Light Blind: Why Encrypt If You Can Share?

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Abstract: The emergence of cloud computing makes the use of remote storage more and more common. Clouds provide cheap and virtually unlimited storage capacity. Moreover, thanks to replication, clouds offer high availability of stored data. The use of public clouds storage make data confidentiality more critical as the user has no control on the physical storage device nor on the communication channel. The common solution is to ensure data confidentiality by encryption. Encryption gives strong confidentiality guarantees but comes with a price. The time needed to encrypt and decrypt data increases with respect to the size of input data, making encryption expensive. Due to its overhead, encryption is not universally used and a non–negligible amount of data is insecurely stored in the cloud. In this paper, we propose a new mechanism, called Light Blind, that allows confidentiality of data stored in the cloud at a lower time overhead than classical cryptographic techniques. The key idea of our work is to partition unencrypted data across multiple clouds in such a way that none of them can reconstruct the original information. In this paper we describe this new approach and we propose a partition algorithm with constant time complexity tailored for modern multi/many-core architectures.

1 INTRODUCTION

Nowadays, it becomes more and more common for people and companies to store data outside their premises. The successful *pay as you go* economic model offered by public cloud providers is attracting more and more customers thanks to its elasticity in resource provision and to its availability guarantees. However, storing data in a public cloud rises serious security concerns. The loss of control of the physical storage and computational devices, and the connected nature of third-party hardware imply an expansion of the attack surface.

Mechanisms to protect data confidentiality and integrity exist (Kamara and Lauter, 2010; Wang et al., 2011) but nevertheless, the amount of *plaintext* data stored in public clouds is non-negligible. Currently, encryption is the main mechanism used to protect data confidentiality. It offers strong guarantees but its computational complexity prevents it from being systematically used by cloud storage consumers. It is time to provide to cloud consumers an alternative system able to guarantee an acceptable level of confidentiality at a much lower computational expense. Such a technique benefits to users and companies that actually do not secure their outsourced data.

In this paper, we propose an alternative to encryption called Light Blind. Our idea is based on the observation that splitting a file in chunks of non-contiguous bits is faster than encrypting. The emergence of multi-cloud systems (Bohli et al., 2013; Stefanov and Shi, 2013) makes it possible to achieve confidentiality by partitioning data chunks over multiple providers. As such, each cloud provider can not access the original data without colluding with all other providers.

The remainder of this paper is organized as follows. Related work on multi–cloud storage and data encryption is reported in Section 2. Section 3 describes the architecture, the partition algorithm and the pattern hiding system. We discuss Light Blind properties in Section 4. Conclusion and future work are depicted in Section 5.

2 Related Work

Srivastava et al. (Srivastava et al., 2012) proposed a simple algorithm to better protect data by splitting it into subfiles which are hosted in different virtual machines within different cloud providers. The paper dealt with operations to distribute and retrieve the required subfiles (data) without encrypting them. The proposed heuristic in (Srivastava et al., 2012) can host all of the data chunks within the same provider leading him to retrieve end-user's data.

In (di Vimercati et al., 2014b), the authors propose

a combination of data distribution and swapping techniques that protect both data and access confidentiality. In their solution data confidentiality is obtained by ciphering the data, while access confidentiality is obtained by changing the physical location of data at every access. They make use of three independent servers to further increase data access protection. In our work we focus on providing data confidentiality at a constant time complexity rather than providing access confidentiality.

In (di Vimercati et al., 2014a), authors consider the problem of protecting data confidentiality in the cloud and point out two main techniques: encryption and fragmentation. An example of fragmentation technique is given in (Aggarwal et al., 2005). They show how to provide confidentiality by partitioning a database over two servers. As in fragmentation techniques, we propose to partition data into chunks which are stored in separate servers. Contrarily to classical fragmentation, we make use of multiple servers to achieve confidentiality at constant time complexity without obfuscating data relations. We focus in an encryption-like mechanism at a lower computational cost than classic cryptography.

For high availability and failure concerns when storing data in the cloud, Qu and Xiong (Qu and Xiong, 2012) proposed a distributed algorithm to replicate data objects in different virtual nodes. According to the traffic load of all considered nodes, the authors defined different actions: *replicate*, *migrate*, or *suicide* to meet end-user requirements. The proposed approach consists in checking the feasibility of migrating a virtual node, performing suicide actions or replicating a copy of a virtual node. However, the stored data suffers from vendor lock-in as the totality of data is stored within one provider.

In (Mansouri et al., 2013), authors dealt with the problem of multi-cloud storage with a focus on availability and cost. The authors proposed a first algorithm to minimize replication cost and maximize expected availability of objects. The second algorithm has the same objective but is driven by budget constraints. However, the paper does not embed security aspects apart from dividing the data into chunks or objects. In (Sachdev and Bhansali, 2013), authors proposed encrypting data locally using the Advanced Encryption Standard (AES) algorithm before sending the data for storage in the cloud.

In (Hadji, 2015), Hadji addresses encrypted data storage in multi-cloud environments and proposes mathematical models and algorithms to place and replicate encrypted data chunks while ensuring high availability of the data. To enhance data availability, the author presents two cost-efficient algorithms based on a complete description of a linear programming approach of the multi-cloud storage problem and then shows the scalability and cost-efficiency of the proposed multi-cloud distributed storage solutions. To guarantee data confidentiality, the author uses data chunks encryption with AES, which imposes a potentially high overhead when uploading and downloading the data.

We notice that most of the aforementioned works refer to the use of symmetric cryptography and AES particularly when providing data confidentiality. AES is a special case of Rijndael algorithm (Daemen and Rijmen, 1998) when considering 128 bits long input blocks. AES supports the following key lengths 128, 192 and 256 bits, and consists of 10, 12 and 14 rounds, respectively. AES can be used in different block cipher modes. The most known modes are the following (Ferguson et al., 2011):

- *Electronic Code Book mode (ECB)*: in ECB mode, we encrypt each plaintext input block P_i separately such as: $C_i = AES\_Encrypt(K, P_i)$ where K is the encryption key and C_i is the corresponding ciphertext. Note that ECB suffers from a pattern recognition problem and its use in practice is deprecated.
- *Cipher Block Chaining mode (CBC)*: in CBC mode, we apply an exclusive OR (XOR) to every plaintext input block with the previous ciphertext block as following $C_i = AES\_Encrypt(K, P_i \oplus C_{i-1})$. Note that the first ciphertext block C_0 is computed from the encryption of the first plaintext block P_0 with the key K as $C_0 = AES\_Encrypt(K, P_0 \oplus IV)$ where IV is a random initialization vector.
- *Output Feedback mode (OFB)*: in OFB mode, $C_i = K_i \oplus P_i$ where $K_i = AES\_Encrypt(K, K_{i-1})$ and $K_0 = IV$. OFB and CBC modes are sequential in that each block can not be treated until getting some information from the previous block.
- *Counter mode (CTR)*: in CTR mode, $K_i = AES\_Encrypt(K, Nonce \parallel i)$ and $C_i = K_i \oplus P_i$.

In our work, we propose a new efficient and scalable solution capable of handling large data thanks to its constant time complexity. We first split the data into small chunks and then apply a new approach to better dispatch them across available data centers and providers. We propose a smart mechanism providing each cloud host with only a random subset of data chunks. Our algorithm provides patterns distribution, without data encryption. It has constant time execution and guarantees data confidentiality. It can be easily implemented over multi-cores architecture and profits from multi-threading. In the following sec-

tion, we discuss in details our proposed solution and how it can tackle secure data storage between different multi-cloud providers.

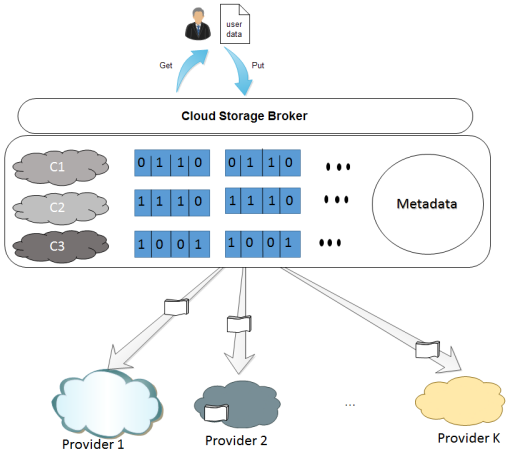


Figure 1: System overview.

3 Light Blind Architecture

We consider a system composed of a set of clients, a broker, and a set of cloud storage providers ($C = \{c_1, c_2, \ldots c_n\}$). The client uses the broker services to securely store its data in the set of clouds storage. The broker is in the client machine or in a cloud trusted by the client (see Figure 1).

3.1 Protocol Overview

The clients send to the broker requests to *store/retrieve* files in/from the cloud.

A *store* request contains a file and a set of constraints (e.g., the minimum/maximum number of providers, the number of replicas or their geographical location, etc.). The broker call a *Policy Service* that returns a set of *destination* clouds that respect, if possible, all the constraints. Then the broker calls a partition algorithm that splits the file into *shares*, one for each cloud identified by the Policy Service. We assume that the Policy Service returns at least two clouds. Finally, it sends each share to the appropriate cloud. The broker store locally all the information needed to retrieve and reconstruct the original file.

A *retrieve* request contains the file identifier. The broker fetch all the shares corresponding to that file and reconstruct the original file that is returned to the client.

The Policy Service mechanism is orthogonal to the obfuscation system described in this paper and

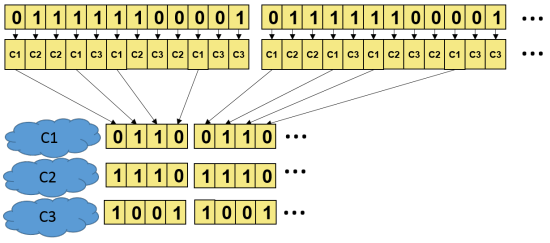


Figure 3: Pattern Example.

well known in the literature (Mansouri et al., 2013; Papaioannou et al., 2012). The details of such a mechanism are out of the scope of this work and not described here.

3.2 Light Blind Partition Algorithm

To partition the input plaintext over a set of cloud providers $C = \{c_1, c_2, \ldots c_n\}$ we proceed as follows: i) we divide the input in blocks of k bits each (except the last block that can be smaller), ii) we generate a key that map each bit of the block to a cloud provider $c_i \in C$, iii) we generate for each cloud a share containing the bits that belong to it according to the key, and iv) we assign each share to its cloud.

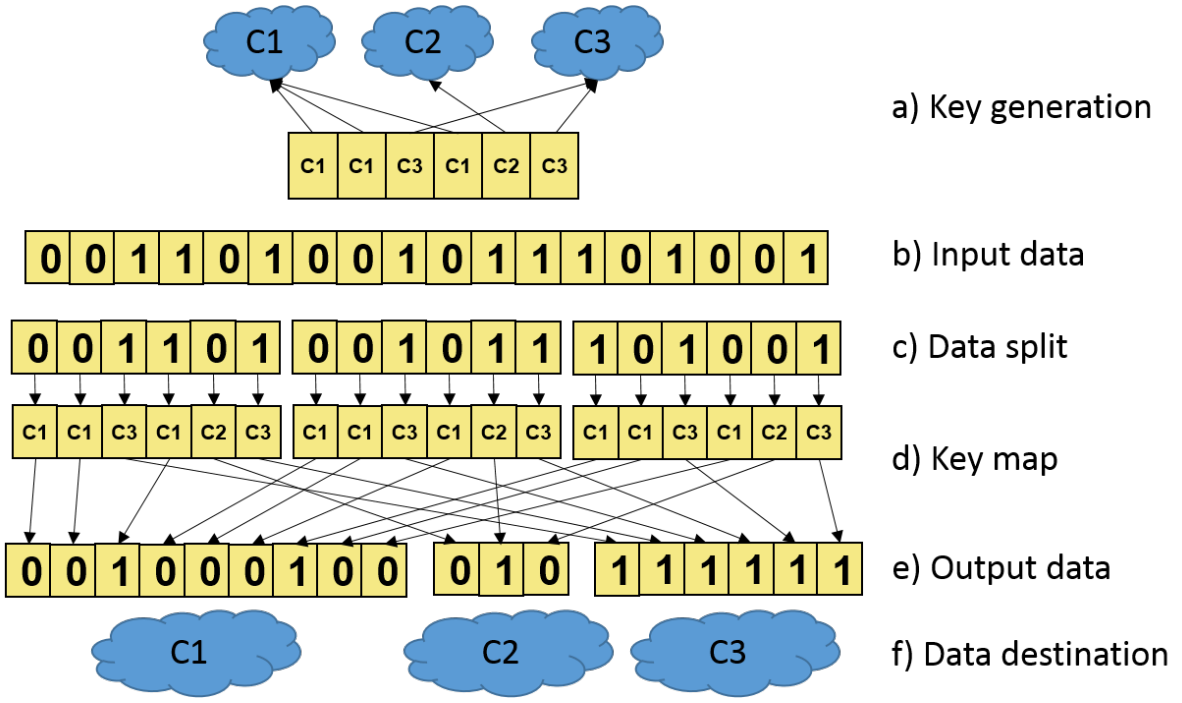
The key is generated by randomly taking for each bit of the block a cloud provider $c_i \in C$. The dimension of the key is proportional to the dimension of the block [1]. Figure 2 shows an example of Light Blind partition algorithm.

The key property of this algorithm is that each step is fully parallelizable and its execution time is constant: does not depend on the plaintext size. That is, each block can be treated in parallel by a different thread with no need of synchronization.

3.3 The Patterns Problem

The partition algorithm does not hide well patterns of the plaintext. Similarly to AES Electronic Code Book (ECB) encryption mode, if the plaintext has a pattern, the pattern will be reflected in the ciphertext. Each block is encrypted using the same key, so for the same blocks corresponds the same ciphertext. In order to solve this problem, other block cipher modes (Section 2) use a different encryption key for each block. As such, patterns of the plaintext are not reflected in the ciphertext .

[1] There is a trade off to consider: in one hand to optimize the amount of data stored in the broker we want to minimize the size of the key (i.e., the smaller, the better), in the other hand for the robustness of the encryption hold the rule "the bigger the better" (see Section 3.7).



An input data of 18 bits is partitioned in three clouds $C1, C2$ and $C3$ using blocks of 6 bits. *(a)* An array of the size of a block (6 in this example) is generated. The array contains in each cell the identifier of one of the target clouds ($C1, C2, C3$) selected randomly. *(b)* - *(c)* The input data is split in blocks of size 6. *(d)* Each block is paired with the key generated in step a. Each bit is moved in a share corresponding to the cloud indicated by its pair in the key. *(e)* - *(f)* Each share generated in step d is moved to its associated cloud.

Figure 2: Light Blind Partition Algorithm Example.

Light Blind faces the patterns problem in an innovative way by hiding patterns without trade on scalability. We modify the algorithm described in Section 3.2 as follow: after having generated the shares (step iii) and before sending them to the clouds (step iv), we perform a series of data transformations that *shuffle* the block content and that cannot be undone unless all the shares are available. That is, clouds collaborate between them to retrieve all the shares or the attacker eavesdrop on the network. This extra step is still fully parallelizable and its execution time is constant.

3.4 The Cut-and-Shuffle Algorithm Overview

As introduced in Section 3.4 the Light Blind partition algorithm does not hide patterns. Figure 3 shows an example of pattern in the input blocks which is reflected in the produced shares for a given key. In the example the three shares show a different pattern that repeats each 4 bits. To solve this problem we do not send shares to clouds right after their generation (step iii in Section 3.2) but we add an extra step that *cut* data contained in the shares and then *shuffle* it. We first cut rows of shares to form pattern-free columns, then we shuffle those columns to form new shares. If a share contains a pattern of n bits and we cut the share in blocks of k bits with $k < n$ and k prime with n, the first n blocks of k bits each will not contain any pattern present in the share (see Figure 4).

Cut phase
In the cut phase we align shares in rows and then we cut each row in blocks of k bits. The first block of each row (i.e., share) forms the first column, the second block of each row forms the second column and so on (vertical red lines in Figure 4). Notice that the first n columns produced in the cut phase do not contain any pattern of the plaintext thanks to the assumption that the cut length k is prime with the plaintext pattern length n.

Shuffle phase
In the shuffle phase we associate the first column to the first cloud, the second column to the second cloud, and so on. When there are no more clouds we restart the association from the first cloud in

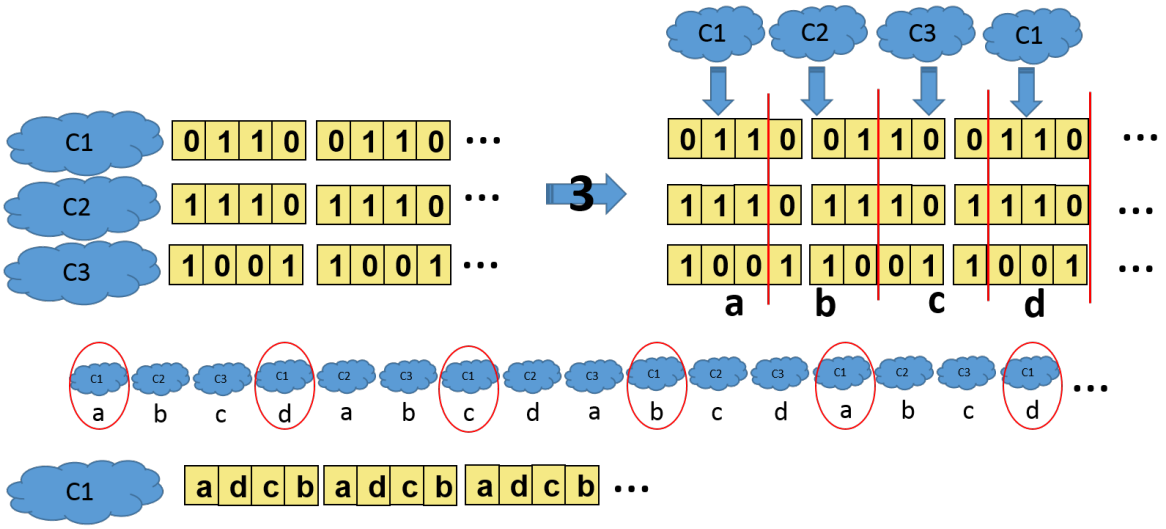


Figure 4: Cut-and-Shuffle Step Example.

a circular manner. This new association between columns and clouds generate a new set of shares that do not contain the pattern of the plaintext.

The problem of the Cut-and-Shuffle algorithm is that new patterns appear: in the cut phase for a pattern of length n, the first n columns are unique. After the n^{th} columns they repeat: the column $n+1$ is equal to the column 1, the column $n+2$ is equal to the column 2, etc.

Consider the example in Figure 4. There are three shares each one containing a pattern of length 4 (0110 for the cloud c_1, 1110 for the cloud c_2 and 1001 for the cloud c_3). In the cut phase (vertical red lines in the Figure 4) we cut the pattern of length $n = 4$ in blocks of length $k = 3$ (notice that 3 is minor than 4 and prime with it), the initial patterns (0110, 1110 and 1001) are broken and none of the generated blocks of three bits contains any pattern. We associate each column to a new share in a circular manner. The figure shows the first four columns, named "a", "b", "c" and "d". Each column contains 9 bits and is unique. The problem comes after the fourth column: cutting a pattern of length 4 in columns of length 3, imply that each four columns the cut repeat, i.e., the column 5 will be equal to the column 1, the column 6 equal to the column 2, and so on. More in general what happen is that cutting a pattern of length n in blocks of length k, the cut will repeat each $n*k$ bits, that is each n blocks. This implies that the column i will be the same as the column i mod n. In the bottom part of Figure 4 we have named the four columns a, b, c and d and we show, for the cloud c_1, the new pattern that arises: a-d-c-b. Since clouds are associated to columns in a circular manner the cloud c_1 will receive the same columns a, d, c and b in this order, repeatedly. This means that cloud c_1 will observe a new pattern composed by the concatenation of columns a-d-c-b. In the example of Figure 4 the new pattern has a length of four columns of 9 bits each. More in general using this technique the new share will contain a pattern that repeats every $k*$ #of rows (clouds) $*n$. This is a key property of the Cut-and-Shuffle algorithm: after a cut-and-shuffle operation the algorithm *mix* together a number of bits, breaking every pattern they can contain.

3.5 The Cut-and-Shuffle Algorithm Iteration

The pattern problem can be mitigated by cutting rows of shares in columns and assigning columns to a new set of shares. The problems of this technique is that i) it does not completely hide patterns but it only makes them somehow bigger and ii) needs to know the pattern length to find a number smaller than the pattern length and prime with it. In practice, we solve those problems by iterating our algorithm multiple times using each time a different prime number. Figure 4 shows how patterns of 4 bits are mixed to form patterns of 36 bits cutting the initial share in columns of 3 bits. The idea is to iterate the same procedure of Cut-and-Shuffle multiple times in order to increase the size of bits mixed to a dimension that will hide all possible patterns.

In our algorithm we repeat the cut and shuffle step ten times. We use the sequence of the first 10 odd prime numbers (3, 5, 7, 11, 13, 17, 19, 23, 29 and 31) to choose the size of the block at each step. For seek of simplicity, we first assume that the input does not

contain patterns that are multiple of any of the prime numbers used in the cut step to avoid breaking the assumption that the length of the cut is prime with the length of the pattern. Then we generalize our description considering those cases.

Figure 5 shows the Cut-and-Shuffle's iterations. We call *size* of a pattern or a column the number of its bits. The first iteration makes a column each 3 bits, the second each 5 bits, then 7 bits, etc., until the last iteration that cuts a column each 31 bits. The Cut-and-Shuffle algorithm breaks patterns regardless their size: the first iteration hides all possible patterns with size not multiple of 3 in bigger patterns of size (3 * #of rows * n) bits where n is the size of the pattern. In the example of Figure 5 after the first iteration the new shares have patterns of size 36. In the second iteration all patterns (we assume they are not multiple of 5) are hidden in bigger patterns of size 5 * #of rows (clouds) * n where n is the size of the pattern generated in the previous iteration (36 in the example). In the instance of Figure 5 after the second iterations the new pattern size is 180 ($= 36 * 5$) bits. After each step of the Cut-and-Shuffle algorithm the size of a potential pattern in the output share is increased by a factor equals to the number used in the cut phase. At the end of the 10^{th} transformation any pattern in the output share cannot be smaller than the initial pattern multiplied by 1.0028×10^{11} (that is $3*5*7*11*13*17*19*23*29*31$). This is equivalent to mixing together blocks of 1.0028×10^{11} bits, making the algorithm hiding every pattern smaller than this size. It can be seen as a classic ECB with a block size (and consequently a key size) of 1.0028×10^{11} bits.

As discussed in Section 3.4, if we cut a share containing a pattern of size n in blocks of k bits, and k is prime with n, the first n blocks of k bits are unique (i.e., do not contain the pattern). More generally, by cutting a pattern of size n in blocks of size k, the generated blocks repeat each n/k blocks if n is divisible by k, or each n blocks otherwise. The amount of unique blocks generated by the cuts is important because the more they are, the better patterns are hided. Intuitively, a sequence of unique blocks of size s mixes all potential patterns in the corresponding s bits in the input. Since we do not know in advance the size of patterns that can be contained in the plaintext, in Cut-and-Shuffle algorithm we have used a sequence of prime numbers for the block size to minimise the probability that the pattern size is divisible by the block size. Moreover, prime numbers do not share any divisor, so a pattern can be divisible by (or multiple of) only one prime number. This implies that in the worst case at most one of the ten iterations of the Cut-and-Shuffle algorithm is not incisive. The impact of having a pattern multiple of one of the ten prime numbers is negligible because in the worst case the algorithm mix together 3.2348×10^9 ($3*5*7*11*13*17*19*23*29$) bits instead of 1.0028×10^{11} ($3*5*7*11*13*17*19*23*29*31$) bits. Mixing 3.2348×10^9 bits is far more than enough to hide all possible patterns in the real (an may be also in the imaginary) world.

For sake of simplicity, in the previous discussion we have considered that patterns reflected from the plaintext to the shares have the same size. This is not necessarily the case. It is possible that a pattern in the plaintext give different patterns of different length in the shares. In this case the Cut-and-Shuffle is even more efficient in hiding patterns because columns repeat with a lower frequency. Intuitively, in the cut step of the Cut-and-Shuffle algorithm, if all rows (i.e., shares) have a pattern of the same size n, the pattern repeats each n columns, while if a row has a pattern of size n and another has a pattern of size n', then the pattern repeats each k columns, k being the least common multiple of n and n'. We recall that the less columns repeat the best Cut-and-Shuffle algorithm works.

3.6 Light Blind Decryption Mechanism

In order to retrieve files, the broker should first fetch all the shares from the clouds. Then, it applies the inverse operation of the Cut-and-Shuffle and finally applies the encryption key to reconstitute the plaintext. Notice that all these operations, same as for encryption, have a constant time complexity (i.e., the time needed to reconstruct the input does not depend on the input size).

To reverse the Cut-and-Shuffle algorithm, it is sufficient to repeat all the cut and shuffle phases using the prime numbers in the inverse order: from 31 to 3. The broker retrieves all the shares, puts them in rows, and starts to cut columns of size 31. Then, it shuffles the columns to form new shares (same as in the encryption phase). Next, it repeats the cut phase with columns of size 29. Once it has iterated all the prime odd numbers, it has the original shares calculated at the first step of the Light Blind Partition Algorithm. In order to reconstruct the original file, the broker uses the encryption key to build the original sequence of bits from the shares.

3.7 Security Analysis

Our system provides data confidentiality by spreading the original input in several clouds.

An adversary needs to access all the shares of the

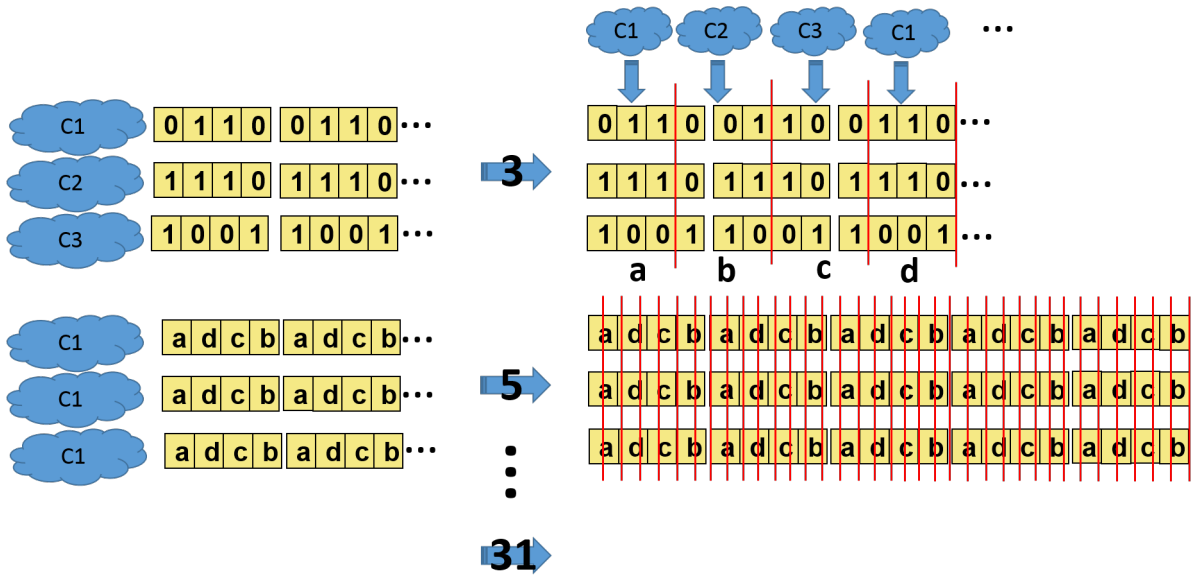


Figure 5: Cut-and-Shuffle Iterations.

original data to be able to undo the Cut-and-Shuffle transformations. If she misses one of the shares there is no way to undo Cut-and-Shuffle transformations and the data is completely opaque: the adversary does not know the original position of the bits it has nor the position of the missing bits in the input. This gives to the user the assurance that, unless the adversary can access all the shares, data confidentiality is kept.

If an adversary can collect all the shares, for example thanks to a collaboration between clouds or eavesdropping in the network during the transmission, the Cut-and-Shuffle step can be easily undone by the adversary and our system rollback to a classic ECB scheme. The problem of ECB is that it does not hide well patterns.

An interesting property of Light Blind is that the use of a secret key to spread data in the clouds is only needed to offer a minimal (ECB-like) protection if an adversary collects all the shares. If we assume that clouds do not collaborate, and that the communication channel is somehow secure, then Light Blind does not need to use any secret because an adversary cannot undo the Cut-and-Shuffle phase. If we assume a public channel then the user may be interested in ensuring the confidentiality of the communications channel, for example by using HTTPS. The discussion of the communication overhead is out of the scope of this paper.

As discussed previously, if all shares are known by an adversary, Light Blind rollbacks to ECB. The difference between a classical ECB and Light Blind is that in our system, the produced output (the shares) is a partial order of the initial input: if a bit b is before a bit b' in a share, then b is before b' also in the plaintext. This translates by a decrease of the possible bits permutations of the ciphertext to produce the plaintext. If a block B of size B_s is divided into n shares $S = (s_1, s_2, \ldots, s_n)$ then the possible permutations of shares in the original block are $\frac{(s_1+s_2+\ldots+s_n)!}{s_1!s_2!\ldots s_n!}$ where $(s_1, s_2, \ldots, s_n)$ represents the size (i.e., the number of bits) of a block in each share. This is weaker than a random key because in the case of a random key the possible permutations are $(s_1 + s_2 + \ldots + s_n)!$.

4 Discussion

The motivation of our work is to provide users with a simple and efficient way to obtain data confidentiality in the cloud at a constant computational time. Constant computational time means that the time needed to transform data to make it unintelligible does not depend on the size of data.

This goal is achieved thanks to the fact that all steps of our algorithm are parallelizable: we process blocks of data and each block has i) the same dimension and ii) applies the same operations.

In the first phase, we encode each block with an encryption key, similarly than in classical ECB in order to obtain shares of the original data. This phase can be executed in parallel in all the blocks, so its

time complexity is constant. In the second phase we iteratively cut and shuffle shares in order to mix them. Each iteration of the Cut-and-Shuffle algorithm can be executed in parallel in all the columns without synchronization, so its time complexity is constant. Since the number of iterations of the second phase is constant as well (10), the time complexity of the second phase is constant.

Of course the bigger is the input, the more are the resources needed to parallelize Light Blind. Nevertheless, modern devices have more and more CPU, and consequently they are able to execute more and more work in parallel, so our algorithm makes a good use of current architectures.

5 Conclusion

In this paper we show an innovative way to make use of multi-cloud systems and block ciphering to obtain data confidentiality at a constant time complexity. Our system provides simultaneously ECB parallelizability and the ability to hide patterns. This is possible thanks to the key idea of splitting data into multiple shares that are stored in different clouds.

Light Blind positions between classic encryption with ECB mode providing confidentiality at a constant time complexity and the ability of hiding patterns provided by other encryption modes such as CBC and OFB.

Our system benefits to users who do not encrypt their data stored in the cloud. The constant time complexity of Light Blind makes suitable data to be protected in a more systematic way. No matter the size of your data or how often you need it, the overhead you have to pay to gain confidentiality is small and predictable.

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