Security and Privacy in Big Data Sharing: State-of-the-Art and Research Directions

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Big Data Sharing (BDS) refers to the act of the data owners to share data so that users can find, access and use data according to the agreement. In recent years, BDS has been an emerging topic due to its wide applications, such as big data trading and cross-domain data analytics. However, as the multiple parties are involved in a BDS platform, the issue of security and privacy violation arises. There have been a number of solutions for enhancing security and preserving privacy at different big data operations (e.g., data operation, data searching, data sharing and data outsourcing). To the best of our knowledge, there is no existing survey that has particularly focused on the broad and systematic developments of these security and privacy solutions. In this study, we conduct a comprehensive survey of the state-of-the-art solutions introduced to tackle security and privacy issues in BDS. For a better understanding, we first introduce a general model for BDS and identify the security and privacy requirements. We discuss and classify the state-of-the-art security and privacy solutions for BDS according to the identified requirements. Finally, based on the insights gained, we present and discuss new promising research directions.

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1 INTRODUCTION

The term big data as the name suggest refers to information assets characterized by high volume, fast access speed, and a large ontological variety. Dealing with big data requires specific technologies and analytical methods for its transformation into value. The term big data sharing (BDS) refers to the act of the data sharer to share big data so that the data sharee can find, access, and use in the agreed ways. BDS not only improves the speed of getting data insights, but can also help strengthen cross-domain data analytics and big data trading. Over the last few years, there is a huge demand for big data sharing in various industries, which has led to an explosive growth of information. Over 2.5 quintillion bytes of data are created every single day, and the amount of data is only going to grow from there. By 2020, it is estimated that 1.7MB of data will be created every second for every person on earth. Due to constraints related to the limitations of data storage

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resources, large storage dedicated centralized servers (e.g., cloud) are usually regarded as the best approach for BDS: on the one hand the centralized server provides a solution which is both scalable and accommodating for BDS and business analytics, while on the other hand BDS provides data analytics for actionable insight and making predictions. However, centralized server comes with a price: it constitutes an added level of security and privacy threats since its essential services are often outsourced to an untrusted third party, which makes harder to maintain the basic data security and privacy requirements, such as confidentiality, integrity and privacy of the shared data. Thus, enforcing security and privacy in BDS as a whole is an important concern. Otherwise, data integrity and confidentiality can always be compromised easily.

1.1 General Model of BDS and its Security and Privacy Concerns

In this section we first discuss the general model of BDS. Then, we describe the general operations needed based on that general model. According to that, we broadly categorize the security and privacy notions needed for BDS.

**General Model of BDS.** Before discussing security and privacy concerns, it is necessary to define a general model of BDS and its input/output. The general model that we consider is based on the centralized server approach. We propose a general model of BDS system that allows data sharer/sharee to **create, store, access, download, search and manipulate databases**, that takes full account of data access control, user accessibility and the form of shared data.

The remote centralized service provider (e.g., Cloud) which stores and manages the data generated by data sharer is considered as an untrusted party by the two other parties. The sharing activity could be either operating on data, e.g., searching or computation or downloading data. The shared data could be either raw or encrypted. Table 1 shows the notations.

![Fig. 1. General Model for BDS](image-url)

Our general model for BDS consists of the two following entities (as shown in Fig. 1):

| Notations | Descriptions |
|-----------|--------------|
| DW        | Downloaded data |
| OP        | Data operations which includes: data searching, data outsourcing, data computation |
| ENC       | Data is encrypted during the storage and sharing process |
| RAW       | Data is raw during the storage and sharing process |
| INT       | Data Sharee/Internal Use |
| EXT       | Data Sharee/External User |
**Data Sharer/Internal User.** A data sharer is the data owner (or internal user) who shares his own data with a larger server storage. In such system, the data sharer can either use and operate on his own shared data or gives its access to data sharee.

**Data Sharee/External User.** A data sharee (or external user) access/uses other’s stored data. In such system, the data sharer gives the access to that data to the data sharee, either by downloading data from the server or by directly operating on data.

After defining what is BDS made of, we explain its general procedures. BDS operations can be divided into a few distinct groups, which have their own characteristics. Herein, we define and discuss the general operations needed for BDS, i.e., data downloading, data storing, data computation, data searching, and data outsourcing:

**Data Sharing.** Data sharer might query on a BDS platform with some constraints, to learn hidden patterns, correlations, compute a function, and other insights. Generally speaking, there are three steps for data querying, i.e., data computation, data downloading, data searching, and data outsourcing, as follows:

- **DATA DOWNLOADING.** Data downloading is the process through which data sharer or data sharee retrieve the result from data querying.

- **DATA OPERATION.**
  1. **DATA COMPUTATION.** Data computation is the process through which data sharer or data sharee jointly compute a function with BDS over their inputs while keeping those inputs private.
  2. **DATA SEARCHING.** Data users might query a BDS platform with some constraints, to learn hidden patterns, correlations and other insights. Data searching needs to be able to search through unstructured and structured data which requires management of huge amounts of data as quickly as possible.
  3. **DATA OUTSOURCING.** Data users might delegate a portion of data to be outsourced to external providers who offer data management functionalities.

Although there are numerous benefits for BDS, it is non-trivial to design a solution because of the requirements. So, security and privacy are necessary for BDS, otherwise its values will be disappeared, i.e., if a BDS is not secure or cannot protect the security and privacy, then the users can hardly trust such a technology and even will not use it. Below, we categorize and explain the basic concerns, i.e., data security, data privacy, and user privacy as follows:

**Security and Privacy Concerns in BDS.** Considering these data sharing operations, we categorize data security and privacy notions needed in BDS, i.e., Data Security, Data Privacy and User Privacy. Data security refers to how data is protected from an attacker, namely: Prevent malicious access, usage, modification or unavailability of the big data from anyone other than the sharing parties. Data Privacy is about protection of individual’s information from being disclosed to others as data may contain individual’s sensitive information, such as Personally Identifiable Information (PII), personal healthcare information, and financial information, which should be protected whenever the data is collected, stored and shared (e.g., by applying governing regulation or law like General Data Protection Regulation (GDPR)). There are two parties in BDS, which are the data sharer and sharee. User privacy is about protecting the identity of data sharer from exposure by other parties and even each other. It requires that the two parties involved in BDS focus on the data itself without knowing each other.

### 1.2 Motivation and Contributions

For the past few years, the topic of big data security and privacy have been explored in many surveys. Most of these survey papers [29, 54, 111, 116, 117] give a short overview on security and
privacy techniques in BDS. This work aims to contribute a comprehensive survey of security and privacy in BDS in terms of formal definitions, security and privacy requirements, security and privacy techniques used to fulfill requirements, classification of techniques and future challenges.

Compared to other surveys that can be found in the literature, our contributions are as follows:

- **New taxonomy.** After providing an in-depth understanding and up-to-date discussion related to the BDS and its operations. We identify security and privacy requirements within BDS and present a novel taxonomy to structure solutions by fulfilled requirements.
- **Comprehensive survey.** In accordance with the taxonomy, we discuss the benefits and limitations of the state-of-the-art solutions that fulfill the identified security and privacy requirements.
- **Future directions.** Finally, based on our survey, we provide the list of lessons learned, open issues, and directions for future work.

1.3 Security & Privacy Concerns in Big Data Sharing Applications

BDS has many applications fields, such as healthcare [102], supply chain management [105][121], and open government [120]. In this section, we introduce three attracting applications that caught the attention of both the industry and academia in recent years.

**Privacy and Pandemic.** Global leaders are increasingly relying on information about individuals and communities to control the spread of COVID-19 and respond to its economic, political, social, and health impacts. Time is of the essence, and leaders must quickly decide essential questions about what personal information they will collect or disclose, to whom, and under what conditions. It is important that privacy concerns do not become an obstacle to effective health and safety measures, but also that we do not open a door to privacy violation or limitless surveillance.

**Federated Learning (FL).** FL is a subset within the field of AI, enables multiple decentralized edge devices or servers holding local data samples to collaboratively learn a shared prediction model while keeping all the training data private. In recent years, FL has received extensive attention from both academia and industry because it can solve privacy problems in machine learning. However, there are many challenges in FL, and although there are solutions to these challenges, most existing solutions need a trusted, centralized authority that is difficult to find.

**Medical Research and Healthcare.** In recent years, more and more health data are being generated. All these big data put together can be used to predict the onset of diseases so that preventive steps can be taken. However, the health data contains personal health information (PHI), due to the risk of violating the privacy there will therefore be legal concerns in accessing the data [75]. Health data can be anonymized using masking and de-identification techniques, and be disclosed to the researchers based on a legal data sharing agreement [50].

1.4 Organisation

This paper is structured as follows: In Section 1, we start by defining BDS, this allows us to discuss the differences between the security and privacy notions in BDS. Next, we provide a comprehensive topical overview of BDS by introducing its general model and general procedures using centralized architecture. Based on this, we describe the different assumptions and scope for that model. In Section 2, we start by describing the basic security requirements as well as additional ones that are needed in BDS and then describing their corresponding techniques. In Section 3, we describe the privacy requirements in terms of data and user privacy and their corresponding techniques. In Section 4, we review, summarize and compare the security & privacy techniques to fulfill the needed security & privacy requirements. In Section 5, we discuss the challenge issues as well as new future research directions for BDS. Finally in Section 6, we conclude this article.
2 SECURITY IN BDS

In this section, we first start defining the required security properties as well as setting the security assumptions. Based on this, we overview the existing cryptographic techniques. It allows us to describe how these techniques can be incorporated in the BDS system. Finally, we provide a classification that compare the various cryptographic techniques.

2.1 Security Requirements in BDS

In this section, we first start recalling the four most fundamental security requirements coming from information system, also known as the CIA triad, which are defined as follows:

Data Confidentiality during Outsourcing. Confidentiality is the cornerstone of BDS security which refers to the protection of data during the sharing process against the unauthorized access. Otherwise, its value could be disappeared.

Data Integrity. We distinguish two types of integrity in data sharing context: Usage Integrity (or Data Integrity) ensuring that any unauthorized modification of sensitive data in the use should be detectable, otherwise its veracity cannot be consistent. While, Data Source Authenticity means that the data should be consistent over the whole BDS process. The distinction done between data integrity and authentication is frequently blurred because integrity can also provide authentication. In essence, an integrity primitive would take as a parameter a message \( m \) and prove that the sender actually mixed his secret with \( m \) to attest \( m \)'s origin. An authentication primitive does not involve any message (no “payload”) and is only meant to check that the authenticated party actually knows a given secret. It follows that to achieve authentication the secret owner can just be challenged to attest the integrity of random challenge \( m \), chosen by the verifier. In practice, this is indeed the way in which numerous commercial products implement authentication using integrity primitives.

Non-repudiation. While integrity ensures a data has not been tampered with, non-repudiation provides evidence that an individual or entity from denying having performed a particular action. In other words, non-repudiation provides proof of the origin of data and the integrity of the data.

Availability. Data availability ensures that data must be available for use whenever authorized users want it. However, the introduction of cloud computing has limited issues of data availability for Big Data due to high has narrowed down issues of cloud. Denial of service (DoS) attack, DDoS attack, and SYN flood attack are the most common attacks to threat data availability.

Besides the basic security requirements of BDS, we specify the additional security requirements that we have identified for BDS context, which are defined as follows:

Data Confidentiality during Computation. Data sharee and data sharer want to jointly compute a function over their inputs while keeping those inputs private. For example, the data collected from different sensors in the IoT system may be aggregated to generate the targeted result; the cloud and the clients may cooperate to provide appropriate services. At the same time, the private information and secret data should be protected. The computation procedures and results on BDS should only be known by the data sharer and sharee during and after computation. Unlike traditional cryptographic scenarios, where cryptography ensures security and integrity of communication or storage and the adversary is supposed an outsider from the system of participants (an eavesdropper on the sender and receiver), the cryptography techniques in this model should protect participants’ privacy from each other.

Data Confidentiality during Searching. Data sharers want to store data in ciphertext form while keeping the functionality to search keywords in the data, i.e, to protect the privacy of
data, data sharer may choose to encrypt the data before uploading them to the cloud. However, while encryption provides confidentiality to data, it also sacrifices the data sharers’ ability to query a special segment in their data. The search requests and results on big data should only be known by the data sharer during and after searching.

**Access control.** Traditionally, cryptography is about providing secure communication over insecure channels, meaning that we want to protect honest parties from external adversaries: only the party who has the decryption key can learn the message. In recent applications, more complicated issues have been introduced, i.e., consists in not trusting everybody with the same information. Access control allows decryption depending on who you are and which keys you have, you can access different parts of the information sent. In other words, access control requirement deals with the issue that someone should only be able to decrypt a ciphertext if the person holds a key for “matching attributes” where user keys are always issued by some trusted party.

**Delegation rights.** This notion deals with the problem of data sharing between different receipts. We distinguish two types of delegation rights: *decryption rights delegation* and *signing rights delegation*. In decryption rights delegation, it turns a ciphertext intended for one data user into a ciphertext of the same data intended for another data user without revealing any information about the data or the secret keys. In signing rights delegation, it allows an entity to delegate its signing rights to another.

![Fig. 2. Assumptions of BDS security](image)

**2.2 Security Assumptions**

In this section, based on the proposed general model for BDS in Section 1.1, we propose the security assumptions needed in BDS systems according to the three following dimensions: user accessibility, data usage and the form of shared data, as shown in Fig. 2. Depending on what action can be performed by each type of user in BDS introduced in Section 1.1, under which form of data, different cryptographic solutions (or the combination of them) should be used to guarantee the security of BDS operations, we divide the assumptions into the following category:

**Assumption 1** (INT, OP, ENC). In such assumption, the encrypted data from the data sharer can only be operated, such as data outsourcing, calculation, searching, viewing. However, it can not be externally accessed, e.g., users store their own data in server and operate/search on it.

**Assumption 2** (EXT, OP, ENC). In such assumption, the encrypted data from the data sharer can only be operated but the sharee which can be from the outside of system, e.g., access to a server storage, which means that it needs an extra secure channel compared with assumption 1.

**Assumption 3** (INT, ENC). In such assumption, the encrypted shared data can be downloaded and then retrieved by the data owner within the system.

**Assumption 4** (EXT, DW, ENC). In such assumption, the encrypted shared data can be downloaded and retrieved by data sharee from the outside of system. Retrieval is a stronger assumption
Table 2. Classification of techniques according to assumptions and fulfilled security requirements

| Assumptions | Fulfilled Security requirements | Security Techniques |
|-------------|--------------------------------|---------------------|
| Asm.1       | Confidentiality during Computation | HE                  |
|             | Confidentiality during Searching  | SSE, PIR            |
|             | Confidentiality during Outsourcing | ORAM               |
|             | Confidentiality during Outsourcing & Integrity | AE                   |
|             | Availability                       | Storage path encryption |
| Asm.2       | Confidentiality during Computation | FE, HE              |
|             | Confidentiality during Searching   | PKEKS               |
|             | Confidentiality during Outsourcing & Integrity | AE, Signcryption   |
|             | Confidentiality during Outsourcing, Integrity & Non-repudiation | Signcryption       |
|             | Availability                       | Storage path encryption |
| Asm.3       | Confidentiality during Outsourcing | N/A                 |
|             | Integrity                          | DS, MAC, PDP       |
|             | Availability                        | Storage path encryption |
| Asm.4       | Confidentiality during Outsourcing & Rights Delegation | PRE               |
|             | Confidentiality during Outsourcing & Access control | ABE, IBE, ABHE    |
|             | Confidentiality during Outsourcing & Integrity | AE, Signcryption   |
|             | Confidentiality, Integrity & Non-repudiation | Signcryption       |
|             | Availability                        | Storage path encryption |
| Asm.5       | Integrity                          | DS, MAC, PDP       |
|             | Availability                        | Storage path encryption |
| Asm.6       | Integrity                          | DS, MAC, PDP       |
|             | Integrity & Non-repudiation         | DS                  |
|             | Confidentiality during Outsourcing, Integrity & Non-repudiation | Signcryption       |
|             | Integrity & Rights Delegation      | PS                  |
|             | Availability                        | Storage path encryption |
| Asm.7       | Confidentiality during Computation | PST, MPC           |
|             | Confidentiality during Searching    | PIR                 |
|             | Integrity                          | VC, DS, MAC, PDP   |
|             | Availability                        | Storage path encryption |
| Asm.8       | Confidentiality during Computation | PST, MPC           |
|             | Integrity                          | DS, MAC, PDP       |
|             | Integrity & Non-repudication        | DS                  |
|             | Integrity & Right Delegation       | PS                  |
|             | Availability                        | Storage path encryption |

than operation since it delivers all data usage to the data sharee, which means they need additional security requirements such as decryption rights delegation between the data sharer and the data sharee and ensuring the non-repudiation property.

Assumption 5 (INT, DW, RAW). In such assumption, data is not encrypted initially and need to be fully downloaded, e.g., the data sharer upload their own data within the server and later download it.

Assumption 6 (EXT, DW, RAW). In such assumption, we require that the data sharee can also download the data securely from the server, which means they need extra requirements such as signing rights delegation and ensuring the non-repudiation property.

Assumption 7 (INT, OP, RAW). In such assumption, the data sharer operates on his own raw data. E.g. a data owner may need some operations that only work on raw data in server storage. So this also requires the consideration in terms of verifiable outsourced computation integrity from the server.

Assumption 8 (EXT, OP, RAW). In such assumption, the data sharee operates on data sharer’s raw data. Comparing with Assumption 7, there is extra security requirements in terms of the signing rights delegation and the non-repudiation.
In table 2, we summarize the security techniques detailed in Section 2.3 that are needed to fulfil the security requirements described in Section 2.1 according to each security assumptions described in 2.2.

2.3 Security Techniques

In this section, we summarize the existing techniques of BDS that can be leveraged to enhance the security and privacy of the introduced BDS in Section[1.1]. For each of the presented techniques, we use the following outline: First, we provide a high-level overview of what protections the cryptographic techniques provides and how it can be used in BDS. Second, we give a more detailed definition of the security achieved and the critical limits of the technique. Finally, we give an in-depth survey of the literature and state of the art developments for the technique to illustrate the differences between individual schemes and their potential uses-cases.

**Message Authentication Code (MAC)** This is a small piece of information used to authenticate a message. In BDS system, a data sharee needs to be assured that a data comes from a legitimate data sharer (authentication) and not from an attacker. This also includes the assurance that the message was not modified during transmission (integrity). The MAC algorithm takes a data D and secret key and outputs a MAC value or "tag". MACs only use secret keys, and rely on symmetric encryption. However, to function as intended the MAC must be able to resist plaintext attacks even if a hacker knows the secret key. Although the hacker can create their own MACs from the key, the MAC algorithm must be strong enough to make it impossible for the hacker to calculate the MAC for other messages. MACs can be built from hash functions; these are known as keyed hash functions. One advantage of MACs over DS is that they are much faster than digital signatures since they are based on either block ciphers or hash functions. The algorithms that are more commonly used in modern applications and one specifically designed for constrained platforms: CMAC [1], PMAC1 [58], GMAC [2] and Marvin [113]. For more details, we refer the interested reader to the survey [112].

MAC consists of a tuple of algorithms (KeyGen, MAC, Verify) satisfying:

- **KeyGen** (key-generator) gives the key k on input $1^n$, where n is the security parameter.
- **MAC** (signing) outputs a tag t on the key sk and the input string x.
- **Verify** (verifying) outputs accepted or rejected on inputs: the key sk, the string x and the tag t.

**Digital Signature (DS)** DS were originally proposed by Diffie and Hellman in [44] DS and Rivest, Shamir, and Adelman [107]. DS deals with the problem of data authentication and integrity in the asymmetric (public key) setting. In BDS system, a data sharee needs to be assured that a data comes from a legitimate data sharer (authentication) and not from an attacker. This also includes the assurance that the message was not modified during transmission (integrity). MACs solved this problem but for the symmetric-key setting. By opposition to MACs, digital signatures have the advantage of being publicly verifiable and non-repudiable. Public verifiability implies the transferability of signatures and, thus, signatures prove useful in many applications, including BDS systems.

Cramer and Shoup [39] and Gennaro, Halevi, and Rabin [58] proposed the first signature schemes that are practical and whose security analysis does not rely on an ideal random function based on the so-called Strong RSA assumption.

A DS [78] is a tuple, $\text{DS} = (\text{KeyGen}, \text{Sign}, \text{Verify})$, of probabilistic polynomial-time algorithms satisfying:

$(sk, pk) \leftarrow \text{KeyGen}(1^n)$ On input security parameter $1^n$, key generation algorithm KeyGen produces a pair $(pk, sk)$ of matching public and private keys.
\[ \sigma \leftarrow \text{Sign}(sk, m) \] Given a message \( m \) in a set \( M \) of messages and a private key \( sk \), signing algorithm \( \text{Sign} \) produces a signature \( \sigma \).

\[ \{0, 1\} \leftarrow \text{Verify}(pk, m, \sigma) \] Given a signature \( \sigma \), a message \( m \in M \) and a public key \( pk \), the verifying algorithm \( \text{Verify} \) checks whether \( \sigma \) is a valid signature on \( m \) with respect to \( pk \).

**Signcryption** In some cases of BDS, we require the confidentiality and authenticity separately, but other cases we require them simultaneously. To achieve this special requirement, Signcryption scheme is used. The first signcryption scheme was introduced by Yuliang Zheng in 1997 [126] based on elliptic curve cryptography. Signcryption is a multi-user primitive that is complex to design [3]. Signcryption Scheme consists of tuple of algorithms defined as follows:

\[
\begin{aligned}
(sk, pk) &\leftarrow \text{Keygen}(1^k) \quad \text{is the key generation algorithm which takes a security parameter} \ k \ \text{and generates a private/public key pair} \ (sk, pk). \\
C &\leftarrow \text{Signcrypt}(1^k, m, sk_a, pk_b) \quad \text{takes} \ k, \ \text{a message} \ m, \ \text{a sender private key} \ sk_a \ \text{and a recipient public key} \ pk_b, \ \text{outputs a ciphertext} \ C. \ \text{m is drawn from a message space} \ M \ \text{which is defined as} \ \{0, 1\}^n \ \text{where} \ n \ \text{is some polynomial in} \ k. \\
(m, \sigma, pk_a) &\leftarrow \text{Unsigncrypt}(1^k, C, sk_b) \quad \text{takes} \ k, C \ \text{and a private key} \ sk_b, \ \text{outputs either a triple} \ (m, \sigma, pk_a) \ \text{where} \ m \in M, \ s \ \text{is a signature and} \ pk_a \ \text{is a public key, or reject which indicates the failure of unsigncryption.} \\
\{0, 1\} &\leftarrow \text{Verify}(1^k, m, \sigma, pk_a) \quad \text{takes} \ k, m \in M, \ \text{a signature} \ \sigma \ \text{and a public key} \ pk_a, \ \text{outputs 1 for a valid signature or 0 otherwise.}
\end{aligned}
\]

**Authenticated Encryption (AE)** The symmetric analogue of a Signcryption is variously called \( \text{AE} \) [13], which simultaneously ensure the confidentiality and authenticity of data. However, similarly to \( \text{MAC} \), \( \text{AE} \) does not provide the non-repudiation. For a comprehensive survey on \( \text{AE} \), we refer the interested reader to [79].

Basically, there are three approaches to \( \text{AE} \):

- MAC-then-Encrypt (MtE): We first MAC \( m \) under key \( sk_1 \) to yield tag \( \sigma \) and then encrypt the resulting pair \( (m, \sigma) \) under key \( sk_2 \).
- Encrypt-then-MAC (EtM): We first encrypt \( m \) under key \( sk_2 \) to yield ciphertext C and then compute \( \sigma \leftarrow \text{MAC}_{sk_1}(C) \) to yield the pair \( (C, \sigma) \).
- Encrypt-and-MAC (E&M): We first encrypt \( M \) under key \( sk_1 \) to yield ciphertext C and then compute \( \sigma \leftarrow \text{MAC}_{sk_1}(m) \) to yield the pair \( (C, \sigma) \).

**Identity Based Encryption (IBE)** IBE [110] allows an access control that is based on the identity of a data user. To protect the privacy of data stored in the cloud, a data user usually encrypts his data in such a way that certain designated data users can decrypt the data. IBE is regarded as an alternative to PKI which is proposed to simplify key management in a certificate based public key infrastructure (PKI) by using human identities like email address or IP address as public keys. To preserve the anonymity of sender and receiver, the first IBE [21] scheme was proposed. Several constructions of IBE have been proposed. From a chronological point of view, the first one is by Boneh and Franklin [22], who proposed a straightforward scheme in the random oracle model [11]. Their construction heavily exploits cryptographic pairings, as well as the power conferred by a random oracle. Later, Boneh and Boyen [19] refined this idea and came up with an identity based encryption in the standard model, but relying on what is called a non-static \( q \)-type assumption, where \( q \) is related to the number of queries the adversary makes for key derivation.

An IBE scheme consists of four algorithms (Setup, KeyGen, Enc, Dec):

\[
\begin{aligned}
\text{(msk, mpk)} &\leftarrow \text{Setup}(1^\lambda) \quad \text{The setup algorithm takes the security parameter} \ \lambda \ \text{and outputs a master secret key} \ msk \ \text{and a (master) encryption key} \ mpk.
\end{aligned}
\]
CT ← Enc(mpk, id, M) The encryption algorithm takes as input an encryption key mpk, an identifier id and a message $M \in M_\lambda$, and outputs a ciphertext CT.

sk$_{id}$ ← KeyGen(msk, id) The key derivation algorithm takes as input an identifier id and outputs the corresponding functional key sk$_{id}$.

$M \leftarrow \text{Dec}(\text{sk}_{id}, \text{id}, \text{CT})$ The decryption algorithm is a deterministic algorithm that takes as input a key sk$_{id}$ and a ciphertext CT and outputs M or a special error symbol ⊥ if decryption fails.

**Attribute Based Encryption (ABE)** ABE technique [69, 109] is regarded as the most appropriate technologies used to control big data access in the cloud environment; it allows more secure and flexible as granular access control is possible and it enables data users to upload their data in encrypted forms to the cloud while sharing them with users possessing certain credentials or attributes. ABE can be viewed as a generalization of IBE. An implementation of this scheme describing how this can be used for access control was given by Pirretti et al. [101]. The class of supported policies was extended to arbitrary boolean formulas by Goyal et al. [70] and Bethencourt, Sahai, and Waters [16].

Basically, ABE techniques are classified into two major classes: Ciphertext-Policy ABE (CP-ABE) introduced by Sahai and Waters [119] and Key-Policy ABE (KP-ABE) [8]. The CP-ABE is a form of ABE in which keys are associated with attributes and data is encrypted according to a policy specifying which attributes are needed to decrypt the ciphertext. While in KP-ABE, attributes are always used to describe the access policies and encrypted data. The user’s secret keys generate using these attributes. There are some available implementations of ABE. The first efficient implementation was given by Bethencourt et al. [16] using the Pairing-Based Crypto library. Another efficient implementation of ABE was given by Khoury et al. [80], achieves 3 ms for ABE encryption and 6 ms for decryption.

ABE A (Ciphertext-Policy) Attribute Based Encryption (CP-ABE) scheme consists of four algorithms $\text{ABE} = \langle \text{Setup, KeyGen, Enc, Dec} \rangle$.

$(\text{mpk, msk}) \leftarrow \text{Setup}(1^\lambda, \mathcal{U})$ The setup algorithm takes security parameter and attribute universe description $\mathcal{U}$ as input. It outputs the public parameters mpk and a master key msk.

$CT \leftarrow \text{Enc}(\text{mpk}, M, \mathcal{A})$ The encryption algorithm takes as input the public parameters mpk, a message $M$, and an access structure $\mathcal{A}$ over the universe of attributes. The algorithm will encrypt $M$ and produce a ciphertext CT such that only a user that possesses a set of attributes that satisfies the access structure will be able to decrypt the message. We will assume that the ciphertext implicitly contains $\mathcal{A}$.

$\text{sk} \leftarrow \text{KeyGen}(\text{msk}, S)$ The key generation algorithm takes as input the master key msk and a set of attributes $S$ that describe the key. It outputs a private key sk.

$M \leftarrow \text{Dec}(\text{mpk}, CT, \text{sk})$ The decryption algorithm takes as input the public parameters mpk, a ciphertext CT, which contains an access policy $\mathcal{A}$, and a private key SK, which is a private key for a set $S$ of attributes. If the set $S$ of attributes satisfies the access structure $\mathcal{A}$ then the algorithm will decrypt the ciphertext and return a message $M$.

An KP-ABE scheme consists of four algorithms:

$(\text{mpk, msk}) \leftarrow \text{Setup}(1^\lambda)$ This is a randomized algorithm that takes no input other than the implicit security parameter. It outputs the public parameters mpk and a master key msk.

$C \leftarrow \text{Enc}(m, \mathcal{A}, \text{mpk})$ This is a randomized algorithm that takes as input a message $m$, a set of attributes $\mathcal{A}$, and the public parameters mpk. It outputs the ciphertext C.

$\text{sk} \leftarrow \text{KeyGen}(A, \text{mpk, msk})$ This is a randomized algorithm that takes as input – an access structure $A$, the master key msk and the public parameters mpk. It outputs a decryption key sk.
This algorithm takes as input – the ciphertext C that was encrypted under the set A of attributes, the decryption key sk for access control structure A and the public parameters mpk. It outputs the message m if \( A \in A \).

**Verifiable Computation (VC)** VC [9] schemes enable a weak data user (internal user) to outsource the computation of a function \( f \) on various inputs to a computationally strong but untrusted cloud, which allows the data user to check the integrity of the computation. Most verifiable computation constructions are based on probabilistically checkable proofs (or PCPs) [4]. A great survey of practical verifiable computation implementations is given in [118]. VC is used which is integrated as follows: A computationally weak data user outsource the storage of many data items to a computationally strong but untrusted prover (or cloud server). Each data item is labeled with a string \( L_i \). The data user wishes to compute on some subset of D’s data a function \( f \), and delegates this task to the cloud server.

Given an input: \( d_1, \ldots, d_k \) and a function \( f \) to evaluate on \( d_1, \ldots, d_k \), the cloud server is expected to produce an output \( y \), along with proof \( \sigma \) that \( y = f(d_1, \ldots, d_k) \) that the data user can use to confirm the correctness of the computation as shown in Fig. 3.

**Proxy re-encryption (PRE)** PRE provides right delegation and confidentiality of shared data. Encryption scheme such as IBE and ABE does not allow the update of ciphertext recipient. PRE, initially introduced by Blaze[17], Bleumer and Strauss [18] in 1998 and improved by Ateniese et al. [7, 71] in 2006, enables a proxy to transform a encrypted data stored on a cloud storage system under the public key of data user (or delegator) into another encrypted data under the public key of data user (or delegatee) without leaking the underlying encrypted data or private keys of delegator/delegatee to the proxy. This form of public key encryption is the best candidate to ensure the security of sharing data in cloud computing. PRE could be combined with IBE, which yields Identity-Based Proxy Re-Encryption IBEPRE, where ciphertexts are transformed from one identity to another [72]. Proxy re-encryption consists of the following algorithms:

\[
\begin{align*}
(pk, sk) &\leftarrow \text{KeyGen}(1^\lambda) \quad \text{On input the security parameter } 1^\lambda, \text{ the key generation algorithm KeyGen outputs a key pair } (pk, sk). \\
rk_{pk_{\rightarrow}pk'} &\leftarrow \text{ReKeyGen}(pk_{\rightarrow}sk, pk') \quad \text{On input a private key } sk \text{ of a delegator and a public key of a delegatee } pk, \text{ algorithm ReKeyGen outputs a unidirectional re-encryption key } rk_{pk_{\rightarrow}pk'}. \\
c &\leftarrow \text{Enc}(pk, m) \quad \text{On input a public key } pk \text{ and a message } m, \text{ algorithm Enc outputs a ciphertext } c. \\
c' &\leftarrow \text{ReEnc}(rk_{pk_{\rightarrow}pk'}, c) \quad \text{On input a re-encryption key } rk_{pk_{\rightarrow}pk'} \text{ and a ciphertext } c', \text{ algorithm ReEnc outputs a ciphertext } c' \text{ decryptable under the secret key } sk'. \\
m &\leftarrow \text{Dec}(sk, pk, c) \quad \text{On input a secret key } sk, \text{ a public key } pk \text{ and a ciphertext } c', \text{ algorithm Dec outputs a message } m \text{ or the error symbol } \bot.
\end{align*}
\]
Proxy Re-Signature

Proxy re-signatures [18] should not be confused with the proxy signatures [74, 92] which definition is given in Dodis et al. [74]. In their general construction, Bob’s signature is considered as a double signature which includes a signature from Alice and one from the proxy. There is clearly no key transformation from valid Alice’s singing secret key into Bob’s ones. In a proxy re-signature scheme, a semi-trusted proxy is given some information which allows it to transform data user’s signature on a data D into data user’s on data D.

A proxy re-signature scheme is a tuple of (possibly probabilistic) polynomial time algorithms PS = (KeyGen, ReKey, Sign, ReSign, Verify), where: (KeyGen, Sign, Verify) form the standard key generation, signing, and verification of DS algorithms as in DS.

\[
\begin{align*}
&rk_{A \rightarrow A} \leftarrow \text{ReKey} \ \text{On input} \ (pk_A, sk \ast A, pk_B, sk_B), \text{the re-encryption key generation algorithm,} \\
&\text{ReKey, outputs a key} \ rk_{A \rightarrow A} \text{for the proxy. (Note:} \ rk_{A \rightarrow A} \text{allows to transform} \ A's \text{signatures into} \ B's \text{signatures} – \text{thus} \ B \text{is the delegator.) The input marked with a } \ast \text{ is optional.} \\
&s_{B}(m) \leftarrow \text{ReSign} \ \text{On input} \ r_{k_{A \rightarrow A}}^{}, \text{a public key} \ pk_A, \text{a signature} \ \sigma, \text{and a message} \ m, \text{the} \ \text{re-signature function, ReSign, outputs} \ s_{B}(m) \text{if Verify}(pk_A, m, \sigma) \text{ and} \perp \text{otherwise.}
\end{align*}
\]

Searchable Symmetric Encryption (SSE) SSE [40] aims to provide confidentiality and searchability simultaneously. The data user can delegate a token for a specific query, which allows the server to perform the query over encrypted data. One approach to provisioning symmetric encryption with search capabilities is with a so-called secure index as shown by Goh in [66]. The client indexes and encrypts its data collection and sends the secure index together with the encrypted data to the server. To search for a keyword w, the data user generates and sends a trapdoor for w which the server uses to run the search operation and recover pointers to the appropriate (encrypted) data [41]. Alternatively, using oblivious RAMs techniques symmetric searchable encryption can be achieved in its full generality (e.g., conjunctions or disjunctions of keywords) with optimal security using the work of Ostrovsky and Goldreich on oblivious RAMs [68, 97]. We assume that the client processes the data collection \( D = \{D_1, \ldots, D_n\} \) and sets up a "database" DB that maps every keyword w in the collection to the identifiers of the documents that contain it. Recall that in our context, we use the term database loosely to refer to a data structure optimized for keyword search (i.e., a search structure). For a keyword w, we’ll write DB[w] to refer to the list of identifiers of documents that contain w. A non-interactive and response-revealing SSE scheme (Setup, Token, Search) consists of:

\[
\begin{align*}
&(sk, EDB) \leftarrow \text{Setup}(1^\lambda, DB) \text{ a Setup algorithm run by the client that takes as input a security} \\
&\text{parameter} \ 1^\lambda \text{ and a database DB}; \text{ it returns a secret key} sk \text{ and an encrypted database EDB;} \\
&tk \leftarrow \text{Token}(sk, w) \text{ a Token algorithm also run by the client that takes as input a secret key} \\
&\text{sk and a keyword} w; \text{ it returns a token} tk; \\
&DB[w] \leftarrow \text{Search}(EDB, tk) \text{ a Search algorithm run by the server that takes as input an} \\
&\text{encrypted database EDB and a token} tk; \text{ it returns a set of identifiers} DB[w].
\end{align*}
\]

Public Key Encryption with Keyword Search (PEKS) PEKS was introduced in 2004 by Boneh et al. [20], mainly based on public key encryption algorithms, enables a data sharee to retrieve encrypted data containing some specific keyword from the centralized server.

A data sharee encrypts both their data and index with the public key and uploads to the remote server provider. A data sharee who has received the corresponding private key can perform the search operation. He generates the trapdoor he wants to search the keyword with the private key and sends it to the server. After receiving trapdoor, the server provider enable test whether a given ciphertext contains the search keyword without knowing the corresponding plaintext of the encrypted data and the keyword. Then, the server provider returns the query results to the data sharee. Finally, the sharee can decrypt the encrypted data sent by the server.

A PEKS scheme consists of the following algorithms: (KeyGen, PEKS, Trapdoor, Test):
(pk_R, sk_R) ← KeyGen(s) takes a security parameter, s, and generates a public/private key pair (pk_R, sk_R).

(pk_R, W) ← PEKS(pk_R, W) : for a public key pk_R and a word W, produces a searchable encryption of W.

T_W ← Trapdoor(sk_R, W) given Receiver’s private key and a word W produces a trapdoor T_W.

(0, 1) ← Test(pk_R, S, T_W) given Receiver’s public key, a searchable encryption S = PEKS(pk_R, W_0), and a trapdoor T_W = Trapdoor(sk_R, W), outputs 1 if W = W_0 and 0 otherwise.

**Secure Multi Party Computation (SMPC)** SMPC introduced by Yao in 1982 [124], is a ‘toolbox’ of cryptographic techniques that allows several different data sharers to jointly analyze data, just as if they have a shared database without violating their underlying sensitive data privacy and only the output of the analysis will be revealed. The concept of MPC is presented a story about two millionaire’s problem to lead to SMPC processing: two millionaires want to know who is the wealthiest one, while they don’t want to reveal individual wealth to another. However, only some simple functions can be carried out, and complex functions are very demanding in terms of efficiency. Yao [124] presented the first two-party protocol for computing functions represented as boolean circuits using a technique called garbled circuits. Later, Goldreich, Micali, and Wigderson [67] made two contributions: First, they introduced the first multi-party protocol, also for boolean circuits, with computational security against a semi-honest adversary, and second a general compiler for transforming any protocol with semi-honest security to one with malicious security. Ben-Or et al and Chaum et al in [14, 30]. More formally, SMPC is stated as follows: Given number of data users: O_1, · · · , O_n, each have private data, respectively D_1, · · · , D_n. Data users want to compute jointly a public function F on their private data: F(D_1, · · · , D_n) while keeping that private data secret. For example, suppose we have three data users Alice, Bob and Charlie, with respective inputs x, y and z denoting their own personal wealth. They want to find out the wealthiest, without revealing to each other how much each of them has as shown in Fig. 4. Mathematically, this translates to them computing:

\[ F(x, y, z) = \max(x, y, z) \]

**Private Set Intersection (PSI)** PSI [33] is a powerful tool from SMPC cryptographic technique that allows two data sharers holding sets, to compare encrypted versions of these sets in order to compute the intersection. For example, PSI allows to test whether the parties share a common datapoint (such as a location, ID, etc). Many PSI protocols have been proposed. For example, in [47]they proposed a protocol based on a novel two-party computation approach which gives better a reasonable efficiency and scalability. Among the first protocols for PSI was [55] which is based on Oblivious Polynomial evaluation (OPE), however it requires heavy cost in
terms of computational complexity. Later, \( PSI \) protocol with reasonable linear computation and communication complexity was introduced in [94] by using the Diffie-Hellman protocol (DH). The most recent and most efficient \( PSI \) protocols are based on either using efficient OT extension and garbled Bloom filters or hashing to bins. Existing \( PSI \) protocols are compared in [100]. PSI

Suppose we have two parties: Alice and Bob such that Alice has a set of items: \( A = (a_1, \ldots, a_n) \) and Bob has another set: \( B = (b_1, \ldots, b_n) \). The goal of \( PSI \) is to allow Alice and Bob to obtain the result of the intersection \( A \cap B \), under the following privacy restriction: The protocol must not reveal anything about items without revealing any additional information beyond the intersection itself. The server-client \( PSI \) variant is user, the EXT user will learn the intersection of his encrypted set with the set of the cloud, without the cloud learning intersection of his set with the client as shown in Fig. 5.

![Fig. 5. Server-client PSI](image)

**Storage path encryption** Recently Cheng et al. [34] proposed a scheme for secure storage of big data on clouds. In the proposed scheme, the big data are first separated into many sequenced parts and then each part is stored on a different storage media owned by different cloud storage providers. To access to the data, different parts are first collected together from different data centres and then restored into original form before it is presented to the data user. Storage path encryption Data will be first separated into a sequence of \( n \) parts and then each part will be stored at \( m \) different storage providers. To retrieve the data, different parts are first collected together from different data centres and then restored into original data before sending it to the data user.

**Oblivious RAM (ORAM)** This technique was introduced by Goldreich and Ostrovsky [98], which enables a data sharer to store data on a cloud server and read/write to individuals locations of the data while hiding the access pattern. The security of ORAM is based on the fact that for any two values \( M_1, M_2 \) and equal-size sequences of read/write operations: \( S_1, S_2 \), the server cannot distinguish between ORAM execution with \( (M_1, S_1) \) and \( (M_2, S_2) \). ORAM A client \( C \) wants to perform read and write operations on a large database residing on a remote, untrusted server \( S \). The database is encrypted with a symmetric key owned by \( C \). Whenever \( C \) wants to perform an operation on the database, it does the following: \( C \) sends a request to \( S \) to download the whole database. Then, \( C \) decrypts the whole database, performs the operation on the desired element, then re-encrypts the database (with the same key). Finally, \( C \) re-uploads the re-encrypted whole database to \( S \).

**Proof of Data Possession (PDP)** PDP [5] is a cryptographic protocol the provide data integrity verification in remote untrusted servers. Client periodically challenges the server to ask relevant evidence that can prove the data exists, then client will compare the relevant with local evidence to verify the integrity of data. PDP supports probabilistic proof, which means client does not need to challenge and compare all evidence corresponding to the data. This property significantly reduces the computation and communication cost during the protocol procedure. Other variants of PDP [6] [42] [53] are also introduced later for improving efficiency, scalability, supporting multiple-replicas and file updated.
Consider we have a client who owns the data $m$ and wants to store the data on server. The definition of general PDP as follows:

$$\text{(pk, sk)} \leftarrow \text{KeyGen}(\lambda)$$

is a probabilistic key generation algorithm run by the client to setup the scheme. It takes a security parameter $k$ as input, and returns a key pair of public and secret key $(\text{pk}, \text{sk})$. $T_m \leftarrow \text{TagBlock}(\text{pk}, \text{sk}, m)$ is a algorithm run by the client to generate the verification metadata. It takes as inputs a public key pk, a secret key sk and a file block $m$, and returns the verification metadata $T_m$.

$\mathcal{V} \leftarrow \text{GenProof}(\text{pk}, \mathcal{F}, \mathcal{c}, \Sigma)$ is run by the server to generate a proof of data possession. It takes a public key pk as input, an ordered collection $\mathcal{F}$ of blocks, a challenge $\mathcal{c}$ and an ordered collection $\Sigma$ which is the verification metadata corresponding to the blocks in $\mathcal{F}$. It returns a proof of data possession $\mathcal{V}$ for the blocks in $\mathcal{F}$ that are determined by the challenge $\mathcal{c}$.

$\{1, 0\} \leftarrow \text{CheckProof}(\text{pk}, \text{sk}, \mathcal{c}, \mathcal{V})$ is run by the client to verify the proof of possession. It takes as inputs a public key pk, a secret key sk, a challenge $\mathcal{c}$ and a proof of possession $\mathcal{V}$. It returns whether $\mathcal{V}$ is a correct proof of possession for the blocks.

**Homomorphic Encryption (HE).** Due to cost-efficiency reasons, data sharers are usually outsourcing their own data to server which can provide access to the data as a service, HE which introduced firstly by Rivest et al. [106] whose main benefit is that for some operations can be allowed over the data user’s encrypted data without decrypting it, which allows to produce result that is still encrypted but when decrypted by the user it matches exactly the result that would be obtained if the same computational operations had been performed on the user’s raw data as opposed to the uploaded encrypted data.

One of the most common scenarios where HE can be used is in outsourced computations: a data sharer sends encrypted data to a server and asks this latter to evaluate a function $F$ on this encrypted data. The inputs and outputs of the computation are encrypted with the client’s secret/public key and the server manipulates only encrypted data.

HE schemes can be roughly classified into 3 following types:

- Somewhat Homomorphic Encryption (SHE): In SHE scheme, both addition and multiplication operation is allowed but with only a limited number of times.
- Fully Homomorphic Encryption (FHE): In FHE scheme, allow to do unlimited number of homomorphic operations by bootstrapping [59].
- Partially Homomorphic Encryption (PHE): In PHE scheme, are in general more efficient than SHE and FHE, mainly because only one type of homomorphic operation is allowed on the encrypted message, i.e., either addition or multiplication operation, with unlimited number of times.

Early homomorphic cryptosystems such as RSA [106], El Gamal [52], and Paillier [99] can only support a single operation on ciphertexts such as addition, multiplication, or XOR and are called partially homomorphic. New cryptographic solutions for computation outsourcing became possible after Gentry’s discovery of the first viable FHE, which solved a long-standing major problem in cryptography and theoretical computer science [59]. The first plausible and achievable FHE scheme, was introduced in 2009 in the seminal work of Gentry [60], which which allows any computable function (both additions and multiplications) to perform on the encrypted data. Gentry split the FHE problem into two components: the design of a somewhat homomorphic encryption scheme ($SWHE$) that allows a limited number of Eval operations, which allows fully homomorphic encryption using a bootstrapping algorithm and the multiple application of $SWHE$. The initial scheme was implemented by Gentry and Halevi [61].
Unlike the public key encryption, which has three security procedures, i.e., key generation, encryption and decryption; there are four procedures in \( \mathcal{HE} \) scheme, including the evaluation algorithm.

The notation \( \mathcal{E}(x) \) is used to denote the encryption of the message \( x \).

Let \( \mathcal{E}(m_1) = m_1^e \) and \( \mathcal{E}(m_2) = m_2^e \).

Then, Addition Homomorphism:

\[
\mathcal{E}(m_1) + \mathcal{E}(m_2) = m_1^e + m_2^e = (m_1 + m_2)^e = \mathcal{E}(m_1 + m_2)
\]

Multiplication Homomorphism:

\[
\mathcal{E}(m_1) \cdot \mathcal{E}(m_2) = m_1^e \cdot m_2^e = (m_1 \cdot m_2)^e = \mathcal{E}(m_1 \cdot m_2)
\]

More formally, Let the message space \( (M, o) \) be a finite (semi-)group, and let \( k \) be the security parameter a \( \mathcal{HE} \) on \( M \) is a quadruple \( (\text{KeyGen}, \text{Enc}, \text{Dec}, A) \) of probabilistic, expected polynomial time algorithms, satisfying the following functionalities:

\[
\begin{align*}
&k \leftarrow \text{KeyGen}(1^\lambda) \text{ On input } 1^\lambda \text{ the Key Generation algorithm KeyGen outputs an encryption/decryption key pair } k = (k_e, k_d) = k \in K, \text{ where } K \text{ denotes the key space.} \\
c \leftarrow \text{Enc}(1^\lambda, k_e, m) \text{ On inputs } 1^\lambda, k_e, \text{ and an element } m \in M \text{ the encryption algorithm E outputs a ciphertext } c \in C, \text{ where C denotes the ciphertext space.} \\
m \leftarrow \text{Dec}(c, 1^\lambda, k) \text{ The decryption algorithm Dec is deterministic. On inputs security parameter,k and an element } c \in C \text{ it outputs an element in the message space } M \text{ so that for all } m \in M \text{ it holds: if } c = \text{Enc}(1^\lambda, k_e, m) \text{ then } \Pr[\text{Dec}(1^\lambda, k, c) \neq m] \text{ is negligible, i.e., it holds that } \Pr[\text{Dec}(1^\lambda, k, c) \neq m] < 2 - k. \\
\end{align*}
\]

Homomorphic Property: \( A \) is an algorithm that on inputs \( 1^\lambda, k_e, \) and elements \( (c_1, c_2) \in C \) outputs an element \( c_3 \in C \) so that for all \( m_1, m_2 \in M \) it holds: if \( m_3 = m_1 \circ m_2 \) and \( c_1 = \text{Enc}(1^\lambda, k_e, m_1), \) and \( c_2 = \text{Enc}(1^\lambda, k_e, m_2), \) then \( \Pr[\text{Dec}(A(1^\lambda, k_e, c_1, c_2)) \neq m_3] \) is negligible.

The security of the most practical \( \mathcal{HE} \) schemes is based on the Ring-Learning With Errors (RLWE) problem, which is a hard mathematical problem related to high-dimensional lattices. Namely, the security assumption of these encryption schemes states that if the scheme can be broken efficiently, then the RLWE problem can be solved efficiently.

**Functional Encryption (\( \mathcal{FE} \)).** \( \mathcal{FE} \) is a public key construction, on which it is possible to produce functional secret keys allowing a party to evaluate a specific function \( \mathcal{F} \) (generally public) on an encrypted input during its decryption. So the input is encrypted and the output is in cleartext: the party performing the (functional) decryption learns the result of the function on the specific data, but nothing else. A \( \mathcal{FE} \) scheme enables a data sharer to encrypt a data set and share the ciphertexts to a data sharee such that the data sharee can obtain a (specific) function value of the data set from the ciphertexts, but nothing more about the data set itself. \( \mathcal{FE} \) has been properly formalized in 2011 by Boneh, Sahai and Waters in [23]. Nowadays, there are no known \( \mathcal{FE} \) schemes that can be used to efficiently evaluate general functions. However, the literature proposes multiple efficient constructions to evaluate linear and quadratic functions.

A \( \mathcal{FE} \) for a functionality \( \mathcal{F} \) defined over a tuple of four PPT algorithms \( (\text{Setup}, \text{KeyGen}, \text{Enc}, \text{Dec}) \) defined as follows:

\[
\begin{align*}
&(\text{mpk, msk}) \leftarrow \text{Setup}(1^\lambda) \text{ On input } 1^\lambda \text{ generate a public mpk and master secret msk key pair.} \\
&\text{sk} \leftarrow \text{KeyGen}(\text{mpk}, k) \text{ On input mpk and k generate secret key for k.} \\
c \leftarrow \text{Enc}(\text{mpk}, x) \text{ Encrypt message } x. \\
y \leftarrow \text{Dec}(\text{msk}, c) \text{ On inputs msk to compute } \mathcal{F}(k, x) \text{ from c.}
\end{align*}
\]
Attribute-Based Homomorphic Encryption (ABHE). The first ABHE was constructed by Gentry et al. in [63] from the Learning with Errors (LWE) problem.

ABHE a data sharer describes a policy (predicates) while encrypting his data, and a trusted party issues a decryption key for the attributes and distributes them among data sharees. A data sharee can decrypt this ciphertext if his attributes satisfy data user’s defined policy.

The only known way to achieve fully ABHE (i.e. where all circuits can be evaluated) is through indistinguishability obfuscation [57], especially the construction in [38].

An ABHE scheme is a tuple of probabilistic polynomial time (PPT) algorithms ABHE = (Setup, KeyGen, Encrypt, Decrpt, Eval) where Setup, KeyGen, Encrypt are defined equivalently to KP-ABE[2.3]. m ← Dec(k_{\bar{f}_1}, \ldots, k_{\bar{f}_k}, c): On input a sequence of k ≤ K secret keys for policies f_1, \ldots, f_k ∈ \mathcal{F} and a ciphertext c, output a plaintext m ∈ M iff every attribute associated with c is satisfied by at least one of the f_i. Otherwise output ⊥.

c′ ← Eval(pp, C, c_1, \ldots, c_l): On input public parameters pp, a circuit C ∈ \mathcal{C} and ciphertexts c_1, \ldots, c_l ∈ \mathcal{C}, output an evaluated ciphertext C′ ∈ \mathcal{C}.

Private Information Retrieval (PIR). PIR is a protocol that allows a user to retrieve an item from a server in possession of a database without revealing which item is retrieved, which is very useful in the cloud outsourcing context. PIR is a weaker version of 1-out-of-n oblivious transfer, where it is also required that the user should not get information about other database items. An important goal in PIR works is to reduce the amount of communication required between the server and the querier. Chor et al. [35] introduced the first PIR scheme in an information-theoretic model with multiple non-colluding servers. Shortly thereafter, several works provided PIR under the assumption that certain cryptographic problems are hard [25, 62, 82].

More formally, a PIR is an interactive protocol between two parties: a database D and a user U. The database stores a data string \{0, 1\}^n, and the user has an index i ∈ [n]. In the first round, the protocol does the following (a) the user sends a query to the database, this is generated by an efficient randomized query algorithm, taking as an input the index i and a random string r_U; (b) The database sends an answer to the user; this is generated by an efficient deterministic answer algorithm, taking as an input the query sent by the user and the database x; and (c) The user applies an efficient reconstruction function (taking as an input the index i, the random string r_U, and the answer sent by the database).

3 PRIVACY IN BDS
In recent years, with the increase in data demand and the development of significant data sharing and the CIA’s requirements, the concept of Privacy has become a new indispensable requirement. The privacy concerns discussed in this article are mainly divided into two aspects: data privacy and user privacy which are defined in Section 1.

In this section, first, we discuss the data privacy requirements of BDS, each of such requirements is targeted at one type of known vulnerabilities. Second, we describe the basic (and inherent) privacy-preserving techniques. Finally, we discuss techniques to achieve user privacy, which is desired by many BDS applications.

3.1 Data Privacy requirements in BDS.
Data Privacy is one of the most important concept of our time, yet it is also one of the most very hard to achieve. Privacy Preserving Data Publishing (PPDP), is the process through which we provide methods and tools for publishing useful information while preserving data privacy. Recently, PPDP has been given a considerable object of attention among researchers [56, 90, 103]. To achieve PPDP, first the data sharer collects data from individuals. Then, the data sharer prepares the data
to be processed and anonymized. Finally, the processed/anonymized data is sent to the data sharee for further analysis or research purposes. The original data are assumed to be sensitive and private if it contains the following four attributes:

- **Identifier (ID):** The attributes which can be used to uniquely identify a person e.g., name, driving license number, and mobile number etc.
- **Quasi-identifier (QID):** The attributes that cannot uniquely identify a record by themselves but if linked with some external dataset may be able to re-identify the records.
- **Sensitive attribute (SA):** The attributes that a person may want to conceal e.g., salary and disease.
- **Non-sensitive attribute (NSA):** Non-sensitive attributes are attributes which if disclosed will not violate the privacy of the user. All attributes other than identifier, quasi-identifier and sensitive attributes are classified as non-sensitive attributes.

Below, we discuss the three types of data privacy requirements in BDS, which we define as follows:

**Data Privacy during Downloading.** It deals with what someone does once he have obtained the data containing sensitive information. Actions include the following: (1) Aggregation: where data is combined, (2) identification: where data is connected to an individual, (3) secondary use: where data is used for a reason other than was intended, (4) exclusion: where data isn’t revealed to the person it was collected from, (5) insecurity: where data is leaked. The publishing procedures on big data should not contain sensitive information of individuals.

**Data Privacy during Computation.** Some operations can be run over encrypted data, e.g. a number of databases around the world currently host a wealth of genomic data that is very useful to researchers conducting a variety of genomic studies. However, patients who volunteer their genomic data face the risk of privacy invasion. The computation procedures and results either through data outsourcing or data sharing on BDS should not contain any sensitive information of individuals.

**Data Privacy during Searching** Searching over encrypted data is required in many scenarios, e.g., users want to query any data on an untrusted BDS platform without revealing sensitive information of the queried data. The queried data can be either public or anonymous, but the service platform should not identify its specific content. Furthermore, the search results on big data should not contain any sensitive information of individuals.

In Table 3 we summarize the set of privacy concerns that need to be addressed by the techniques described in Section 3.2.

We have three main groups of privacy preservation techniques: cryptographic tools, **Format-Preserving Encryption**, **Differential Privacy (DP)** and **K-anonymity** (with further enhanced version like **L-diversity** and **T-closeness**) that we present in the next section.

### Table 3. Summumization of existing privacy-preserving techniques for BDS

| Data Privacy Requirements | Privacy-preserving Techniques |
|---------------------------|-------------------------------|
| Data Privacy During Downloading | K-anonymity, L-diversity, and T-closeness |
| Data Privacy During Computation | HE, MPC, DP, FPE |
| Data Privacy During Searching | ORAM, PEKS, SSE for various search, e.g., keyword, range, boolean, and KNN |
### 3.2 Data Privacy Techniques

In this section, we present a comprehensive overview on recent anonymization techniques used for PPDP. Specifically, our review explains anonymization approaches related to the individual privacy protection.

**Format-Preserving Encryption (FPE)**. FPE [10] is designed to encrypt data of some specified format into a ciphertext of identical format, such as the format of equal length as the original data. FPE can be constructed based on symmetric encryption and other formats also be developed, such as date-time [88] and character [84].

The FPE scheme is $E_{K}^{N,T}$ on $X_{N}$ where $E$ is the encryption algorithm, $K$ is the encryption key, \{X_{N}\}_{N\in N}$ is the collection of domains. $X_{N}$ is a slice that $X = \bigcup_{N} X_{N}$. $N$ is the format space. $T$ is the tweak.

**Differential Privacy (DP)**. Another important privacy-preserving model is Differential Privacy (DP) [43, 49, 93]. It is considered as equivalent to perturbing the original data and then computing the queries over that modified data. An algorithm is said to be differentially private if by looking at the output, one cannot tell whether any individual’s data was included in the original dataset or not. It consists on introducing a certain amount of random noise to data queries such that any statistical analysis over the whole set is significantly close to the real results, but inference over any data is infeasible.

In DP analyst are not provided the direct access to the database containing personal information but an intermediary software is allowed between the database and the analyst to protect the privacy. Currently, DP is becoming a practical privacy-preserving technique and applied in various application scenarios [73, 123, 125].

Consider we have two databases $D_{1}$ and $D_{2}$ differ in at most one element. The general of requirement [48] of DP can be:

$$\Pr [\mathcal{K}(D_{1}) \in S] \leq \exp(\varepsilon) \times \Pr [\mathcal{K}(D_{2}) \in S]$$

Where $\mathcal{K}$ is the algorithm applied by the curator when releasing information. The output of it is transcript. If it satisfies the requirement, we say that $\mathcal{K}$ gives $\varepsilon$-differential privacy if for all data sets $D_{1}$ and $D_{2}$ differing on at most one element, and all $S \subseteq \text{Range } (\mathcal{K})$.

**K-anonymity**. The k-anonymity [51, 83, 95, 115] property is satisfied in a release of dataset if individuals information contained in this release cannot be distinguished from at least $k-1$ individuals in this dataset release.

To achieve K-anonymity, it is required to have at least $k$ individuals in the dataset who share the set of attributes that might become identifying for each individual. However, k-anonymity prevents identity disclosure but not attribute disclosure. If there is no diversity in the values of the sensitive attributes, an attacker can easily discover the sensitive value of an data through a homogeneity attack. In fact, there are two enhancements of k-anonymity:

The definition of K-anonymity is divided into three parts:

1. **Attributes**. Let $B (A_{1}, \ldots, A_{n})$ be a table with a finite number of tuples. The finite set of attributes of $B$ are $\{A_{1}, \ldots, A_{n}\}$

2. **Quasi-identifier**. Given a population of entities $U$, an entity-specific table $T (A_{1}, \ldots, A_{n})$, $f_{c}: U \rightarrow T$ and $f_{i}: T \rightarrow U'$, where $U \subseteq U'$. A quasi-identifier of $T$, written $Q_{T}$, is a set of attributes $\{A_{1}, \ldots, A_{n}\} \subseteq \{A_{1}, \ldots, A_{n}\}$ where: $\exists p_{i} \in U$ such that $f_{i} (f_{c} (p_{i}) [Q_{T}]) = p_{i}$

3. **K-anonymity**. Let $RT (A_{1}, \ldots, A_{n})$ be a table and $Q_{RT}$ be the quasi-identifier associated with it. $RT$ is said to satisfy $k$-anonymity if and only if each sequence of values in $RT [Q_{RT}]$ appears with at least $k$ occurrences in $RT [Q_{RT}]$
**L-diversity.** The L-diversity model is an extension of the k-anonymity model which reduces the granularity of data representation using techniques including generalization and suppression such that any given record maps onto at least k-1 other records in the data. An equivalence class is said to have l-diversity if there are at least l “well-represented” values for the sensitive attribute. A table is said to have l-diversity if every equivalence class of the table has l-diversity [89, 122]. Compared with k-anonymity, l-diversity can prevent Homogeneity Attack and Background Knowledge Attack. Meanwhile, it also enable more applications in the early like [87].

L-diversity extends the concept of k-anonymity. Besides the three definition from it, L-diversity has the definitions:

- **Domain Generalization:** A domain \( D^* = \{P_1, P_2, \ldots \} \) is a generalization (partition) of a domain \( D \) if \( \cup P_i = D \) and \( P_i \cap P_j = \emptyset \) whenever \( i \neq j \). For \( x \in D \) we let \( \phi_D^*(x) \) denote the element \( P \in D^* \) that contains \( x \).
- **Lack of Diversity.** Lack of diversity in the sensitive attribute manifests itself as follows:
  \[
  \forall s' \neq s, \quad n_{(q^*, s')} \ll n_{(q^*, s)}
  \]
- **L-diversity.** A \( q^* \)-block is L-diverse if it contains at least L well-represented values for the sensitive attribute \( S \). A table is L-diverse if every \( q^* \)-block is L-diverse.

The principles of well-present are:

| Distinct \( \ell \)-diversity | The simplest understanding of "well represented" would be to ensure there are at least \( \ell \) distinct values for the sensitive attribute in each equivalence class. Distinct \( \ell \)-diversity does not prevent probabilistic inference attacks. An equivalence class may have one value appear much more frequently than other values, enabling an adversary to conclude that an entity in the equivalence class is very likely to have that value. This motivated the development of the following two stronger notions of \( \ell \)-diversity. Entropy \( \ell \)-diversity. The entropy of an equivalence class \( E \) is defined to be
  \[
  \text{Entropy}(E) = - \sum_{s \in S} p(E, s) \log p(E, s)
  \]
  A table is said to have entropy \( \ell \)-diversity if for every equivalence class \( E \), \( \text{Entropy}(E) \geq \log \ell \). Entropy \( \ell \)-diversity is strong than distinct \( \ell \)-diversity. As pointed out in [12], in order to have entropy \( \ell \)-diversity for each equivalence class, the entropy of the entire table must be at least \( \log(\ell) \). Sometimes this may too restrictive, as the entropy of the entire table may be low if a few values are very common. This leads to the following less conservative notion of \( \ell \)-diversity.

| Recursive \((c, \ell)\)-diversity | Recursive \((c, \ell)\)-diversity makes sure that the most frequent value does not appear too frequently, and the less frequent values do not appear too rarely. Let \( m \) be the number of values in an equivalence class, and \( r_i, 1 \leq i \leq m \) be the number of times that the \( i \text{th} \) most frequent sensitive value appears in an equivalence class \( E \). Then \( E \) is said to have recursive \((c, \ell)\)-diversity if \( r_1 < c (r_1 + r_{1+1} + \ldots + r_m) \). A table is said to have recursive \((c, \ell)\)-diversity if all of its equivalence classes have recursive \((c, \ell)\)-diversity. |

where \( q^* \) the quasi-identifier attribute from generalized domain.

\( S \) is the domain of the sensitive attribute.

\( p(E, s) \) is the fraction of records in \( E \) that have sensitive value \( s \).

\( n_{(q^*, s')} \) is the number of tuples \( t^* \) in the anonymized table \( T^* \) such that \( t^* [S] = s \) and \( t^* [Q^*] = q^* \).

**T-closeness.** Since L-diversity is insufficient to prevent attribute disclosure, researchers find two attack Skewness Attack and Similarity Attack and propose T-closeness model [85, 104]. An equivalence class is said to have T-closeness if the distance between the distribution of a sensitive
attribute in this class and the distribution of the attribute in the whole table is no more than a threshold $t$. A table is said to have T-closeness if all equivalence classes have T-closeness. It is regarded as a more advantageous than the first two techniques and has more general applications like data publishing [86, 114], data anonymization [46], randomization [104]. T-closeness use Earth Mover’s distance (EMD) to measure the distance between the distribution of a sensitive attribute:

$$D[P, Q] = \text{WORK}(P, Q, F) = \sum_{i=1}^{m} \sum_{j=1}^{m} d_{ij} f_{ij}$$

Then we have two conclusion:

1. If we have $0 \leq d_{ij} \leq 1$ for all $i, j$, then $0 \leq D[P, Q] \leq 1$. It means that if the ground distances are normalized, i.e., all distances are between 0 and 1, then the EMD between any two distributions is between 0 and 1. This gives a range from which one can choose the $t$ value for $t$-closeness.

2. Given two equivalence classes $E_1$ and $E_2$, let $P_1$, $P_2$, and $P$ be the distribution of a sensitive attribute in $E_1$, $E_2$, and $E_1 \cup E_2$, respectively. Then

$$D[P, Q] \leq \frac{|E_1|}{|E_1| + |E_2|} D[P_1, Q] + \frac{|E_2|}{|E_1| + |E_2|} D[P_2, Q]$$

It follows that $D[P, Q] \leq \max (D[P_1, Q], D[P_2, Q])$. This means that when merging two equivalence classes, the maximum distance of any equivalence class from the overall distribution can never increase. Thus T-closeness is achievable for any $t \geq 0$.

The above fact entails that T-closeness with EMD satisfies the following two requirements.

**Generalization Property**. Let $\mathcal{T}$ be a table, and let $A$ and $B$ be two generalizations on $\mathcal{T}$ such that $A$ is more general than $B$. If $\mathcal{T}$ satisfies T-closeness using $B$, then $\mathcal{T}$ also satisfies T-closeness using $A$.

**Subset Property**. Let $\mathcal{T}$ be a table and let $C$ be a set of attributes in $\mathcal{T}$. If $\mathcal{T}$ satisfies T-closeness with respect to $C$, then $\mathcal{T}$ also satisfies T-closeness with respect to any set of attributes $D$ such that $D \subseteq C$.

### 3.3 User Privacy Techniques

In this section, we provide techniques to achieve the user privacy notion, defined in Section 1. We argue that, to ensure user privacy, the BDS should be enhanced by other cryptographic techniques that we will be describe in this section.

**Group Signature**. A group signature [31] is non-interactive construction for proving that the data sharer (here the signer) of a certain big data belongs to some group without revealing its identity, which provide anonymity for a data user. In some systems these functionalities are separated and given to a membership manager and revocation manager respectively. Notably, revocable [64, 96], traceable [36], or distributed traceable [65], or fully dynamic model of [24]. Efficient constructions were proposed in [26, 32], however all of them suffer from the drawback that the size of a public group key and the signatures are proportional to the size of a group. A group signature is called dynamic, if the public group key remains unchanged when members join or leave the group or modify their key pairs. The first construction of a dynamic group signature scheme was proposed by Camenisch and Stadler [28]. Group signature was formalized with concurrent join and an efficient construction by Kiayias and Yung [81].

A group signature scheme $GS = (\text{GKg}, \text{GSig}, \text{GVf}, \text{Open})$ consists of four polynomial-time algorithms:
The randomized group key generation algorithm GKg takes input $1^k, 1^n$, where $k \in \mathbb{N}$ is the security parameter and $n \in \mathbb{N}$ is the group size (i.e., the number of members of the group), and returns a tuple $(gpk, gmsk, gsk)$, where $gpk$ is the group public key, $gmsk$ is the group manager’s secret key, and $gsk$ is an n-vector of keys with $gsk[i]$ being a secret signing key for player $i \in [n]$.

$\sigma \leftarrow \text{GSig}(gsk[i], m)$. The randomized group signing algorithm GSig takes as input a secret signing key $gsk[i]$ and a message $m$ to return a signature $\sigma$ of $m$ under $gsk[i]$ ($i \in [n]$).

$(1, 0) \leftarrow \text{GVf}(gpk, m, \sigma)$. The deterministic group signature verification algorithm GVf takes as input the group public key $gpk$, a message $m$, and a candidate signature $\sigma$ for $m$ to return either 1 or 0.

$(i, \perp) \leftarrow \text{Open}(gmsk, m, \sigma)$. The deterministic opening algorithm Open takes as input the group manager secret key $gmsk$, a message $m$, and a signature $\sigma$ of $m$ to return an identity $i$ or the symbol $\perp$ to indicate failure.

**Ring Signature.** A ring signature scheme [108] is a group signature scheme but without group manager to setup a group or revoke a signer’s identity. The formation of a group is spontaneous in the way that group members can be totally unaware of being integrated to that group. The scheme of Dodis et al. [45] was the first to achieve sublinear size signatures in the Random Oracle Model (ROM) [12].

Chow et al. and Bender et al. [15, 37] simultaneously proposed ring signatures in the standard model. Malavolta and Schroder [15] build setup free and constant size ring signatures assuming hardness of a variant of the knowledge of exponent assumption. Ring signature

A ring signature scheme is a triple $(\text{KeyGen}, \text{Sig}, \text{Ver})$.

$(x, y) \leftarrow \text{KeyGen}(1^k)$ is a probabilistic algorithm which takes security parameter $k$ and outputs private key $x$ and public key $y$.

$\sigma \leftarrow \text{Sig}(1^k, 1^n, x, L, m)$ is a probabilistic algorithm which takes security parameter $k$, group size $n$, private key $x$, a list $L$ of $n$ public keys which includes the one corresponding to $x$ and a message $m$, produces a signature $\sigma$.

$1/0 \leftarrow \text{Ver}(1^k, 1^n, L, m, \sigma)$ is a boolean algorithm which accepts as inputs security parameter $k$, group size $n$, a list $L$ of $n$ public keys, message $m$ and signature $\sigma$, returns 1 or 0 for accept or reject, respectively. We require that for any message $m$, any $(x, y) \leftarrow \text{Gen}(1^k)$ and any $L$ that includes $y$, $\text{Ver}(1^k, 1^n, L, m, \text{Sig}(1^k, 1^n, x, L, m)) = 1$.

**Attribute-based Signature (ABS).** In ABS [91], data sharer signs data with any predicate of their attributes issued from an attribute authority. ABS Let $\mathcal{U}$ be universe of possible attributes. $\Gamma$ is a claim-predicate over $\mathcal{U}$ which is a boolean function. We say that an attribute set $\vec{x} \subseteq \mathcal{U}$ satisfies $\Gamma$ if $\Gamma(\vec{x}) = 1$. An ABS scheme consists of four algorithms : Setup, KeyGen, Sign, Verif, which is parameterized by a universe of possible attributes $\mathcal{U}$ and message space $\mathcal{M}$.

$\text{msk}^* \leftarrow \text{Setup}(1^k)$ The attribute-issuing authority $\mathcal{A}$ runs this algorithm. It takes as input the security parameter $1^k$ and outputs a master secret key $\text{msk}^* = (\text{msk}, \text{msk}')$. We call $\text{msk}$ the master secret signing component and $\text{msk}'$ the master secret verification component.

$\text{sk}_x \leftarrow \text{KeyGen}(\text{msk}, \vec{x} \subseteq \mathcal{U})$ $\mathcal{A}$ runs this randomized algorithm. The KeyGen algorithm takes as input the master secret signing component $\text{msk}$ with a set of attribute $\vec{x}$. It outputs a secret key $\text{sk}_x$ corresponding to $\vec{x}$.

$\sigma \leftarrow \text{Sign}(\text{mpk}, \text{sk}_x, m \in \mathcal{M}, \Gamma)$ The signer $S$ runs this algorithm. It takes as input a message $m$, the secret key $\text{sk}_x$ where $\Gamma(\vec{x}) = 1$, outputs $\sigma$.

$(0, 1) \leftarrow \text{Verif} (\text{mpk}, m, \Gamma, \sigma)$ Outputs either $\text{Ac} = 0$ or $\text{Rej} = 1$.  

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| S&P Requirements   | S&P techniques | Advantages                                                                 | Drawbacks                                                                 |
|-------------------|----------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Confidentiality of Data | IBE           | Complete access over all resources                                        | PKG knows the secret key users Data must be downloaded and decrypted      |
|                   | ABE           | More complex access control on decryption operation than IBE             | High computation cost Data must be downloaded and decrypted               |
|                   | PRE           | Delegating decryption rights Can be deployed in IBE or ABE scheme       | Average computational overhead Data must be downloaded and decrypted       |
|                   | HE            | Securely data outsourcing sensitive data operations                      | Inefficient But SHE and PHE are usable                                   |
|                   | ABHE          | Operation on encrypted data Confidentiality Access control               | Computational overhead is very high                                       |
| Integrity         | DS            | Provides the non-repudiation                                             | Don’t prevent the replay attack Slower than MAC                         |
|                   | MAC           | Efficient Suitable for lightweight devices                               | Does not provide the non-repudiation Establishment of Shared Secret       |
|                   | PDP           | Easy and reliable test of data integrity                                 | High computation and communication cost                                   |
|                   | PS            | Delegating signing rights Provides the non-repudication                  | Unlimited signing rights to the proxy signer                              |
|                   | AE [2,3]      | Many efficient AE modes have been developed                               | Does not provide the non-repudiation                                     |
| Data Privacy during Computation | PSI          | Joint analysis on sensitive encrypted data                              | High computation and communication cost                                   |
|                   | HE            | Operation on encrypted data it outputs encrypted data                    | High computation and communication cost                                   |
|                   | FE            | Operates on encrypted data                                              | Efficient to evaluate linear and quadratic functions.                    |
|                   | MPC           | Joint analysis on sensitive raw data Does not require a centralized party | High computation and communication cost                                   |
| Secure Data Outsourcing | ORAM         | Strong level of data privacy                                             | Tends to leak information than using SHE                                  |
|                   | VC            | Provides the integrity Publicly verifiable                               | Current solutions are not fully practical                                 |
| Data Privacy during Searching | SSE          | More Efficient than using PEKS                                            | It is not suitable for multi-user data sharing scenarios                  |
|                   | PEKS          | Can be deployed in IBE and ABE                                           | Balancing between query expressiveness and efficiency                     |
| User Privacy      | Group Signature | Provides traceability                                                        | The requirement of a group manager                                       |
|                   | ABS           | Access control is based on use’s attribute                               | Credential authority to issue attribute certificates                      |
|                   | Ring Signature | More flexibility. No group manager, and the dynamics of group choice      | No anonymity-revocation property Hard to manage/coordinate between several signers |
|                   | ACS           | Provides anonymity, authentication and accountability                    | Less efficient than ABS Does not support complex predicates               |
| Data Privacy      | K-anonymity   | Easy to implement Reidentification is less when the value of k is high   | Background knowledge Attack Homogeneity attacks Long processing time       |
|                   | L-diversity   | Reduce dataset into summary form Sensitive attribute have at most same frequency | Similarity Attack Skewness Attack                                         |
|                   | T-closeness   | Prevent data from skewness attack                                        | Complex computational procedure Utility is damaged when t is very small   |
|                   | DP            | Most suitable for big data Provides strongest privacy guarantee           | Complex computational procedure data Utility is damaged when t is very small Noise and loss of information |
Anonymous Credential Systems (ACS). In ACS [27], organizations know the users only by pseudonyms. Different pseudonyms of the same user cannot be linked. Yet, an organization issues a credential to a user whom he knows by a pseudonym. The corresponding user (under certain pseudonym) can prove to any other organizations that he is the owner of his credential without revealing anything more than the fact that that user owns such a credential.

A basic anonymous credential system consists of three entities: Users, an Authority, and Verifiers. An anonymous credential system has three procedures: KeyGen, Credential Issuing Protocol and Credential Proving Protocol, as follows:

KeyGen is run by Authority, given security parameter $1^k$, outputs a pair of public key and secret-key: $(pk, sk)$.

Credential Issuing Protocol is run by user $U$, on $m$ that $U$ wants to obtain a certificate for. Examples of $m$ are properties such as "belongs to some University", "is over the age of 20." or rights such as "can access the secure room". How Auth detects whether $m$ is valid or not with regard to $U$ is outside this protocol. $U$ executes the credential issuing protocol for $m$ with Auth by using $U$'s input $m$ and Auth's $sk$s. At the end of the protocol, $U$ obtains a credential $Cred$, corresponding to $m$.

Credential Proving Protocol After $U$ obtains the credential of $m$, $U$ executes the credential proving protocol of $m$ with a verifier $V$, that proves $U$’s possession of $Cred$. At the end of the protocol, $V$ outputs accept if $U$ really has a valid $Cred$, otherwise outputs reject.

4 COMPARISON OF EXISTING SECURITY & PRIVACY TECHNIQUES

This section presents a comparison of existing security and privacy techniques for BDS that we will classify on the basis of fulfilled security and privacy requirements, their advantages and drawbacks as shown in Table 4. To achieve security and privacy in a complex BDS system that needs to meet multiple security and privacy requirements with desired features, we would like to mention the following three notes: (1) No single techniques is a a universal remedy for security and privacy of BDS. Therefore, the appropriate security and privacy techniques (or a combination of them) should be chosen with respect to the security and privacy requirements and the context of BDS application. (2) There is no technique that has no side effects or is perfect in all aspects. When we add a new technique to such complex system, it usually raises new types of attacks or problems. (3) There is always a trade-off between security, privacy and efficiency to make.

5 CHALLENGING ISSUES & FUTURE DIRECTIONS

Although security and privacy techniques have been studied for many years, its implementation and practical adoption is still some unaddressed challenging issues. In this section, we discuss some challenge issues and research directions for security and privacy in BDS:

Private Key Management. Recently, due to the increase in the volume and types of data processed in cloud environments, techniques that allow easy access to Big Data stored in heterogeneous devices in different network environments are emerging security issues for Big Data. Jeong and Shin [77] have explained different approaches for key management in big data context such as MPC, server-aided approach, and encryption with signature. In key management with Threshold Signature Scheme, data sharers do not need to keep any key on their own, but instead, they have to share secrets among multiple servers. Keys can be reconstructed using a minimum defined number of secrets using SSS.

Balancing Data Sharing Value and Privacy. To protect the individual privacy inside the data, the privacy-preserving techniques such as anonymizing data using whether masking or de-identification techniques are used. However, it’s such a double-edged sword: on the one hand
it protects the sensitive information inside data such as personal health information (PHI) from disclosure, on the other hand data will lose its quality and would not be enough accurate for analysis anymore. Therefore coming up with a balance between the privacy-protection solutions (anonymization, sharing agreement, and security controls) and accurate data for analysis is essential to be able to access a data that is usable for analytics.

**Improving Efficiency of Existing Solutions.** Recent cryptographic methods such as private set intersection and homomorphic encryption are powerful cryptographic primitives that have been deployed to solve many security and privacy issues. While these schemes have relatively good communication cost, the running time can be prohibitive when the set sizes become large due to the need to perform modular exponentiation for every item in both sets several times. Understanding and balancing these trade-offs theoretically and empirically is a considerable challenge for performing secure BDS.

**Eliminating Single Point of Failure: From Centralization to Decentralization, Blockchain as a Solution.** Blockchain technologies is a form of Distributed Leger Technologies (DLT’s) that provide decentralized platforms which eliminate the need of a single trusted third party (a central authority) and thus get rid of the well-known Single Point of Failure (SPOF) issue (which means if the central node goes down, the entire network becomes nonfunctional). This issue provides a breeding ground for cybercriminals as they can target the massive centralized data storage servers vis DDoS, DoS attacks as illustrated in Fig. 6.

![Centralized vs. decentralized networks](image)

Blockchain is enabled by a combination of technologies such as: peer-to-peer networks, consensus-making, cryptography, smart contract and market mechanisms, among others linking the records (blocks) of the ledger. The main properties of blockchain are as follows:

- Transparency: The chain is exportable to anywhere and can be downloaded and viewed over the internet.
- Immutability: Once data is in the chain it cannot be tampered with or altered.
- Decentralisation: No single entity controls what goes into the chain.

**How Blockchain will improve Data Sharing Security?** The combination of blockchain technology and BDS would allow numerous interesting opportunities to improve its security and privacy (as summarized in Figure 7):

- it provides fault tolerance property, which means the distributed nature of blockchain removes the single point of failure; All data is therefore distributed between the nodes of the network. If something is added, edited or deleted in any computer, it will be reflected in all the computers in the network. Contrary to centralized-based BDS, in case of database failures, the total system
Blockchain advantages over traditional database

1. **Ensuring Trustworthiness and Transparency**
   - Ensuring Data Integrity
   - Resilience (Database Recovery)

2. **Interference Issues**
   - Fault Tolerance Property
   - Blockchain Advantages over Traditional Database

Fig. 7. Blockchain advantages over traditional database

of centralized big data is suspended; in blockchain when one workstation goes down, the system will continue operation even with less processing power. It provides database Recovery which means replication of data automatically helps in data recovery if database in any site is damaged. No interference between users when accessing, sharing and manipulation BDS. Contrary to traditional BDS systems, with blockchain anyone can track data from the source to the end. There are no weak points for data to altered or tampered with. Participants of network have access to the holdings and transactions. Using an explorer equipped with a user’s public address is enough to perform their transactions and actions.

Blockchain ensures trust of data by maintaining a decentralized ledger. Data recorded on the blockchain are trustworthy because they must have gone through a verification process which ensures its quality. Data integrity is ensured when details of the origin and interactions concerning a data block are stored on the blockchain and automatically verified (or validated) before it can be acted upon. It also provides for transparency, since activities and transactions that take place on the blockchain network can be traced.

With recent research progress, the future development direction of Blockchain Technology includes the following aspects:

1. **DDoS attacks.** A denial-of-service attack refers to as the DoS attack on a host. It is the type of cyber-attacks that disrupt the hosted Internet services by making the host machine or the network resource on the host unavailable to its intended users. DoS attacks attempt to overload the host system or the host network resource by flooding with superfluous requests, consequently stalling the fulfillment of legitimate services.

2. **Linkability.** Different from user privacy, users should require that the transactions related to themselves cannot be linked. Because user behaviors in blockchain are traceable, blockchain systems need to protect the transaction privacy of users.

3. **The majority 51% consensus attack.** If an attacker were to take control of 51% or more of the nodes comprising the blockchain network, the consensus mechanism could be overridden allowing for double spending.

4. **Private key theft.** Transactions in any Blockchain system are authenticated by digital signatures. For example in cryptocurrency context, if Alice wants to send Bob some money,
she should sign a transaction by her private key to say "Pay this coin, C to Bob". However, once a Alice’s private key is lost or stolen, it cannot be recovered. Consequently, the user’s blockchain account can be tampered by others.

(5) **Irreversibility.** Blockchain cannot go back as data is immutable, that cannot always be regarded as a positive aspect, but can quickly turn out to be a major problem in the event of accidents, faulty transactions or fraudulent exchange of goods. Also, such feature does not meet the "Right to be Forgotten" which gives individuals the right to request that their personal data be removed from a record that is regarded as an important concept in data privacy.

(6) **Selfish-mining attack.** One popular use case related to fairness in block mining in Proof-of-Work (PoW) blockchains, which intuitively requires that a node’s mining rewards be proportional to its relative computational power. That is, no node should be able to mine selfishly to obtain more rewards than its fair share.

How to secure against unauthorized data re-sharing attack? BDS unauthorized data re-sharing preservation is well known to be impossible to achieve. Despite this limitation, many approaches provide solutions of practical interest by weakening somewhat that requirement. Such approaches include watermarking and copyrighting, that are used as a solution to identify the sharers in re-sharing activity [76]. Unfortunately, such approaches cannot prevent unauthorized data re-sharing but only tracking it.

Using signcryption as a solution to identify the sharers in re-sharing activity is threefold: ① It provides non-repudiation which provides the victim with transferable evidence against the cheating sharee. ② In our construction verifiers (e.g., Smart Contract) will be given the means to determine when the unauthorized user C tries to reshare the A’s data. When this happens, verifiers will be able to contact the data sharer who will provide the proof of his data ownership (this is achieved with the non-repudiation property). ③ It provides authenticated data between different receipts: in order to update the ciphertext recipient, the data owner needs to download it then decrypt the requested data, and further re-signcrypt it under the target user’s public key. This solution is very demanding in terms of computation and communication costs to the data owner which contradicts the motivation of cloud computing. For this reason, to handle this problem in data sharing context, we propose the solution of proxy re-signcryption between different receipts, without compromising the secret key of the data owner.

Furthermore, the server might ensure that the posted data is not a plaintext but a well encrypted ciphertext in such a way the server can only store the "encrypted content". To handle this problem, we introduce a new security notion that we call **verifiable plaintext-aware** that we add to proxy re-signcryption scheme (as described in Fig. 8), which consists of the following steps:

1. The data sharer uploads the signcrypted data onto the server.
2. The data sharer convinces the server that the signcrypted data is not a plaintext but a well signcrypted file.
3. If so, the server stores the signcrypted file $C_a$.
4. The data sharee requests decryption delegation with his public key $p_k_b$.
5. The data sharee creates and sends the transformation key $r_{k_a \rightarrow b}$ to the server.
6. The server re-signcrypts $C_a$ with $r_{k_a \rightarrow b}$ and outputs $C_b$.
7. The data sharee downloads and decrypts $C_b$ with $s_k_b$ to recover the original data.

Now let consider three entities: Data Sharer A, Data Sharee B and Unauthorized User C. We introduce a novel form of unauthorized data resharing prevention called legal unauthorized re-sharing preserving defined as follows:
6 CONCLUSION

We have presented a survey on security and privacy of BDS with a number of contributions. First, we characterized the security and privacy requirements of BDS into two broad categories: fundamental requirements and additional requirements in the context of BDS. Second, we described the security and privacy techniques for achieving these security and privacy requirements in BDS. With growing interest of BDS in both academic research and industry, the security and privacy of BDS have attracted huge interests, it is impossible to design next generation applications without publishing and executing data driven algorithms. We conjecture that developing light-weight cryptographic algorithms as well as other practical security and privacy methods will be a key enabling technology in the future development of BDS and its applications.

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