Towards Software-Defined Data Protection:
GDPR Compliance at the Storage Layer is Within Reach
[Vision Paper]

Zsolt István
IMDEA Software Institute, Madrid
zsolt.istvan@imdea.org

Soujanya Ponnapalli
University of Texas, Austin
soujanya.ponnapalli@utexas.edu

Vijay Chidambaram
University of Texas, Austin and VMWare
vijay@cs.utexas.edu

Abstract

Enforcing data protection and privacy rules within large data processing applications is becoming increasingly important, especially in the light of GDPR and similar regulatory frameworks. Most modern data processing happens on top of a distributed storage layer, and securing this layer against accidental or malicious misuse is crucial to ensuring global privacy guarantees. However, the performance overhead and the additional complexity for this is often assumed to be significant – in this work we describe a path forward that tackles both challenges. We propose “Software-Defined Data Protection” (SDP), an adoption of the “Software-Defined Storage” approach to non-performance aspects: a trusted controller translates company and application-specific policies to a set of rules deployed on the storage nodes. These, in turn, apply the rules at line-rate but do not take any decisions on their own. Such an approach decouples often changing policies from request-level enforcement and allows storage nodes to implement the latter more efficiently.

Even though in-storage processing brings challenges, mainly because it can jeopardize line-rate processing, we argue that today’s Smart Storage solutions can already implement the required functionality, thanks to the separation of concerns introduced by SDP. We highlight the challenges that remain, especially that of trusting the storage nodes. These need to be tackled before we can reach widespread adoption in cloud environments.

1 Introduction

Our online presence has been generating unprecedented amounts of data, a large portion of which are personally identifiable and hence prone to misuse. Even though companies have long used different access control and encryption techniques to secure the information they collect, with the emergence of regulatory frameworks such as GDPR in the EU [10] and CCPA in California [6], there is a need to homogenize and perhaps standardize these techniques to enforce rules at all levels of application stacks [38, 34]. In this work, we focus on enforcing privacy rules at the storage level, but tracking data through processing steps of large-scale applications or when shared with third parties, is just as important. Nonetheless, analysis of GDPR finds that more than 30% of the articles enforcing data protection are related to storage [36]. Maintaining strict compliance is challenging because it requires computational resources beyond the capacity of storage nodes and could slow down data access.

There have been two emerging trends that bring an optimistic outlook to enforcing privacy rules directly in the storage layer. First, disaggregated architectures in the cloud and datacenters are increasingly offering some form of in-storage processing [33, 8] and flexible data management [17, 13] with high-speed network connectivity. Second, as an effort to keep the management, configuration and monitoring of a large number of storage nodes scalable, Software-Defined Storage (SDS) has been proposed [39] – albeit the goal of existing SDS systems is almost exclusively to guarantee performance isolation and service levels in distributed multi-tenant settings [27].

In this vision paper, we propose Software-Defined Data Protection (SDP) that decouples policy interpretation and decision making (control plane) from request processing (data plane), reducing the complexity of the functionality required inside the storage nodes that often have limited hardware resources. As a result, SDP makes it feasible to implement complex policies, such as GDPR, with state-of-the-art smart storage devices that incorporate several low-power CPU cores and programmable fabric (FPGAs) [33]. Furthermore, the logically centralized control
plane ensures that regardless of the physical location of the storage nodes, the same privacy rules apply, keeping behavior consistent even across datacenters.

Somewhat surprisingly, when adopting the SDP approach, GDPR-compliant storage, to a large extent, can be already provided with existing “building blocks”. We sketch how these could assemble into a high bandwidth pipeline within the storage node. We also highlight the most important remaining challenge in the cloud context, namely adding Trusted Execution Environments (TEEs) \[15\] inside the storage nodes that would allow for remote attestation of the firmware by the controller.

To summarize, our vision is that using in-storage computation together with a control-plane/data-plane separation will allow enforcing GDPR at line-rate, without requiring storage nodes to be implemented with large, power-hungry, servers. The proposed Software-Defined Data Protection (SDP) can achieve this goal by re-purposing hardware building blocks that have been extensively studied in different contexts, and through this, bring GDPR-compliance to storage at little added cost. By sketching how a working solution would look like, we identify the one missing piece in the state-of-the-art needed to make our vision reality: the possibility of using Trusted Execution Environments inside storage nodes with heterogeneous hardware and near-data processing.

2 Background and Related Work

2.1 Implications of GDPR in the Cloud and on Storage

The General Data Protection Regulation (GDPR) outlines the rights and responsibilities of the companies handling the personal data of EU citizens. GDPR, in 99 articles and 173 recitals, regulates the entire life cycle of personal data, from its collection to its deletion.

GDPR outlines that it is the responsibility of a company to use third-party services that do not violate GDPR standards. A vast majority of companies today rely on cloud services providers, for their infrastructural needs, making GDPR compliance in cloud environments a necessity. Therefore, rich related work proposes frameworks enabling cloud users to develop GDPR-compliant applications \[32\], along with studies that outline the challenges faced by cloud users in the face of GDPR \[9\], and the support for the right to be forgotten in hybrid clouds \[18\].

The impact of GDPR on storage systems \[36\] has been broadly studied previously. GDPR’s impact on databases \[37\] and how databases, by design, can comply with GDPR \[34\] \[22\] are also analyzed. Recent work investigates how systems can violate GDPR \[38\], proposes benchmarks \[37\] and provides tools \[26\] that test GDPR-compliance, and that explore the benefits of Trusted hardware to prove GDPR-compliance \[28\].

The six features required from a GDPR-compliant storage system \[36\] are as follows:

1. **Deletion.** GDPR introduces the right to be forgotten, allowing users to demand the deletion of personal data. GDPR also states that personal data cannot be stored beyond its purpose in its storage limitation clause, requiring storage systems to support user data deletion.

2. **Logging and Monitoring.** With GDPR, companies are vested with the responsibility of detecting potential data breaches, informing users about those data breaches, and proving their compliance. GDPR also provides users with the right to access, allowing them to request with whom and why their personal data is shared. These rights and requirements necessitate some form of logging and monitoring at the storage layer.

3. **Metadata and Secondary Indexes.** As GDPR requires personal data to be associated with a specific purpose, storage has to accommodate for additional metadata. As a performance optimization, secondary indexes that categorize data as per purposes can be useful.

4. **Fine-grained Permissions.** With GDPR’s right to object, users can object to using their personal data for specific purposes. Further, with the purpose limitation clause, GDPR disallows companies to process user’s data beyond its purpose and without appropriate security measures. To comply with these clauses, fine-grained permission checks and access control becomes crucial at the storage layer.

5. **Encryption.** GDPR mandates that personal data should be protected against accidental loss or damage and should be incomprehensible to any person unauthorized to access it. Encrypting personal data is a suitable measure to comply with this clause.

6. **Location Control.** GDPR requires companies to adhere to its standards, independent of the geographical location of where personal data is stored.

7. **Data Integrity.** We further identify that GDPR requires storage systems to resist or detect malicious activities that compromise the integrity and confidentiality of personal data. We propose using checksums or Merkle tree-based data integrity checks to comply with the integrity and confidentiality clause of GDPR.

2.2 Emerging Smart Storage Devices.

Two kinds of smart storage devices are developed recently: those which incorporate small CPU cores, such as ARM cores \[16\] \[20\], and those which deploy specialized compute elements or FPGAs \[17\] \[13\] \[33\] \[8\]. The former category offers more flexibility, but as explored in depth in the work of Koo et al. \[20\], it can be difficult to predict
the performance of the in-storage computation, and this can lead to performance degradation. Those solutions that rely on FPGAs and similar specialized hardware are a better match for network-focused implementations because they can guarantee network line-rate processing by design. To sample from our previous work, we have shown, among other operations, that it is possible to implement line-rate hash-tables [13], deduplication schemes [23], in-storage filtering with regular expressions [12] on FPGA-based distributed storage. These operations are similar in nature to those required for building an SDP system (discussed in Section 3.1).

Overall, the SDP approach is beneficial in both cases because it reduces the complexity of the code running inside the storage nodes and allows developers to think of the enforcement as pipeline stages. We sketch our proposal targeting hardware platforms with a combination of ARM cored and FPGA fabric (as depicted in Figure 1), such as the Fidus Sidewinder-100 [3] or the Samsung SmartSSD [33, 7]. The presence of both a general-purpose, albeit low power, CPU core, and a reprogrammable specialized hardware element ensures that the devices can be managed easily in a cloud setting and, at the same time, can deliver high-performance behavior for privacy-related processing.

3 Software-Defined Data Protection

SDP targets cloud and datacenter use-cases where data is being stored and processed within the context of a large corporation with several applications but governed by a single set of privacy rules. In line with DGPR requirements, we assume that user data can be identified explicitly through a universal user identifier and a purpose identifier. These identifiers are valid across applications of the company, and the SDP controller has a global view of which application can access what purposes. All users within a purpose are accessible to the application, unless consent has been revoked.

Figure 2 shows the three types of nodes in SDP: storage, processing, and controller. Storage nodes implement a general-purpose key-value store (KVS) interface on binary data, can be shared across applications, and all communication with them happens over an encrypted channel (e.g., TLS).

Applications run on one or several processing nodes and are managed under the governance of the developers. Applications have to register with the controller before accessing data but once granted access, can carry out most of their operations with the storage nodes.

The controller node is logically centralized and is trusted by both the storage and processing layers and is controlled by the company’s data officers. It interprets policies and maintains data mappings and is used to bootstrap storage nodes, authenticate application nodes, and manage their permissions. Storage nodes are trusted once configured by the controller (see Section 4 for how this could be ensured in practice in the cloud). As we explain in the following subsections, once authenticated and configured, in common case neither the application nor the storage nodes have to communicate with the controller. For this reason, we do not consider the controller as an obvious bottleneck for performance.

3.1 Required Functionality

In Table 1, we summarize the GDPR articles relevant to storage and what type of functionality is required for their fulfillment. We also indicate for each aspect, whether the SDP’s storage nodes (data plane) or the controller (control plane) would bear most of the required complexity. Naturally, even if the storage node performs almost all the computation, for instance, as is the case with Encryption, the controller will still have to bootstrap the nodes.

In the following, we discuss in more detail how the required functionalities can be implemented with state of the art modules in hardware (FPGA) as part of an SDS-inspired pipeline on the storage nodes. It is possible to
implement most of the functionalities independent of each other (Figure 3), and in future systems, non-performance-critical steps could be moved to low power CPU cores (for instance, Authentication that is only carried out once per session), achieving this way heterogeneous processing.

**Encryption.** In the following, we sketch how encryption can be implemented inside the storage layer in a way that a) relies on existing schemes and best practices and b) makes it possible to map the key-management operations to the SDP scheme we propose.

Data needs to be encrypted both at rest and on the move. We envision a system where clients (processing nodes) receive plain-text tuples over encrypted channels. Block ciphers underlying TLS have been shown to work well on FPGAs [5, 11] reaching throughputs high enough to saturate even 40Gbps links.

Persistent data on flash is always encrypted, assuming industry-standard, symmetric-key cryptography (e.g., AES). The storage nodes must not persist cipher keys. Instead, they have to remain in memory and need to be configured and managed by the SDP controller at run-time. This forbids unauthorized access to the drives and prevents leaks. One difference to traditional encrypted storage is that in the GDPR context it can be beneficial if each tuple is encrypted with a key specific to the user whose data it represents (or even the user-purpose combination) because, as later explained in the Deletion subsection, this enables quick logical deletion of data.

A side-effect of having multiple (de)encryption keys is that each client request will have to retrieve a different one. Since requests encode user and purpose explicitly, the storage node can use this to lookup the cipher key in an internal ephemeral cipher key table (KT). It is important that this table can sustain high access rates because, in contrast to other meta-data structures described later, this one has to be accessed on every incoming client request.

---

Table 1: This table summarizes the GDPR articles relevant to storage and the high level functionality that the storage nodes and SDP controller need to fulfill those. Functionality outside of the scope of this paper is marked with †.

| No. | GDPR article                                                                 | Required functionality               | Impacts mostly          |
|-----|------------------------------------------------------------------------------|--------------------------------------|-------------------------|
| 5.1 | Purpose limitation (data collected for specific purpose)                     | Fine-grained permissions             | Storage, Controller     |
| 21  | Right to object (data not used for objected reason)                          | Fine-grained permissions             | Storage, Controller     |
| 5.1 | Storage limitation (data not stored beyond purpose)                          | Deletion                             | Controller              |
| 17  | Right to be forgotten                                                        | Deletion                             | Controller              |
| 15  | Right of access by users                                                      | Metadata (and Secondary indexes)     | Storage                 |
| 20  | Right to portability (transfer data on request)                              | Metadata (and Secondary indexes)     | Storage                 |
| 5.2 | Accountability (ability to demonstrate compliance)                           | Logging and Monitoring                | Storage, Controller     |
| 30  | Records of processing activity                                                | Logging                              | Storage                 |
| 33, 34 | Notify data breaches                                                      | Logging and Monitoring                | Storage, Controller     |
| 25  | Protection by design and by default                                          | Encryption                           | Storage                 |
| 32  | Security of data                                                             | Encryption and Access control        | Storage                 |
| 13  | Obtain user consent on data management                                       | High level policy†                   | Controller              |
| 46  | Transfers subject to safeguards                                              | Location control†                    | Controller              |

---

**Encryption.** In the following, we sketch how encryption can be implemented inside the storage layer in a way that a) relies on existing schemes and best practices and b) makes it possible to map the key-management operations to the SDP scheme we propose.

Data needs to be encrypted both at rest and on the move. We envision a system where clients (processing nodes) receive plain-text tuples over encrypted channels. Block ciphers underlying TLS have been shown to work well on FPGAs [5, 11] reaching throughputs high enough to saturate even 40Gbps links.

Persistent data on flash is always encrypted, assuming industry-standard, symmetric-key cryptography (e.g., AES). The storage nodes must not persist cipher keys. Instead, they have to remain in memory and need to be configured and managed by the SDP controller at run-time. This forbids unauthorized access to the drives and prevents leaks. One difference to traditional encrypted storage is that in the GDPR context it can be beneficial if each tuple is encrypted with a key specific to the user whose data it represents (or even the user-purpose combination) because, as later explained in the Deletion subsection, this enables quick logical deletion of data.

A side-effect of having multiple (de)encryption keys is that each client request will have to retrieve a different one. Since requests encode user and purpose explicitly, the storage node can use this to lookup the cipher key in an internal ephemeral cipher key table (KT). It is important that this table can sustain high access rates because, in contrast to other meta-data structures described later, this one has to be accessed on every incoming client request.

---

**Figure 3:** SDP enables separation of concerns, and as a result, policy enforcement can be laid out as pipeline within the storage nodes. The SDP controller configures and manages the nodes from the outside.

One challenge of creating fast hash tables on specialized hardware is that it is unlikely that cipher keys will fit on on-chip SRAM memory and will have to spill into off-chip DRAM. There is recent work in the context of high-performance key-value stores built on FPGAs [13, 25] using DRAM, which can be adequate for this purpose.

**Fine-grained Permissions.** Beyond the question of how clients can reach storage devices (solved by SDS), an authentication step is necessary. Authentication matches a client’s identity to a set of permissions (read/write/insert
rights per purpose). To carry out authentication, an Authentication Table (AT) holds the public keys belonging to applications. A Permission Table (PT) stores the mapping of identities to permissions. Both tables are ephemeral and are populated and managed by the controller. In most workloads, the number of purposes (e.g., number of internal applications) will be orders of magnitude smaller than that of individual users. Therefore the PT can be represented compactly, perhaps even on on-chip caches.

Permissions in the PT are orthogonal to the presence/absence of cipher keys in the KT: even if a client has the right to read all key-value pairs belonging to a purpose, only those for which the storage device holds a cipher key in the KT can be successfully read. The same holds for inserting tuple belonging to a new user or purpose. The SDP controller has to first insert the corresponding entries in the KT. It is important to note that permissions in themselves do not forbid applications to, for instance, make copies of data under bogus user keys. For this reason, end-to-end information tracking is required, as we highlight this in Section 4.

Metadata and Indexing. By GDPR regulations it has to be possible to retrieve all tuples belonging to a specific user or purpose. This can be achieved by relying on metadata stored with the key-value pairs (and by enforcing a naming scheme of tuples).

While not strictly necessary, if such reads will occur often, it can be beneficial to maintain secondary indexes for performance reasons. Even though write operations will become more expensive, these data structures can be used to avoid scanning TBs of data to find a specific user’s entries. For this purpose, there are already FPGA-based key-value stores with low cardinality secondary index [13] and by using the same hash table approach as for permissions, etc., higher cardinality cases could be also handled.

Logging and Monitoring. Logging is important for ensuring auditability of the storage layer and can be implemented at various granularities. The storage node will persist an encrypted log (the key for the log is configured at run-time by the SDP controller) and implement some form of integrity check at the tuple level. While we foresee no challenges with the former task, the latter might require further investigation. Increasing the efficiency of data structures that ensure the integrity storage are still a topic in exploration [31, 30, 2].

For monitoring, the storage node has to notify the SDP controller of any request that failed any of the validation steps outlined above or has retrieved a key-value pair whose decryption key is missing. These events allow the controller to take adequate action, rectifying misconfiguration, revoking permissions, etc.

Deletion. In this work we focus on logical deletion of user data, since physically destroying all copies, and proving this to a third party, is orthogonal to our goals and a challenge in itself [22, 19]. If using an encryption scheme with a single key, the SDP controller can delete tuples belonging to a user and purpose by delegating this task to the storage device that will either scan the tuple space or use a secondary index. But in case an encryption scheme with multiple keys is used, deletion can be performed more efficiently by simply removing the corresponding cipher keys from the KT of the storage nodes. As a result, deleted tuples will not be accessible any more as plain-text, and without the cipher keys, cannot be decrypted. This approach is in-line with existing practices [4, 42].

Depending on the encryption scheme chosen, the logical delete operation could be performed with a single request to the storage node or in linear time. If (1) the encryption of tuples is only based on the user they belong to, then the controller can remove all tuples of a user in constant time but will have to rely on secondary indexes to physically remove all tuples belonging to a purpose. As an alternative, (2) distinct cipher keys can be generated for each user:purpose pair. This allows more fine-grained deletions and, even though not constant time, deleting all data of a user:purpose pair. This enables constant time deletions of either all data of a user or all data belonging to a purpose, but more fine-grained deletions require costly scans in the storage. Regardless of the choice of the scheme, the functionality on the storage nodes changes very little because most of the complexity is handled by the controller.

3.2 Features and Questions out of Scope

Location: The mapping of user and purpose to the actual storage devices is carried out by the controller following either general purpose sharding strategies or depending on the privacy policies at the high level. GDPR, however, mandates that regardless of the physical location of data belonging to a user, the same rules apply to it. The logically centralized nature of the SDP controller is essential for ensuring rule consistency at scale.

High level policies: The question of how company- and application-wide policies are written, managed and translated to SDP rules is out of the context of this paper. There is rich related work [21, 40, 41, 35] which demonstrates how to translate high level policies to compliant queries in databases (or compliant accesses in data storage layers) and we believe that they could be layered on top of SDP since our proposal envisions functionality which is a superset of such proposals.

Fault Tolerance by Replication: For simplicity, in our discussion we assumed that each piece of data resides inside a single storage node. In a real system, however,
replication will be required to ensure fault tolerance. As highlighted by the above two points, the task of setting up and controlling replication is external to our proposal and can be tackled by numerous existing schemes. Nonetheless, there is work on performing transparent, line-rate, replication of the KVS running on the FPGAs [14] that could be easily adapted to be managed by the Controller.

**Performance of the Controller:** In our SDP vision, the Controller is required to actively participate only in a subset of operations. After carrying out initial authentications and configuring encryption keys and permissions, it is seldom accessed by either the processing nodes (application) or the storage nodes. Once exception is when data belonging to a new user or purpose is inserted for the first time. Such operations, however, are less common than regular reads and updates of existing data. Nonetheless, it is likely that the Controller will have to be implemented as a logically centralized by physically decentralized solution, to be able to keep up with the workloads of large enterprises.

**4 Future Challenges**

In the previous section we described an SDS-inspired design for smart storage nodes that could enforce privacy rules and make existing storage solutions GDPR-compliant. There are, however, two challenges to be addressed before such a solution can be deployed in practice:

**Trusted Execution Environments.** There are several trust-related challenges in the proposal we made above. First of all, the security of the encrypted data at rest hinges on the assumption that the storage device cannot and will not leak cipher keys. Furthermore, the assumption that all permissions are verified and honored correctly depend on whether the storage node is running the expected software/firmware. For this reason, the Controller has to be able to trust the storage node once it has been powered on and “booted”. For this, we propose expanding the storage node with a small Trusted Execution Environment that can attest the correctness of the software and hardware contents to the Controller.

Today, ARM processors can already offer guarantees with the TrustZone extensions but emerging research projects, such as Keystone [24], can implement TEEs with custom hardware components. This approach fits the use-case of SDP well, because a small RISC-V or ARM core could be used to load the firmware on the storage node that the controller provides. This firmware, in turn, can be verified not to be able to read out cipher keys to clients, etc. FPGAs have been also proposed to be used as TEEs in project examples such as Cipherbase [1] where they perform transaction processing in an always-encrypted database management system.

**Data Tracking Beyond Storage.** While making sure that the storage layer protects privacy and respects all rules, data misuse can happen at other layers of the application stack as well. There is no guarantee that a buggy or malicious application does not store, for instance, data belonging to one user under some other, potentially non-existent, one’s data; or that results of processing do not leak personally identifiable information to the outside world. Countering such behavior has been the subject of numerous studies in the context of Information Flow Control, but practical, general purpose, solutions are still not widely available. Even though the SDP approach does not solve this challenge, we believe that at least it makes it easier: On the one hand, removing all decision making and policy interpretation from the storage nodes and moving it into a logically centralized controller allows for better overview of the system. Other monitoring tools might be used to augment the monitoring capability of the controller, achieving this way better coverage. Furthermore, by not allowing storing new tuples into the storage unless they belong to a user and purpose known to the controller, some misuse scenarios can be limited and be audited after the fact (identifying, for instance, the application that created non-existent user IDs).

**5 Conclusion**

In this paper we painted our vision for a GDPR-compliant storage solution that relies on a control path/data path separation to simplify the complexity of in-storage processing necessary for enforcing privacy rules, and hence making practical implementations possible. We call this approach **Software-Defined Data Protection (SDP),** inspired by the Software-Defined Storage trend. Thanks to SDP, implementing a processing pipeline in smart storage to ensure complex privacy rules at high bandwidth is within reach. As we sketch in this paper, such functionality could indeed be provided by re-purposing existing building blocks. There are, however, open challenges to be tackled. Importantly, SDP requires storage nodes to be treated as a trusted cloud resource.

This paper is a call to arms for security and systems researchers to join forces in making privacy protecting, GDPR-compliant, distributed cloud storage a reality.

**References**

[1] A. Arasu, K. Eguro, M. Joglekar, R. Kaushik, D. Kossman, and R. Ramamurthy. Transaction processing on confidential data using cipherbase. In *2015 IEEE 31st International Conference on Data Engineering*, pages 435–446. IEEE, 2015.
[2] M. Bailleu, J. Thalheim, P. Bhatotia, C. Fetzer, M. Honda, and K. Vaswani. {SPEICHER}: Securing lsm-based key-value stores using shielded execution. In 17th {USENIX} Conference on File and Storage Technologies ({{FAST} '19}), pages 173–190, 2019.

[3] W. Bauer, P. Holzinger, M. Reichenbach, S. Vaas, P. Hartke, and D. Fey. Programmable hsa accelerators for zynq ultrascale+ mpsoc systems. In European Conference on Parallel Processing, pages 733–744. Springer, 2018.

[4] D. Boneh and R. J. Lipton. A revocable backup system. In USENIX Security Symposium, pages 91–96, 1996.

[5] A. M. Caulfield, E. S. Chung, A. Putnam, H. Angepat, J. Fowers, M. Haselman, S. Heil, M. Humphrey, P. Kaur, J.-Y. Kim, et al. A cloud-scale acceleration architecture. In 2016 49th Annual IEEE/ACM International Symposium on Microarchitecture (MICRO), pages 1–13. IEEE, 2016.

[6] CCPA. California Consumer Privacy Act. California Civil Code, Section 1798.100, Jun 28 2018.

[7] K. Chapman, M. Nik, B. Robatmili, S. Mirkhani, and M. Lavasani. Computational storage for big data analytics. In Proceedings of 10th International Workshop on Accelerating Analytics and Data Management Systems (ADMS’19), 2019.

[8] J. Do, S. Sengupta, and S. Swanson. Programmable solid-state storage in future cloud datacenters. Communications of the ACM, 62(6):54–62, 2019.

[9] B. Duncan. Eu general data protection regulation compliance challenges for cloud users. 05 2019.

[10] GDPR. Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46. Official Journal of the European Union, 59(1-88), 2016.

[11] A. Hodjat and I. Verbauwhede. A 21.54 gbits/s fully pipelined aes processor on fpga. In 12th Annual IEEE Symposium on Field-Programmable Custom Computing Machines, pages 308–309. IEEE, 2004.

[12] Z. István, D. Sidler, and G. Alonso. Runtime parameterizable regular expression operators for databases. In 2016 IEEE 24th Annual International Symposium on Field-Programmable Custom Computing Machines (FCCM), pages 204–211. IEEE, 2016.

[13] Z. István, D. Sidler, and G. Alonso. Caribou: intelligent distributed storage. Proceedings of the VLDB Endowment, 10(11):1202–1213, 2017.

[14] Z. István, D. Sidler, G. Alonso, and M. Vukolic. Consensus in a box: Inexpensive coordination in hardware. In 13th {USENIX} Symposium on Networked Systems Design and Implementation ({{NSDI} '16}), pages 425–438, 2016.

[15] P. Jauernig, A.-R. Sadeghi, and E. Stapf. Trusted execution environments: Properties, applications, and challenges. IEEE Security & Privacy, 18(2):56–60, 2020.

[16] I. Jo, D.-H. Bae, A. S. Yoon, J.-U. Kang, S. Cho, D. D. Lee, and J. Jeong. Yoursql: a high-performance database system leveraging in-storage computing. Proceedings of the VLDB Endowment, 9(12):924–935, 2016.

[17] S.-W. Jun, M. Liu, S. Lee, J. Hicks, J. Ankorn, M. King, and S. Xu. Bluedbm: Distributed flash storage for big data analytics. ACM Transactions on Computer Systems (TOCS), 34(3):1–31, 2016.

[18] M. Kelly, E. Furey, and K. Curran. How to achieve compliance with gdpr article 17 in a hybrid cloud environment. Sci, 2(2):22, 2020.

[19] M. Kim, J. Park, G. Cho, Y. Kim, L. Orosa, O. Mutlu, and J. Kim. Evanesco: Architectural support for efficient data sanitization in modern flash-based storage systems. In Proceedings of the Twenty-Fifth International Conference on Architectural Support for Programming Languages and Operating Systems, pages 1311–1326, 2020.

[20] G. Koo, K. K. Matam, I. Te, H. K. G. Narra, J. Li, H. W. Tseng, S. Swanson, and M. Annavaram. Summarizer: trading communication with computing near storage. In 2017 50th Annual IEEE/ACM International Symposium on Microarchitecture (MICRO), pages 219–231. IEEE, 2017.

[21] R. Krahn, B. Trach, A. Vahldiek-Oberwagner, T. Knauth, P. Bhatotia, and C. Fetzer. Pesos: Policy enhanced secure object store. In Proceedings of the Thirteenth EuroSys Conference, pages 1–17, 2018.

[22] T. Kraska, M. Stonebraker, L. M. Brodie, S. Servan-Schreiber, and J. D. Weitzner. Schengendb - a data protection database proposal. Poly/DMAH@VLDB, pages 24–38, 2019.

[23] L. Kuhring, E. Garcia, and Z. István. Specialize in moderationbuilding application-aware storage services using fpgas in the datacenter. In 11th
[24] D. Lee, D. Kohlbrenner, S. Shinde, K. Asanović, and D. Song. Keystone: an open framework for architecting trusted execution environments. In Proceedings of the Fifteenth European Conference on Computer Systems, pages 1–16, 2020.

[25] B. Li, Z. Ruan, W. Xiao, Y. Lu, Y. Xiong, A. Putnam, E. Chen, and L. Zhang. Kv-direct: High-performance in-memory key-value store with programmable nic. In Proceedings of the 26th Symposium on Operating Systems Principles, pages 137–152, 2017.

[26] Z. S. Li, C. Werner, and N. Ernst. Continuous requirements: An example using gdpr. In 2019 IEEE 27th International Requirements Engineering Conference Workshops (REW), pages 144–149, 2019.

[27] R. Macedo, J. Paulo, J. Pereira, and A. Bessani. A survey and classification of software-defined storage systems. ACM Computing Surveys (CSUR).

[28] M. Mazmudar. Mitigator: Privacy policy compliance using intel sgx. 2019.

[29] S. Mitra and M. Winslett. Secure deletion from inverted indexes on compliance storage. In Proceedings of the second ACM workshop on Storage security and survivability, pages 67–72, 2006.

[30] S. Ponnapalli, A. Shah, A. Tai, S. Banerjee, V. Chidambaram, D. Malkhi, and M. Wei. Scalable and efficient data authentication for decentralized systems. arXiv preprint arXiv:1909.11590, 2019.

[31] P. Raju, S. Ponnapalli, E. Kaminsky, G. Oved, Z. Keener, V. Chidambaram, and I. Abraham. mlsm: Making authenticated storage faster in ethereum. In 10th {USENIX} Workshop on Hot Topics in Storage and File Systems (HotStorage 18), 2018.

[32] E. Rios, E. Iturbe, X. Larrucea, M. Rak, W. Mallouli, J. Dominiak, V. Muntés, P. Matthews, and L. Gonzalez. Service level agreement-based gdpr compliance and security assurance in (multi)cloud-based systems. IET Software, 13:213–222, 2019.

[33] Samsung. Samsung smartssd product brief. https://www.nimbix.net/wp-content/uploads/2020/02/SmartSSD_ProductBrief_12.pdf, 2020.