Eavesdropping on and Emulating MIFARE Ultralight and Classic Cards Using Software Defined Radio

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Abstract

In this report, we describe a Software-Defined Radio (SDR) approach for eavesdropping on Near Field Communications (NFC) and Radio Frequency Identification (RFID) cards operating at 13.56 MHz. We show that GNU Radio and Python make a great platform for prototyping, while maintaining sufficient performance for passive attacks without extensive optimizations and using only modest processing power. We successfully eavesdrop on real MIFARE Ultralight and Classic 1K cards by capturing the raw radio waves with a home-made antenna. We recover the plaintext of both reader and tag fully by demodulating the incoming radio waves, parsing individual bits and error detection codes into packets, and then decrypting them if necessary. On the transmission side, we achieve full software emulation of the reader and of MIFARE Ultralight and Classic 1K cards (including encryption), and partial hardware emulation, where we correctly modulate the signal, but not within the strict timing limits of the protocol. Our transmissions can also be used to prevent legitimate communication by interfering with the intended reader or tag signals.

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1. Introduction

Contactless cards and tags have become very popular in recent years, with everyday applications including e-passports [25], ticketing [26, 6, 8], access control [27], and payment [16, 7] systems. However, as these devices operate wirelessly, adversaries can pick up the radio signals and eavesdrop on the communication between a tag and a reader. Traditionally, such attacks on radio communications required dedicated hardware for particular frequencies and modulation types, but with the advent of Software-Defined Radio (SDR), it is possible to use generic equipment and perform the demodulation in software. Even so, despite a range of embedded devices and Field-Programmable Gate Arrays (FPGAs) that are capable of various attacks on Near Field Communication (NFC), Radio Frequency Identification (RFID), and related technologies, to the best of our knowledge no open-source SDR implementation exists for High-Frequency (HF) NFC.[1]

To this end, we developed such an implementation on an Ettus Research Universal Software Radio Peripheral (USRP) using Python and GNU Radio with an antenna made out of simple wire that allows passive eavesdropping on reader-tag communication. Though our implementation is easily extensible, we focused on MIFARE cards by NXP Semiconductors, since MIFARE has "a market share of more than 77% in the transport ticketing industry", with "150 million reader and 10 billion contactless and dual interface IC's sold" [19]. Specifically, we use Ultralight [21] and Classic 1K [20] cards, as the former does not employ any encryption, while the latter uses a broken cryptographic algorithm (Section **??**), making them ideal candidates for such exploration. Moreover, we achieve full software and partial hardware reader and tag emulation, that can also be used to jam signals between a legitimate tag and reader. In summary, our contributions are as follows:

1. We implement in pure Software-Defined Radio a demodulator for NFC/RFID readers and tags operating in the 13.56 MHz frequency, which decodes radio waves into plaintext packets.
2. We test our implementation by eavesdropping on real MIFARE Classic 1K and Ultralight communications with an RFID reader using a home-made antenna and a USRP, successfully decoding any encrypted packets.
3. We additionally implement in software the emulation of both readers and tags, including encryption if necessary.

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[1]Though they exist for UHF Gen2 cards. See `https://github.com/brunoprog64/rfid-gen2` and `https://github.com/yqzheng/usrp2reader` for instance.

4. Though our transmission capabilities cannot keep up with the strict timing requirements of the protocol, we show how our implementation can jam real reader-tag communications and prevent the successful transmission of data.

5. Overall, our work shows that prototyping using Software-Defined Radio is sufficient in practice for passive attacks, without the need for extensive optimizations or heavy computing power.

PAPER STRUCTURE

2. Related Work

Early work on RFID Hacking was conducted in a non-academic context, and focused on finding vulnerabilities in access control systems [23, 26]. Later, Buettner and Wetherall [4, 5, 3] experimented more systematically with RFID and SDR, but focused primarily on Gen 2 cards operating at 900 MHz. Their work was extended by others, typically in the context of proposing better protocols [2, 29], but still for Ultra High Frequencies (UHF), with the exception of a recent work by Hassanieh et al. [10], which also included an extension to HF.

There have also been a number of designs which use microcontrollers and Field-Programmable Gate Arrays (FPGAs) for signal processing, such as the Proxmark 3 [28], and RFIDler [15]. Though such projects allow the use of custom firmware for additional functionality, they also require dedicated hardware in their design.

The MIFARE Classic cryptographic protocol was reverse-engineered by Nohl et al. by dissolving the plastic surrounding the chips, recovering the individual logic gates and converting them to a high-level algorithm [18]. Garcia et al. then discovered additional vulnerabilities of the protocol based on its nested authentication and parity bits [8]. Due to the wide range of applications of the MIFARE Classic, the topic became very popular for Master's thesis projects [24, 6, 22, 27], which found additional vulnerabilities, or examined the problem within the context of a specific application.

Finally, given the widespread availability of NFC-enabled mobile devices, researchers have also focused on NFC relay attacks using mobile phones [16, 7], as well as exploring [17] and protecting [9] the NFC mobile phone stack.

3. Background

The terms Radio Frequency Identification (RFID), Near Field Communication (NFC), contactless smartcards, proximity cards and vicinity cards are often used interchangeably, but they are covered by different standards and concern different parts of the radio spectrum. In this project, we looked at the ISO/IEC 14443 standard, with physical characteristics defined in [11], modulation and encoding in [13], initialization and anticollision in [14] and transmission protocols in [12].

Specifically, we focus on **Type A** communications, whose **carrier frequency** is $f_c = 13.56$ MHz. The reader – or **Proximity Coupling Device (PCD)** – communicates with the card – or **Proximity Integrated Circuit Card (PICC)** – through **100% Amplitude Shift Keying (ASK)**, with data using the **Modified Miller** encoding. The communication from tag to reader utilizes **Load Modulation** with a **subcarrier frequency** of $f_s = f_c/16 = 847.5$ kHz, using **Manchester Encoding**, and both transmit at a rate of 106 kbit/s.

Because the carrier frequency is $f_c = 13.56$ MHz, the wavelength is $c/f_c \approx 22$ meters, making it impossible to deploy antennas that would fit in a card-size form-factor. Additionally, because the cards are **passive** (i.e. do not have their own power source), both the communication and the power source are achieved through **inductive coupling** from the PCD's antenna loop to the PICC's antenna loop.

SECTION STRUCTURE

3.1 PCD Transmissions

Amplitude Shift Keying (ASK) of depth $X\%$ is a form of digital modulation which specifies that if the amplitude of the signal representing a digital 1 is equal to A and the amplitude of the signal representing a digital 0 is equal to B, then $X = \frac{A-B}{A+B}$, as showing in Figure 1. Specifically, for 100% ASK, no signal is sent at all during a digital 0, indicating that such periods must be very brief, since the PICC needs to keep charge (using a capacitor) for the period of silence.
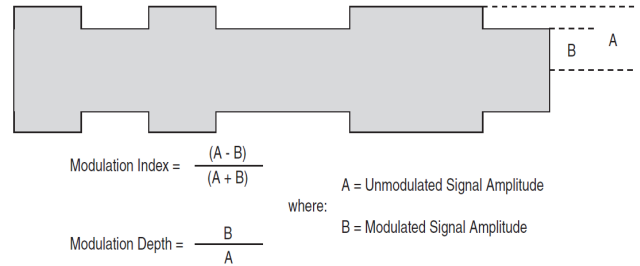

$$\text{Modulation Index} = \frac{(A - B)}{(A + B)}$$

$$\text{Modulation Depth} = \frac{B}{A}$$

where:
A = Unmodulated Signal Amplitude
B = Modulated Signal Amplitude

Figure 1. Amplitude Shift Keying (ASK) [1]

This is achieved through the Modified Miller Encoding, which ensures that there is no period of more than $3\mu s$ of silence ("pause"). Specifically, every bit is represented as a (combination of) signals lasting a total of $t_b = 128/f_c \approx 9.44\mu s$. The encoding (show in Figure 2) is as follows:

- A 1 is encoded as an unmodulated signal for $t_b/2 \approx 4.72\mu s$, followed by a period of silence for $3\mu s$, followed by an unmodulated signal for $t_b/2 - 3 \approx 1.72\mu s$
- A 0 after a 0 is encoded as a silence period for $3\mu s$ followed by an unmodulated signal for $t_b - 3 \approx 6.44\mu s$
- A 0 after a 1 is encoded as an unmodulated signal for a period of $t_b \approx 9.44\mu s$
- To indicate the beginning and the end of a transmission, a logical 0 is used for both the start and the end

In practice, however, because of hardware imperfections, the pause is not perfect, but needs to comply with the requirements shown in Figure 3. As a result, the modulated carrier for the encodings resembles Figure 4.
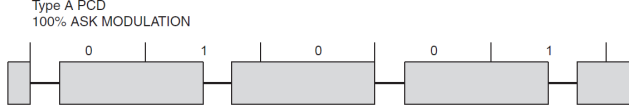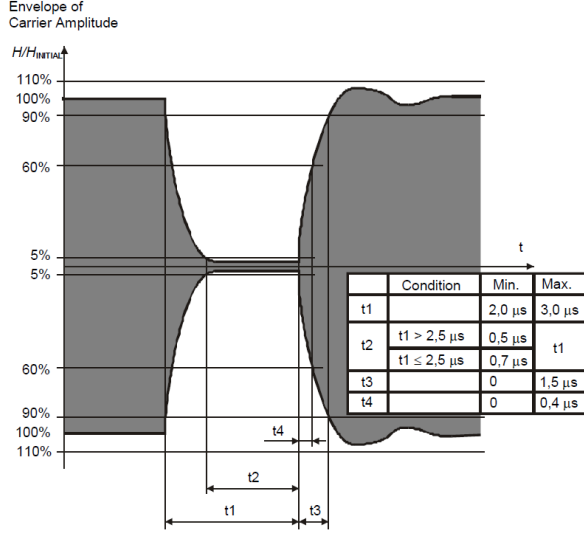
Type A PCD
100% ASK MODULATION

Figure 2. Miller Encoding at 100% ASK [1]

Envelope of
Carrier Amplitude

$H/H_{INITIAL}$

	Condition	Min.	Max.
t1		2,0 µs	3,0 µs
t2	t1 > 2,5 µs	0,5 µs	t1
	t1 ≤ 2,5 µs	0,7 µs	
t3		0	1,5 µs
t4		0	0,4 µs

Figure 3. Real Pause Requirements [13]

modulated carrier

data bit "1":
9.44 µs
3µs

data bit "0":
9.44 µs
previous bit "0"
3µs

9.44 µs
previous bit "1"

Figure 4. Realistic Miller Encoding [19]

PCD   PICC
"1"   "0"
128 T_0 = 9.44µs — data manchester coding
subcarrier
16 T_0 = 1.18µs — subcarrier modulation
closed
open
load modulation

T_0 : carrier period
k : coupling coefficient

Figure 5. Manchester Encoding with Load Modulation [19]

3.2 PICC Transmissions

As mentioned above, the tag does not have sufficient power for active transmissions. Consequently, the PICC achieves data transmission passively, by changing its *load*, which can be inferred as a voltage drop on the PCD, hence the term **load modulation**. Switching the load generates a **subcarrier**, which has a frequency $f_s = f_c/16 = 847.5$ kHz.

The bits are then encoded using **On-Off Keying (OOK)** or **Manchester Encoding** as follows, with a total duration also equal to $t_b \approx 9.44\mu s$, which also equals 8 periods of the subcarrier, also shown in Figures 5 and 6:

- A 1 is encoded by modulating the subcarrier for the *first* half ($= t_b/2 \approx 4.72\mu s$) of the bit duration
- A 0 is encoded by modulating the subcarrier for the *second* half ($= t_b/2 \approx 4.72\mu s$) of the bit duration
- A logical 1 starts the transmission
- No modulation signifies the end of a transmission

3.3 The Protocol

Though the ISO/IEC 14443A protocol is general, we will focus on a few key aspects that are relevant to our discussion. As a result, we will refer the reader to [14] for more details such as timing requirements.

First of all, it is worth noting that each byte is **ordered** from the Least Significant Bit (LSB) to the Most Significant Bit (MSB), and that each byte is followed by an **odd parity**
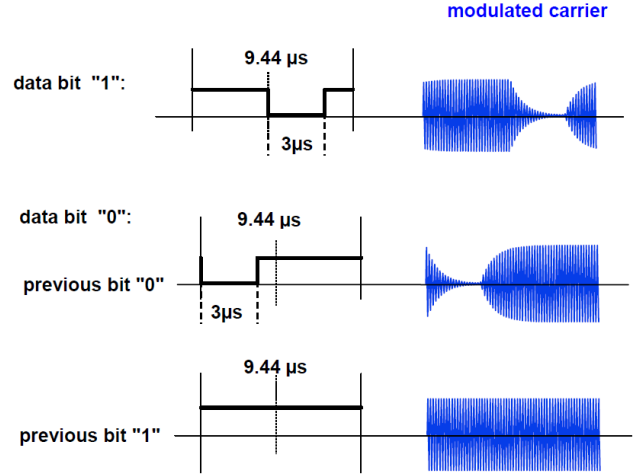
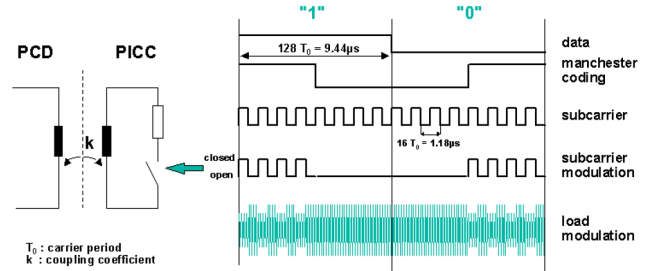**bit**, meaning that an even number of high bits (ones) is followed by another high bit (one), whereas an odd number of ones is followed by a low bit (zero). For example, the byte 0x3F is encoded as 1111 1100 1.

The PCD signifies that it is waiting to read tags by repeatedly sending a **REQA (0x26)** or a **WUPA (0x52)**, where the "A" signifies that type A protocol is used. The difference between the REQA request and the WUPA wake-up request is that the latter also wakes up PICCs that were previously asked to HALT. Unlike all other commands, they are sent using a *short frame* that only consists of 7 bits, and which does not include a parity bit. As a result, the REQA command (including the beginning and end transmission zero bits) is sent as the sequence of bits 0 0110 010 0.

The standard has also defined **Anticollision** and **Selection** phases before the transmission of actual data which are used to ensure the non-interference from multiple tags and the correct selection of the tag. However, we only discuss them in the context of the MIFARE cards in Appendix A, since they are not necessary for understanding the rest of this report.

Finally, we mention that to detect errors with longer transmissions, for some requests and responses a **Cyclic Redundancy Check (CRC)** is used on the transmitted bytes (but excluding start/end and parity bits). The polynomial used is $x^{16} + x^{12} + x^5 + 1$, with a starting value of 0x6363, under the assumption that "FF0 shall be the leftmost flip-flop where data
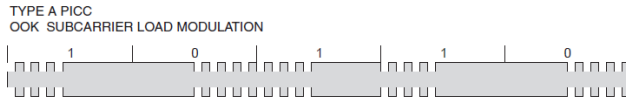
Figure 6. Envelope of Load Modulation [1]

Figure 8. Second Part of Authentication [20]

is shifted in [and] FF15 shall be the rightmost flip-flop where data is shifted out" [14]. For example, the **HALT/HLTA** command uses 2 bytes (0x50 0x00) followed by the two CRC bytes which can be calculated as 0x57 0xCD.

3.4 MIFARE Classic 1K Encryption

Even though the MIFARE Ultralight is ISO/IEC 14443 A compliant [21], the MIFARE Classic 1K uses a proprietary cryptographic protocol called CRYPTO1 [20]. The details of the protocol were not made publicly available, with the MIFARE datasheets only broadly explaining the 3-pass protocol [20]. Each **sector** (equal to 4 **blocks** of 16 bytes each) has two 6-byte keys (**Key A and B**), which on delivery are set to [0xFF 0xFF 0xFF 0xFF 0xFF 0xFF] (but can be changed later on a per-sector basis). Each authentication happens with one of the two keys chosen by the reader, and can only be used to access a specific sector. Each sector contains one block (the **sector trailer**) which contains the two keys and some **access bits** which determine the allowed operations for the 4 blocks (See Appendix A.2 for more details).

The PCD indicates to the PICC that it wants to authenticate through a command indicating which key to be used and what address to use. As shown in Figures 7 and 8, the three-pass scheme consists of a 4 byte challenge sent from the PICC to the PCD (Token RB), an 8-byte challenge and response (of 4 bytes each) send from the PCD to the PICC (Token AB) and a response from the PICC to the PCD (Token BA), if the reader's encryption was correct. After the first challenge (Token RB), **all** traffic is encrypted, even subsequent authentications, which leads to a weakness known as **nested authentication** [8].
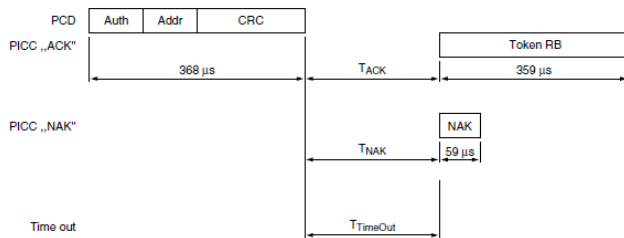

Figure 7. First Part of Authentication [20]

Though we discuss the encryption algorithm in greater detail in Appendix B, it is worth noting a few things based on the research in [18, 8]. The CRYPTO1 encryption scheme is a stream cipher which consists of a 48-bit (equal to the key length) Linear Feedback Shift Register (LFSR) and a non-linear **filter** function [18]. The encryption incorporates both the tag's Unique Identifier (UID) and the random nonce RB, which however is only generated using a 16-bit LFSR.
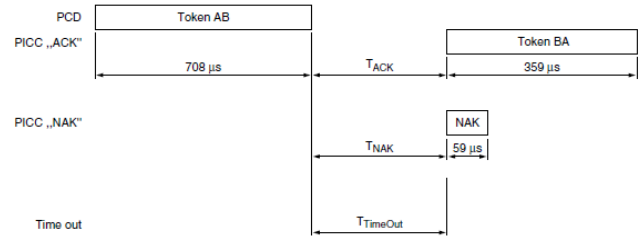
Nonetheless, both challenge responses only depend on the tag's nonce (and not the reader's nonce or the UID), and use the same LFSR as the Random Number Generator (RNG).

What is more, the parity bits are also encrypted (making the MIFARE Classic 1K *incompatible* with the ISO 14443 protocol), and "the bit of keystream used to encypt the parity bits is reused to encrypt the next bit of plaintext" [8]. This vulnerability, in combination with the nested authentication mentioned above (which causes the token RB to also be encrypted) leaks data which can be used to guess the nonce or to reveal the secret key.

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Appendices

A MIFARE Cards

In this section, we focus on the MIFARE Ultralight and Classic 1K cards, with more general ISO details in [14].

A.1 MIFARE Ultralight [21]

The memory layout for a MIFARE Ultralight card can be found in Figure 10. The card has a 7-byte UID SN[0-6], including 2 check bytes BCC[0-1]. SN0 is the manufacturer ID (0x04 for NXP Semiconductors), and the check bytes are defined as follows: $BCC0 = 0x88 \oplus SN0 \oplus SN1 \oplus SN2$ and $BCC1 = SN3 \oplus SN4 \oplus SN5 \oplus SN6$. Lock bytes can be used to turn pages into read-only mode, while One-Time Pad (OTP) bytes can be set to 1, but never set back to 0 again. As can be seen in Figure 9, Ultralight cards go through 2 rounds of ANTICOLLISION and SELECT commands.
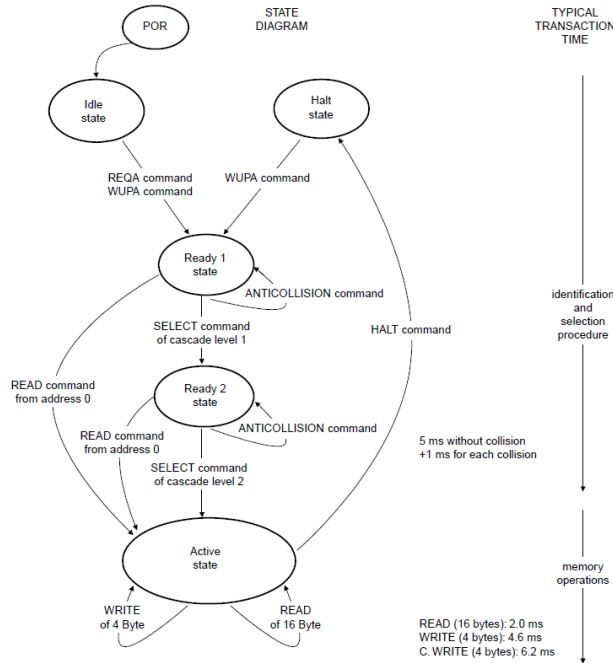

Figure 9. MIFARE Ultralight FSM

Page address		Byte number			
Decimal	Hex	0	1	2	3
0	00h	serial number			
1	01h	serial number			
2	02h	serial number	internal	lock bytes	lock bytes
3	03h	OTP	OTP	OTP	OTP
4 to 15	04h to 0Fh	user memory			

Figure 10. MIFARE Ultralight Memory Layout

Table 1 shows the possible commands when communicating with a MIFARE Ultralight card. The address for the READ and WRITE commands are between 0x00 and 0x0F and include roll-over C[0-1] is the CRC, and D[0-15] refers to data bytes.

Table 1. MIFARE Ultralight Commands

Command	Code	Response
REQA	0x26	0x44 0x00 (ATQA)
WUPA	0x52	0x44 0x00 (ATQA)
ANTICOLLISION (1)	0x93 0x[20-67]	0x88 SN0 SN1 SN2 BCC0
SELECT (1)	0x93 0x70 0x88 SN0 SN1 SN2 BCC0 C0 C1	0x04 C0 C1
ANTICOLLISION (2)	0x95 0x[20-67]	SN3 SN4 SN5 SN6 BCC1
SELECT (2)	0x95 0x70 SN3 SN4 SN5 SN6 BCC1 C0 C1	0x00 C0 C1
READ	0x30 [Addr] C0 C1	D0 D1 ⋯ D15 C0 C1
WRITE	0xA2 [Addr] D0 D1 D2 D3 C0 C1	[ACK/NAK]
COMPATIBILITY WRITE (1)	0xA0 [Addr] C0 C1	[ACK/NAK]
COMPATIBILITY WRITE (2)	D0 D1 ⋯ D15 C0 C1	[ACK/NAK]
HALT	0x50 0x00 C0 C1	[passive ACK/NAK]

A.2 MIFARE Classic 1K [20]

The memory layout for Classic 1K cards can be seen in Figure 11. The card does not have a globally-unique identifier, but instead uses a 4-byte Non-Unique Identifier (NUID) in block 0. Each sector has a block called the "trailer", which contains the two keys and the access bits. The layout for these access bits is shown in Figure 12, where CX_y is the X'th access bit for block y. These access bits are interpreted differently based on whether the block is a trailer block (Figure 13) or a data block (Figure 14).
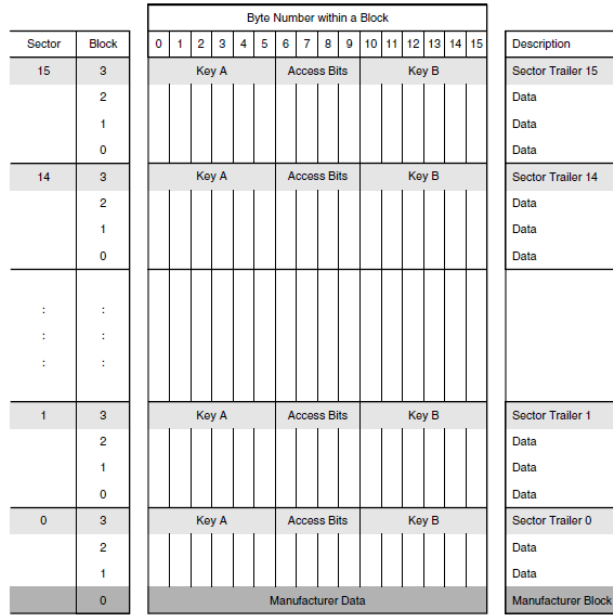

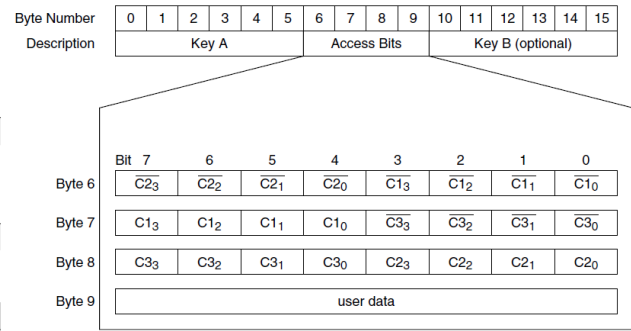**Figure 11.** MIFARE Classic 1K Memory Layout

Figure 12. MIFARE Classic 1K Access Bits

Figure 13. Trailer Block Access Conditions

Figure 14. Data Block Access Conditions

It is worth noting that the data blocks can be used for simple read/write operations, or they can be used as "value blocks" for applications which need more robustness and backups and could benefit from operations like INCREMENT and DECREMENT (see below). The layout for such blocks is shown in Figure 15.
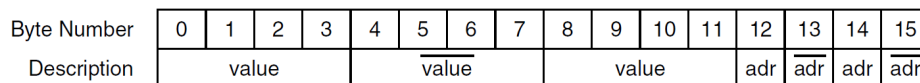
Figure 15. Value Block Layout

As indicated in Figure 16, the Classic 1K only uses a single round of ANTICOLLISION and SELECT commands, but includes a much more complicated 3-pass authentication mechanism. We explain in detail the encryption scheme in Appendix B, but we include the un-encrypted commands in Table 2, where NID[0-3] represents the NUID and $BCC = NID0 \oplus NID1 \oplus NID2 \oplus NID3$. Addresses range from 0x00 to 0x3F, while C[0-1] refers to the Checksum and D[0-15] to data bytes.
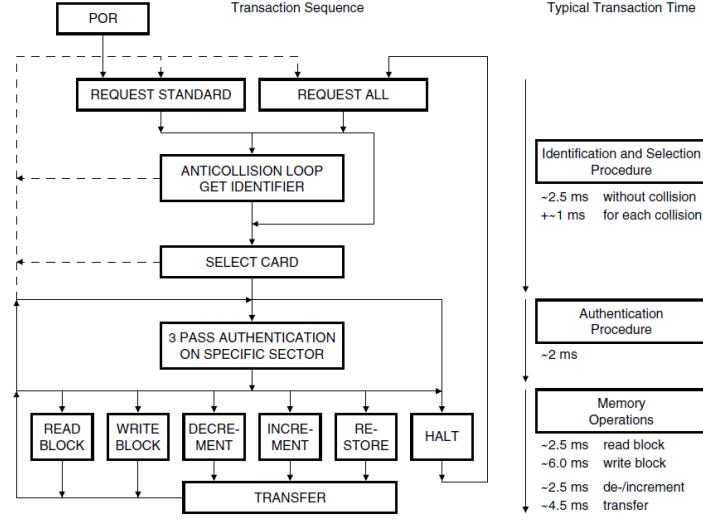
Figure 16. Classic 1K FSM

Table 2. MIFARE CLASSIC 1K Plaintext Commands

Command	Code	Response
REQA	0x26	0x04 0x00 (ATQA)
WUPA	0x52	0x04 0x00 (ATQA)
ANTICOLLISION	0x93 0x20	NID0 NID1 NID2 NID3 BCC
SELECT	0x93 0x70 NID0 NID1 NID2 NID3 BCC C0 C1	0x08 C0 C1
AUTHA	0x60 [Addr] C0 C1	D0 D1 D2 D3 [TOKEN RB]
AUTHB	0x61 [Addr] C0 C1	D0 D1 D2 D3 [TOKEN RB]
AUTH3 [TOKEN AB]	D0 D1 $\cdots$ D7	D0 D1 D2 D3 [TOKEN BA]
READ	0x30 [Addr] C0 C1	D0 D1 $\cdots$ D15 C0 C1
WRITE (1)	0xA0 [Addr] C0 C1	[ACK/NAK]
WRITE (2)	D0 D1 $\cdots$ D15 C0 C1	[ACK/NAK]
INCREMENT (1)	0xC1 [Addr] C0 C1	[ACK/NAK]
DECREMENT (1)	0xC0 [Addr] C0 C1	[ACK/NAK]
RESTORE (1)	0xC2 [Addr] C0 C1	[ACK/NAK]
INC/DEC/RES (2)	D0 D1 $\cdots$ D15 C0 C1	[passive ACK/NAK]
TRANSFER	0xB0 [Addr] C0 C1	[ACK/NAK]
HALT	0x50 0x00 C0 C1	[passive ACK/NAK]

B CRYPTO1

In this section, we summarize the CRYPTO1 algorithm as reverse-engineered in [18, 8], but do not discuss the numerous vulnerabilities with the cipher which are addressed in the original papers. In the notation of [8], let the (unencrypted) nonce RB be denoted by n_T, the token AB be denoted as $\{n_R\}, \{a_R\}$ and the token BA be denoted as $\{a_T\}$. Also denote by k the key, u the tag's unique identifier (UID), and for any x, let x_i be its i-th bit (for i for which this is well-defined). The CRYPTO1 algorithm uses a Linear Feedback Shift Register (LFSR) of size equal to 48 bits which is initialized by the key (also of length 48). Thus, as $\alpha_i = a_i a_{i+1} \ldots a_{i+47}$ the internal state of the LFSR at time i, we get that:

- $a_i := k_i$, for $0 \le i \le 47$
- $a_{48+i} := L(a_i, \ldots, a_{47+i}) \oplus n_{T,i} \oplus u_i$, for $0 \le i \le 31$
- $a_{80+i} := L(a_{32+i}, \ldots, a_{79+i}) \oplus n_{R,i}$, for $0 \le i \le 31$
- $a_{112+i} := L(a_{64+i}, \ldots, a_{111+i}), \forall i \in \mathbb{N}$

where L is the LFSR "**feedback function**" defined by:

$$L(x_0 x_1 \ldots x_{47}) := x_0 \oplus x_5 \oplus x_9 \oplus x_{10} \oplus x_{12} \oplus x_{14} \oplus x_{15} \oplus x_{17} \oplus x_{19} \oplus x_{24} \oplus x_{25} \oplus x_{27} \oplus x_{29} \oplus x_{35} \oplus x_{39} \oplus x_{41} \oplus x_{42} \oplus x_{43}$$

The outputs are encrypted using a "**filter function**":

$$f(x_0x_1\ldots x_{47}) := f_c(f_a(x_9,x_{11},x_{13},x_{15}), f_b(x_{17},x_{19},x_{21},x_{23}), f_b(x_{25},x_{27},x_{29},x_{31}), f_a(x_{33},x_{35},x_{37},x_{39}), f_b(x_{41},x_{43},x_{45},x_{47})), \text{ where}$$

$$f_a(y_0,y_1,y_2,y_3) := ((y_0 \vee y_1) \oplus (y_0 \wedge y_3)) \oplus (y_2 \wedge ((y_0 \oplus y_1) \vee y_3))$$
$$f_b(y_0,y_1,y_2,y_3) := ((y_0 \wedge y_1) \vee y_2) \oplus ((y_o \oplus y_1) \wedge (y_2 \vee y_3))$$
$$f_c(y_0,y_1,y_2,y_3,y_4) := (y_0 \vee ((y_1 \vee y_4) \wedge (y_3 \oplus y_4))) \oplus ((y_0 \oplus (y_1 \wedge y_3)) \wedge ((y_2 \oplus y_3) \vee (y_1 \wedge y_4)))$$

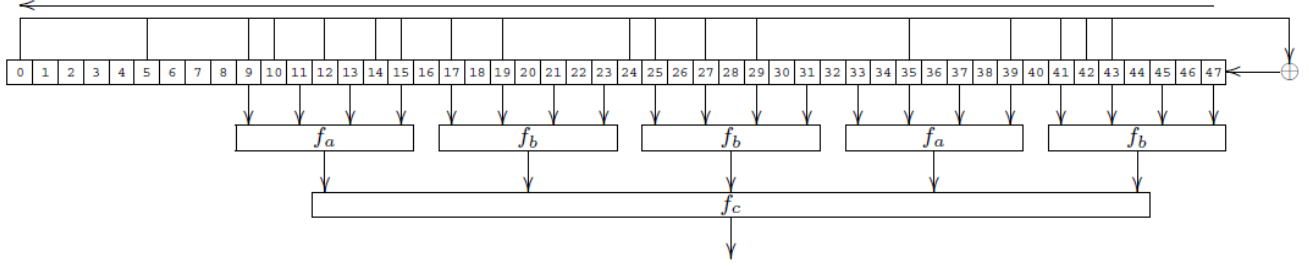These two main functions are summarized in Figure 17.

Figure 17. Crypto1 LFSR [8]

The keystream bit b_i is then defined by $b_i := f(a_i\ldots a_{47+i})$, and the encryptions of the i-th regular bit (i.e. excluding start/end and parity bits) is defined by XORing with b_i. Specifically, for $0 \le i \le 31$, $\{n_{R,i}\} = n_{R,i} \oplus b_{32+i}$, $\{a_{R,i}\} = a_{R,i} \oplus b_{64+i}$, $\{a_{T,i}\} = a_{T,i} \oplus b_{96+i}$. Note that the first 32 bits are not used in the first authentication, but they are used in all subsequent authentications, as the tag nonce is encrypted (and the cipher is re-initialized), so that $\{n_{T,i}\} = n_{T,i} \oplus b_i$.

The challenges only depend on the random nonce n_T, with $a_R = suc^{64}(n_T)$ and $a_T = suc^{96}(n_T)$, where the "**successor function**" (used for the Pseudo Random Number Generation (PRNG)) is iteratively applied 64 and 96 times respectively. It is defined by $suc(x_0x_1\ldots x_{31}) := x_1x_2\ldots x_{31}(x_{16} \oplus x_{18} \oplus x_{19} \oplus x_{21}))$ which only depends on the last 16 bits of the input.

It is worth noting that the start and ending transmission bits are not encrypted, but the parity bits are — by reusing the encryption bit for the next bit to be encrypted: $\{p_j\} := p_j \oplus b_{8j+8}$. This leaks information, and makes the protocol incompatible with the ISO standard, since the parity bits can be inverted. See Appendix C for an example.

C Example Traces

In this section we show two example traces, one for the MIFARE Ultralight (Table 3) and one for the Classic 1K (Table 4). For the latter, only part of the trace is shown. The key used is 0xFF 0xFF 0xFF 0xFF 0xFF 0xFF, and the exclamation points indicate inverted parity bits.

Table 3. MIFARE Ultralight Trace

Direction	Bytes	Explanation
PCD→PICC	0x26	REQA
PICC→PCD	0x44 0x00	ATQA
PCD→PICC	0x93 0x20	ANTICOLLISION (1)
PICC→PCD	0x88 0x04 0xBE 0x6F 0x5D	ANTICOLLISION (1) RESPONSE 0x88 UID0 UID1 UID2 BCC0 $UID0 \oplus UID1 \oplus UID2 \oplus BCC0 = 0x88$
PCD→PICC	0x93 0x70 0x88 0x04 0xBE 0x6F 0x5D 0xA1 0x8E	SELECT (1) 0x88 + UID[0-2] + BCC0 CRC
PICC→PCD	0x04 0xDA 0x17	SELECT (1) RESPONSE CRC
PCD→PICC	0x95 0x20	ANTICOLLISION (2)
PICC→PCD	0x22 0x09 0x29 0x80 0x82	ANTICOLLISION (2) RESPONSE UID[3-6] + BCC1 $UID3 \oplus UID4 \oplus UID5 \oplus UID6 = BCC1$

Direction		Explanation
PCD→PICC	0x95 0x70 0x22 0x09 0x29 0x80 0x82 0xD8 0xBA	SELECT(2) UID[3-6] + BCC1 CRC
PICC→PCD	0x00 0xFE 0x51	SELECT (2) RESPONSE CRC
PCD→PICC	0x30 0x00 0x02 0xA8	READ ADDR CRC
PICC→PCD	0x04 0xBE 0x6F 0x5D 0x22 0x09 0x29 0x80 0x82 0x48 0x00 0x00 0xE1 0x10 0x12 0x00 0xF8 0x99	UID UID UID + INTERNAL + LOCK BYTES OTP CRC
PCD→PICC	0x30 0x04 0x26 0xEE	READ ADDR CRC
PICC→PCD	0x01 0x03 0xA0 0x10 0x44 0x03 0x00 0xFE 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x81 0x3B	USER DATA (1) USER DATA (2) USER DATA (3) USER DATA (4) CRC
PCD→PICC	0x30 0x08 0x4A 0x24	READ ADDR CRC
PICC→PCD	0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x37 0x49	USER DATA (1) USER DATA (2) USER DATA (3) USER DATA (4) CRC
PCD→PICC	0x30 0x0C 0x6E 0x62	READ ADDR CRC
PICC→PCD	0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x37 0x49	USER DATA (1) USER DATA (2) USER DATA (3) USER DATA (4) CRC
PCD→PICC	0x50 0x00 0x57 0xCD	HALT CRC

Table 4. MIFARE Classic 1K Trace

Direction	Plaintext Bytes	Encrypted Bytes	Explanation
PCD→PICC	0x26	-	REQA
PICC→PCD	0x04 0x00	-	ATQA
PCD→PICC	0x93 0x20	-	ANTICOLLISION
PICC→PCD	0xCD 0x76 0x92 0x74 0x5D	-	ANTI RESP UID[0-3] BCC $\oplus UID = BCC$
PCD→PICC	0x93 0x70 0xCD 0x76 0x92 0x74 0x5D 0x45 0xDD	-	SELECT UID[0-3] + BCC CRC

Direction			
PICC→PCD	0x08 0xB6 0xDD	-	SELECT RESPONSE CRC
PCD→PICC	0x60 0x3C 0x1A 0x80	-	AUTH (KEY A) ADDR CRC
PICC→PCD	0x0E 0x61 0x64 0xD6	-	n_T
PCD→PICC	0x15 0x45 0x90 0xA8 0x4F 0x4E 0x67 0x4E	0x78 0x5A 0x41 0x80! 0x50! 0x04! 0x8F 0x22!	n_R a_R
PICC→PCD	0x41 0x3E 0xEB 0xCF	0xCE! 0xCA! 0x0D! 0x83	a_T
PCD→PICC	0x30 0x3F 0x76 0x61	0x69! 0xAC! 0x4F! 0x02	READ ADDR CRC
PICC→PCD	0x00 0x00 0x00 0x00 0x00 0x00 0xFF 0x07 0x80 0x69 0xFF 0xFF 0xFF 0xFF 0xFF 0xFF 0xD4 0x55	0xBC 0x2F 0xBD! 0xB1! 0x75! 0x44! 0x3C 0xD7! 0xD2 0x28 0x3B! 0xA5! 0x08 0x04 0x88! 0x18! 0x89 0x42!	KEY A (INACCESSIBLE) ACCESS BITS KEY B CRC
PCD→PICC	0x30 0x3E 0xFF 0x70	0x71! 0xF7 0x9F! 0x31	READ ADDR CRC
PICC→PCD	0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x37 0x49	0xE2! 0x99! 0x8D 0xE0 0x3F 0x96! 0xEF 0xC5 0xD0 0xD3! 0x24! 0x87! 0xF7 0x15! 0x06! 0x55! 0xA0! 0x97!	USER DATA (1) USER DATA (2) USER DATA (3) USER DATA (4) CRC
PCD→PICC	0x30 0x3D 0x64 0x42	0xC1! 0x43 0x22!0x92!	READ ADDR CRC
PICC→PCD	0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x37 0x49	0xD2 0x00! 0x9D 0x87! 0xD9 0x0D 0x25 0x73 0x51 0x27 0x44 0xCC! 0x55 0x44! 0x85 0x9D 0x44 0xF6	USER DATA (1) USER DATA (2) USER DATA (3) USER DATA (4) CRC
PCD→PICC	0x30 0x3C 0xED 0x53	0x27 0x02 0x5C 0x41!	READ ADDR CRC
PICC→PCD	0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x37 0x49	0x8B! 0xD1! 0xE3 0x87! 0x63! 0x75! 0x44 0x34 0x3B 0xAF! 0x27 0x0A! 0xAD! 0x84 0x1C 0xDB! 0xD8 0x4A	USER DATA (1) USER DATA (2) USER DATA (3) USER DATA (4) CRC
PCD→PICC	0x60 0x38 0x3E 0xC6	0xC6 0xDC 0xBA! 0x11!	(NESTED) AUTH (KEY A) ADDR CRC
PICC→PCD	0x8F 0x82 0x69 0x9E	0x70! 0xBD 0xED! 0x81	(ENCRYPTED) n_T
PCD→PICC	0x01 0x3A 0x6B 0xBA 0x73 0xD4 0x42 0x2D	0xFC! 0x1A 0x1A! 0x1D! 0x7D! 0x90 0x7E! 0x24!	n_R a_R
PICC→PCD	0xD0 0xA2 0x28 0xDB	0x87 0x4D 0xFF! 0x8A	a_T
PCD→PICC	0x30 0x3B 0x52 0x27	0x31 0x56 0xA1! 0x84	READ ADDR CRC
PICC→PCD	0x00 0x00 0x00 0x00 0x00 0x00 0xFF 0x07 0x80 0x69 0xFF 0xFF 0xFF 0xFF 0xFF 0xFF 0xD4 0x55	0x64 0x85! 0x16 0x6D 0xCF! 0xF7 0x3C! 0x62 0xD2 0xB4 0x3B! 0x5F! 0xA8! 0x71 0xD1 0x6B! 0x6C! 0x42	KEY A (INACCESSIBLE) ACCESS BITS KEY B CRC

PCD→PICC	0x30 0x3A 0xDB 0x36	0x02! 0x44! 0xD4! 0x47!	READ ADDR CRC
PICC→PCD	0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x37 0x49	0x41 0xBC! 0x42! 0xD9 0x39 0x4C! 0x9A 0x80! 0x4E 0x76 0xB1! 0xA1! 0xA4 0xD1 0x82! 0x61 0x28 0xBC!	USER DATA (1) USER DATA (2) USER DATA (3) USER DATA (4) CRC
PCD→PICC	0x30 0x9 0x40 0x04	0xA5 0x63 0x90! 0x32!	READ ADDR CRC
PICC→PCD	0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x37 0x49	0xBD! 0xC3 0xA6! 0x15 0x8B 0x2A! 0x6A! 0x03 0x72! 0xEF! 0x02! 0x38 0x05! 0xC5! 0x3F 0x4E! 0x94! 0x08	USER DATA (1) USER DATA (2) USER DATA (3) USER DATA (4) CRC
PCD→PICC	0x30 0x38 0xC9 0x15	0xE2 0x1C! 0x8A 0x16!	READ ADDR CRC
PICC→PCD	0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x37 0x49	0x51 0x1B 0xA6! 0x49 0x29! 0xF2 0x75 0x35! 0x1B! 0xE1 0x72 0x68 0x7F 0x3F 0x2A 0xE9! 0x73 0x0F	USER DATA (1) USER DATA (2) USER DATA (3) USER DATA (4) CRC
PCD→PICC	0x60 0x34 0x52 0x0C	0x7F! 0xB8! 0x88 0x7B!	(NESTED) AUTH (KEY A) ADDR CRC
PICC→PCD	0xDC 0xFC 0x96 0x2B	0x23! 0x23! 0x6E 0xF4!	(ENCRYPTED) n_T
PCD→PICC	0xEE 0x08 0xB0 0x0A 0xF6 0x01 0xBA 0x11	0x1A 0xB9! 0xEF! 0x7B! 0xC5 0xC3 0x51 0x57!	n_R a_R
PICC→PCD	0x6E 0x27 0x63 0x93	0x3E 0x19 0x48! 0xF4!	a_T
PCD→PICC	0x30 0x37 0x3E 0xED	0xD6! 0x59! 0xB4! 0x73!	READ ADDR CRC
PICC→PCD	0x00 0x00 0x00 0x00 0x00 0x00 0xFF 0x07 0x80 0x69 0xFF 0xFF 0xFF 0xFF 0xFF 0xFF 0xD4 0x55	0x32! 0x84 0xE6 0xB1! 0x45! 0x56! 0x5C! 0x1A! 0xED! 0xD3! 0xED! 0x76 0x32! 0x5F 0x5D! 0x4D 0x96! 0xFC!	KEY A (INACCESSIBLE) ACCESS BITS KEY B CRC
PCD→PICC	0x30 0x36 0xB7 0xFC	0xBB! 0x4D! 0xF8 0x55	READ ADDR CRC
PICC→PCD	0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x37 0x49	0x7E 0x9E! 0x34! 0x38! 0xDC! 0xE2! 0xF9 0x98! 0xA0 0x88 0x78! 0xA9! 0xCD! 0xEE! 0x17 0xD8 0xFF! 0xFD!	USER DATA (1) USER DATA (2) USER DATA (3) USER DATA (4) CRC