Algebraic Attacks on the Crypto-1 Stream Cipher in MiFare Classic and Oyster Cards

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Disclaimer: this paper is an early announcement of a research in progress.

Abstract. MiFare Crypto 1 is a lightweight stream cipher used in London's Oyster card, Netherland's OV-Chipcard, US Boston's CharlieCard, and in numerous wireless access control and ticketing systems worldwide. Recently, researchers have been able to recover this algorithm by reverse engineering [11, 13].

We have examined MiFare from the point of view of the so called *algebraic attacks*. We can recover the full 48-bit key of MiFare algorithm in 200 seconds on a PC, given 1 known IV (from one single encryption).

The security of this cipher is therefore close to zero. This is particularly shocking, given the fact that, according to the Dutch press, 1 billion of MiFare Classic chips are used worldwide, including in many governmental security systems.

Keywords: London Oyster card, Dutch public transit OV-Chipcard, Boston's CharlieCard RFID tags, Mifare Crypto 1 algorithm, stream ciphers, algebraic cryptanalysis, Boolean functions, Gröbner bases, SAT solvers.

1 Background

Recently, several researchers have been able to reverse-engineer the MiFare Classic cryptographic algorithm Crypto-1 that is used (among others) in London's Oyster card, Netherland's OV-Chipcard, US Boston's CharlieCard, and in numerous wireless access control and ticketing systems worldwide [11, 13].

The MiFare cipher is a proprietary algorithm and its specification was not published so far. The researchers have been fair play: they informed the authorities and announced that the industry should have some time to upgrade their systems. However this does not make the system very secure: if we don't publish Crypto 1 for the time being, hackers will without doubt recover it very soon.

How secure are these algorithms? Dutch researchers exploited mostly the protocol vulnerabilities of MiFare [13]. After a report by the Dutch security agency TNO that found the MiFare Classic tags to be secure enough for some applications [17], Karsten Nohl announced the first cryptographic attack on the system [12]. This attack exploits statistical weaknesses of the cipher, in combination with a weakness in the random number generator in the tag reader. By combining these two vulnerabilities, cards can be cloned within minutes on a PC [12].

We have examined MiFare from the point of view of *algebraic attacks.* These are general-purpose attack techniques developed in the last years by Courtois, Meier, Faugère *et al.* Our attacks are purely cryptographic attacks and work independently of the quality of the random numbers. Furthermore, our new attacks are an order of magnitude faster and do not require any active interaction with reader or card to find the secret key.

2 How to Solve It - Algebraic Attacks on MiFare

Our attack is an *algebraic attack* in the sense that it recovers the secret key by solving a large system of polynomial equations [1, 2]. Equations are written using a method that is identical to one of the algebraic attacks on DES described in [4]. We write a system of symbolic Boolean equations that involves the output bits, the key bits, the IV bits, and a large number of intermediate variables. The encryption process is decomposed into a large number of very simple elementary steps. Each of these simple steps is described algebraically as a small set of simple algebraic equations of low degree, with variables over $GF(2)$.

One of the method for solving such equations is to use so called Gröbner bases, which in the past allowed to break several stream ciphers [2, 6]. However, new particularly efficient techniques of algebraic cryptanalysis with SAT solvers were discovered recently [4, 5]. Accordingly, resulting system of equations is converted to a SAT problem by the exact method described in [5]. Then a well-known open-source SAT solver program is executed, [10] that finds a solution to the system of equations.

In our attacks we require about 50 bits of the keystream output by the stream cipher to recover the secret key (or the initial state). This is the minimum required to uniquely determine the key, and we do not need much more. These 50 bits may come from one single or several encryptions with different IVs. An elegant way of recovering the keystream from MiFare Classic cards has recently been presented by de Koning Gans et al. [7].

3 Summary of Claims

We can recover the full 48-bit key of MiFare Crypto-1 algorithm in 200 seconds on a PC, given 1 known IV and 50 output bits (from one single encryption).

With 4 chosen IVs we can recover the key in 12 seconds.

In addition we expect to be able to crack the MiFare cipher as it is used in products (e.g London Oyster cards) in the weakest possible scenario – passive eavesdropping of one single transaction. This has to be confirmed and implemented in full detail. Preliminary results indicate that the whole attack (collecting data, finding the secret key, and creating a clone card) should not take more than a few minutes. More details will be published soon.

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