV basics: key set-up

- Card and issuer have shared symmetric key
  - which the terminal does *not* have
- Issuer has private/public keypair, used to sign data
  - which the terminal can verify
- *Some* cards have a private/public keypair, used to sign data
  - which the terminal can verify

EMV basics: parameterisation using DOLs

- Data Object Lists specify a list of data elements and their formats
  - eg date, country, amount, primary acount number (pan), application transaction counter (atc), card/terminal generated nonce, ...
- Card contains several DOLs that specify
  - inputs required by the card
  - (signed/MACed) output produced by the card

  at some protocol step

  Eg CDOL specifies which data is signed in a transaction cryptogram

EMV protocol phases

I. Initialisation

Terminal reads some data from the card, incl. several DOLs

I. Card Authentication

II. Cardholder Verification (optional)

III. Transaction

II. Card Authentication: SDA

1. SDA – Static Data Authentication
   - card present static data (card no, expiry date etc) signed by issuer
   - problem: can be replayed, so card can be cloned
     - clone will always say offline PIN check succeeded

   - hence: *offline terminal can be fooled*
     - transaction is signed (MACed) using symmetric key, but terminal cannot check this MAC
     - issuer will spot this fraud later

II. Card Authentication: DDA

1. SDA – Static Data Authentication
2. DDA – Dynamic Data Authentication
   - card has (Pub,Priv) keypair and does challenge-response
     - requires more expensive card than SDA: one that can do asymmetric crypto
   - problem : card authenticated, but not the transaction
   - hence: *offline terminal can still be fooled*
     - issuer will spot fraud later

II. Card Authentication: CDA

1. SDA – Static Data Authentication
2. DDA – Dynamic Data Authentication
3. CDA – Combined Data Authentication
    - card has (Pub,Priv) keypair , as in DDA
    - signature now added over all the transaction data
        - so even an offline terminal can check authenticity

II. Card Authentication

1. SDA – Static Data Authentication
2. DDA – Dynamic Data Authentication
3. CDA – Combined Data Authentication

- Most cards in use are SDA or DDA
- SDA is being phased out
  - eg Visa & Mastercard forbid issuance of offline capable SDA cards starting 1/1/2011
- Nobody seems to be phasing in CDA cards yet…

III. Cardholder Verification Mechanisms

1. PIN
   a. online: PIN checked by the issuer
   b. offline: PIN checked by the chip
      - unencrypted
        PIN could be eavesdropped using shim
      - encrypted
        requires a card that can do asymmetric crypto
1. Handwritten signature
2. Nothing

Note: only offline PIN involves the smartcard chip

One more weakness…

- Terminal can be fooled into thinking a transaction was *with* PIN, while card & issuer know it was *without* PIN
  - using a wedge aka Man-in-the-Middle attack
  - for online and offline transactions
  - root cause: terminal cannot authenticate response to offline pin verification

    [Murdoch, Drimer, Anderson, Bond, "Chip & PIN is broken", 2010]
- This allows a stolen card to be used without PIN, but only
  - as long as the card is not reported stolen (for online)
  - if issuer allows PIN-less transactions (as is case in UK)

  or… if the issuer misses the correct checks for this in the back-end

IV. Transaction

- For the transaction the card generates cryptograms

  ie data with a MAC, and for CDA-cards, also a digital signature

- For online transaction the card generates 2 cryptograms
  - first cryptogram (ARQC) forwarded to the bank for approval
  - second cryptogram (TC) confirming the transaction
    - only after the card receives approval by the bank
- For offline transaction the card just generates oneTC cryptogram
  - A card may refuse an offline transaction, and force the terminal to go online

Complexity of the EMV specs

- Moral of the story: specs too complex to understand
  - long specs, split over 4 books
  - little discussion of security goals or design choices
  - little abstraction or modularity

- Eg why not build on a notion of session level integrity & confidentiality as in SSL/TLS?
- Who really takes responsibility for ensuring these specs are secure? EMVCo, credit card companies, or banks?

Formalising EMV ?

- Can formal security analysis tools cope with EMV?

- First attempt: formalising EMV in ProVerif

  Horrible! If-statements in applied pi-calculus cause huge duplication

- Second attempt: formalising EMV in F#

  Much better! F# allows sequential if-statements & functions

Formalisation of EMV in F#

Formalisation of EMV in F#

- EMV can be formalised in 370 lines of F# code
  - including all options
    - SDA, DDA, CDA
    - any card holder verification mechanism
    - off/online transations

    Booleans parameters controlling these options can be left unspecified (to study all these options) or fixed (to consider just one)
  - but remaining configuration (DOLs) has to be fixed
    - we use minimal assumptions on DOLs taken from Dutch bank/credit cards
    - hardcoded in the model, but could easily be changed

Part of EMV model: DDA

```
// Perform DDA Authentication if requested, otherwise do nothing
let card_dda (c, atc, (sIC,pIC), nonceC) dda_enabled =
  let data = Net.recv c in
  if Data.INTERNAL_AUTHENTICATE = APDU.get_command data then
     if dda_enabled then
         begin   let nonceT = APDU.parse_internal_authenticate data in
                 let signature = rsa_sign sIC (nonceC, nonceT) in
                  Net.send c (APDU.internal_authenticate_response nonceC signature);
                 Net.recv c
        end
     else  failwith "DDA not supported by card"
  else  data
```

Analysis of the F# model

- F# can be translated to pi calculus by FS2PV tool and then analysed using ProVerif
- Translation to pi calculus explodes things a bit
  - 370 lines of F# becomes 3 kloc of pi calculus
- But… ProVerif can still verify security properties
  - usually in minutes, but *this requires some care!*

Properties checked with ProVerif

1. sanity checks to ensure absence of deadlock
2. secrecy of private keys
3. highest supported card authentication method is used
   - eg no fallback to say SDA can be forced

1. 'transaction security': if a transaction is completed, then everyone agrees on the parameters (eg with/without pin, off/online, amount,…)

query evinj:TerminalTransactionFinish(sda,dda,cda,pan,amount,…)

==> evinj:CardTransactionInit(sda,dda,cda,pan,amount,…).

No new attacks found, but all existing weaknesses confirmed

Future work

- Including formal model of the issuer
  - we don't know the configuration, so can only check EMV's example configuration
- Using F7 instead of ProVerif for verification
  - F7 might give better /more predictable response time
- Making F# model executable
  - with helper functions that implement low-level smartcard interaction, the model could interact with real cards *and* terminals
    - gives high confidence that our model is correct
    - could be used for model-based testing?

Future work: EMV CAP?

- use EMV chip for internet banking or e-commerce
  - EMV CAP defined on top of EMV:
    an EMV-CAP session is an *aborted* EMV session
  - internet banking
    - Mastercard : CAP (Card Authentication Program)
    - Visa : DPA (Dynamic Passcode Authentication)
  - e-commerce
    - Mastercard: SecureCode
    - Visa: Verified by Visa

- *CAP specs are secret but have been partially reverse-engineered*
  - *also some patents discuss EMV-CAP*

Reverse engineering EMV-CAP

Conclusions

- EMV protocol suite is far too complicated
  - too many options, written down in confusing way
- Formalisation possible in F#
  - and result is comprehensible!
- Formal analysis using FS2PV & ProVerif reveals all known weaknesses

- The future of skimming
  - Will skimmers move to the USA?

    For skimming cards there, or using the data they skim here?

cross-channel possibilities