UNCONDITIONALLY SECURE CREDIT/DEBIT CARD CHIP SCHEME AND PHYSICAL UNCLONABLE FUNCTION

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Abstract. The statistical-physics-based Kirchhoff-law–Johnson-noise (KLJN) key exchange offers a new and simple unclonable system for credit/debit card chip authentication and payment. The key exchange, the authentication and the communication are unconditionally secure so that neither mathematics- nor statistics-based attacks are able to crack the scheme. The ohmic connection and the short wiring lengths between the chips in the card and the terminal constitute an ideal setting for the KLJN protocol, and even its simplest versions offer unprecedented security and privacy for credit/debit card chips and applications of physical unclonable functions.

1. Introduction

Modern chip-based credit, debit and bank cards utilize physical unclonable function (PUF) hardware keys for payment, and their protocol and cryptography utilize the Europay, MasterCard and Visa EMV scheme [1]. The PUF in these cards relies on conditionally secure communication, data authentication and a private key stored in a secure memory that must be able to self-destruct when tampered with. However, the cards’ software-based secure communication protocols (such as RSA [1]) offer only conditional security, and it is not surprising that criminals have been able to crack the EMV system and steal large amounts of money [2]. Even though it appears unlikely that a hacker has sufficient computational power or is able to invent a sufficiently efficient factoring algorithm to crack the key, a skilled hacker can efficiently utilize a known-plaintext attack, which constitutes the major vulnerability of all conventional mathematics-based secure key exchange protocols [3].

For high-security credit cards and PUF applications it is essential to utilize unconditionally secure communication [3] which is immune also against known-plaintext attacks; otherwise the cards’ entire PUF protocol is highly vulnerable and hackers will no doubt in the foreseeable future develop devices to copy them. Unconditionally secure key exchange with one-time-pad encryption makes the communication unconditionally secure and immune against any types of attacks, including mathematics-based and statistics-based alternatives.

Up till now, only two schemes offer unconditional security: (i) quantum encryption including its enhanced versions [3] and (ii) the electronic-noise-based Kirchhoff-law–Johnson-noise (KJLN) scheme [4] which is the main topic of the present article and is elaborated below. A disadvantage of quantum encryption is that it is bulky and hence it cannot be integrated on a chip. KJLN, on the other hand, offers the possibility of chip integration. The latter scheme requires electrical wire connection between the communicating parties, which makes it well suited for chip-based credit and debit cards which employ wire connection to communicate with the terminal during payment, and consequently a KJLN chip is feasible for applications.
In Section 2, we briefly describe the KLJN scheme, which is the core of the unconditionally secure credit card protocol of unclonable credit/debit cards and PUF applications discussed in Section 3.

2. The KLJN key exchange scheme

The KLJN secure key exchange scheme [4–13] was proposed in 2005 [5,6] and, including its advanced versions [8–10], there are currently about ten different protocols. It is a statistical/physical competitor to quantum key exchange, and the security is based on Kirchhoff’s Loop Law and the Fluctuation–Dissipation Theorem. The security of the ideal KLJN scheme is as strong as the impossibility to build a perpetual motion machine of the second kind.

Figure 1 depicts a binary version of the KLJN scheme and shows that, during a single-bit exchange, the communicating parties (Alice and Bob) connect their randomly chosen resistor (including its Johnson noise generator) to a wire channel. These resistors are randomly selected from the publicly known set \( \{ R_L, R_H \} \), \( R_L \neq R_H \), representing the Low and High bit values. The Gaussian voltage noise generators—mimicking the Fluctuation–Dissipation Theorem and delivering band-limited white noise with publicly agreed bandwidth—produce enhanced thermal (Johnson) noise at a publicly agreed effective temperature \( T_{\text{eff}} \); typically \( T_{\text{eff}} \gg 10^{10} \text{K} \) so that the temperature of the wire can be neglected. The noises are statistically independent of each other and from the noise of the former bit period.

Fig. 1. Core of the KLJN scheme without defense circuitry [4,5] against active (invasive) attacks and attacks utilizing non-idealities. The \( R_L \) and \( R_H \) resistors, identical pairs at Alice and Bob, represent the Low (\( L \)) and High (\( H \)) bit values. The corresponding noise spectra \( S_L \) and \( S_H \) also form identical pairs at the two ends, but they belong to independent Gaussian stochastic processes. Both parties are at the same temperature, and thus the net power flow is zero. The \( LH \) and \( HL \) bit situations of Alice and Bob produce identical voltage and current noise spectra, \( S_L \) and \( S_H \) in the wire, implying that they represent a secure bit exchange. The \( LL \) and \( HH \) bit arrangements, which occur in 50% of the cases, have singular noise levels in the wire, and hence they do not offer security because Eve can distinguish them. Consequently 50% of the bits must be discarded. This system works also with arbitrary, non-binary resistor values as an analog circuitry to exchange continuum information about the distribution of random resistors.

In the case of secure bit exchange—i.e., the \( LH \) or \( HL \) bit situations for Alice and Bob—an eavesdropper (Eve) cannot distinguish between these two situations by measuring the noise spectra \( S_L(f) \) and \( S_H(f) \), of voltage and/or current in the cable, respectively, because the \( LH \) and \( HL \) noise levels are identical (degenerated). Thus when Alice and Bob detect the noise spectra (or noise levels) characteristic of the \( LH \) and \( HL \) situation, they know that the other party has the opposite bit and that this bit is secure. Then one of them will invert the bit (it is publicly pre-agreed who will do this) to get the same key bit.
as the other party. The KLJN scheme offers unconditional (information theoretic) security under both ideal and slightly non-ideal (i.e., practical) conditions [4].

The security against active (invasive) attacks is provided by the robustness of classical-physical quantities, which guarantees that they can be continuously monitored and exchanged between Alice and Bob via authenticated communication [11,12]. Therefore the system, and the consistency of the measured and exchanged voltage and current data with known cable parameters and model, can be checked continuously and deterministically without destroying these data, which is totally different from the case of a quantum key distribution.

One should keep in mind that the KLJN secure information exchanger is basically an analog circuit and can work with arbitrary resistances because, even if the resistance values are not pre-agreed, Alice can calculate Bob’s resistance from the measured data [5] by using Johnson’s formula, and vice versa. For example, by using the measured current spectrum in the wire one obtains

$$R_B = \frac{4kT_{\text{eff}}}{S_i} - R_A.$$  

(1)

It is important to note that Eve is also able to determine an arbitrary, non-pre-agreed (non-publicly known) resistor pair connected to the line by using measured voltage and current spectra [5]. The two solutions of the relevant second order equation provide two resistance values of the pair according to

$$R_{1,2} = \frac{4kTS_u \pm \sqrt{(4kTS_u)^2 - 4S_u^3S_i}}{2S_uS_i}.$$  

(2)

However, Eve cannot determine which resistor is with Alice and which is with Bob, and hence the information exchange about the distribution of arbitrary, non-binary resistor values is secure in the original KLJN system.

Under ideal conditions, the system delineated above offers unconditional (information theoretic) security against passive (listening) attacks only. To achieve unconditional security against active (invasive) attacks, and/or attacks that utilize non-ideal features of the building elements, the following extra elements are essential: (a) an external Gaussian noise generator to emulate thermal noise [5] and to have stable noise temperature with high accuracy, (b) filters for limiting the frequency range to the measurement bandwidth and to the no-wave limit [5], and (c) measurement of the instantaneous voltage and current values at the two ends (by Alice and Bob) and comparison of them via an authenticated public channel [11] or, in more advanced set-ups, with a cable simulation model fed by real-time data [12]. A difference between the two measurements in (c) serves as an indication of invasive eavesdropping, and the corresponding bits must be discarded. Section 3 below discusses the number of secure bits consumed by the authentication.

Several active attacks have been proposed against the KLJN system [5,11,12], but the defense method mentioned above is able to protect the system and maintain its unconditional security under general conditions [12]. Specifically, the KLJN system has been proposed to deliver unconditional security for hardware in computers, games and instruments [13] and to be used as a PUF device [14].
3. The new credit/debit/PUF card protocol

The credit/debit/PUF card (referred to as the “Card” below) is used by the consumer at the terminal where the Card is plugged in, and a wire correction is then built between the chip in the Card and the interface in the terminal as indicated in Figure 2. The terminal interface communicates with a Server (located at banks, etc.), which is not shown in this figure. We furthermore assume that the communication between the Terminal and the Server is secure and free from malevolent parties. The protocol has several phases as elaborated in detail below.

![Core hardware scheme of the terminal and the Card chip. Units regarding terminal–server communication, transaction input, etc., are not shown.](image)

3.1. Private key initialization during fabrication

During initialization, a private key—which is a binary bit string signified by $X = [A; B; C]$—is generated by a true random number generator. The string $X$ contains three independent, non-overlapping sections—denoted $A$, $B$ and $C$—which are themselves also used as independent private keys. Specifically, $A$ is used for the authentication of the Card, $B$ is for the encryption of the transaction data and $C$ is for the authentication of current and voltage data during the KLJN key exchange when using the Card. The private key $X$ is stored on the Server at a memory location that is associated with the publicly known card identification data (the public key), such as card number, cardholder’s name, expiration date, etc. The private key is also stored in the tamper-proof secure memory on the Card.

3.2. Authentication of the Card during use

During its use, when the Card is inserted into the Terminal, the authentication of the Card takes place according to eight steps as follows:

(i) the Card Processor sends its publicly known card identification data (the public key) to the Processor in the Terminal, which forwards these data to the Server;

(ii) the Server locates the corresponding private key in its memory and forwards that information to the Processor in the Terminal;

(iii) the Terminal Processor generates a random bit string $Y$, which is as long as $A$;

(iv) the Terminal’s cipher encrypts $Y$ by using a One-Time-Pad (OTP) with $A$, i.e., produces a string $Z$ with the XOR operation ($\oplus$) according to
\[ Z_i = A_i \oplus Y_i , \]  

where index \( i \) stands for the \( i \)-th bit in \( Z, A \) and \( Y \);

(v) the Terminal Processor sends \( Z \) to the Card Processor (in PUF applications, \( Z \) is called the “Challenge”);

(vi) the Card Cipher encrypts \( Z \) with \( A \) by using an OTP, \( i.e., \) it produces a string \( W \) by
\[ W_i = A_i \oplus Z_i ; \]  

(vii) the Card Processor sends \( W \) to the Terminal Processor (in PUF applications, \( W \) is called the “Response”); and

(viii) the Terminal Processor checks whether
\[ W_i = Y_i , \]  

for all \( i \).

Finally, if the answer is “yes” at step (viii), the Card is successfully authenticated because
\[ A_i \oplus (A_i \oplus Y_i) = Y_i \]  

and
\[ \overline{A_i} \oplus (A_i \oplus Y_i) = \overline{Y_i} . \]

3.3. Transaction

During the Transaction, the Card and the Terminal encrypt their communication by the private key \( B \). This communication includes also the identification of the user (via a PIN code), if needed. This step may also use OTP to provide unconditional security, particularly for the known-plain-text parts of the communication.

3.4. Generating and sharing the new and unconditionally secure private key

After each successful use of the Card, a new and independent unconditionally secure private key is generated. The Card and the Terminal execute a KLJN key exchange to generate the new private key \( X' \) that is independent from the former \( X \). As a consequence of the short distance (<0.1 meter) between the key chips in the Card and the Terminal, the conditions are practically ideal and the key exchange can take place at high speed and with minimal information leak towards passive (listening) attacks. Nevertheless, a simple three-stage XOR-based privacy amplification [15] (yielding an eightfold slowdown) may be applied to account for unforeseen situations.

The private key \( C \) is used for authentication of current and voltage data during the KLJN key exchange. Assuming a simple hashing-based [16] data authentication, the minimum length \( N_c \) of \( C \) is given as
\[ N_c = K \log_2 \left( N_d \right) , \]  

where \( N_d \) is the length of the string containing the current and voltage sampling data and
\( K \) is the number of allowed unsuccessful trials before the Card gets locked and its private key \( X \) becomes erased.

### 3.5 Speed of the protocol

Considering the very short wire separation between the Card chip and the chip in the Terminal, one can conclude that the practical KLJN key exchange speed is not limited by distance [5] but by the electronics. Inexpensive chip design allows 100-kHz bandwidth in an effortless way, which translates to about thousand bits/second KLJN key exchange speed. This rate guarantees that the generation/sharing of the new KLJN key (see Section 3.4), which is the most time consuming process of the protocol, takes only two to three seconds even if long private keys (such as 1024 bits) are used.

### 4. Conclusion

We demonstrated that the KLJN key exchange scheme offers a new, simple and unclonable system for credit/debit card chip authentication and payments. The key exchange, the authentication and the communication are unconditionally secure, and thus neither mathematics- nor statistics-based attacks are able to crack the scheme. The proposed simple protocol offers unprecedented security for credit/debit card chips and PUF applications by providing new, unconditional private keys after each transaction.

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