Rethinking Block Storage Encryption with Virtual Disks

Danny Harnik
IBM Research

Effi Ofer
IBM Research

Oded Naor
Technion

Or Ozery
IBM Research

ABSTRACT

Disk encryption today uses standard encryption methods that are length preserving and do not require storing any additional information with an encrypted disk sector. This significantly simplifies disk encryption management as the disk mapping does not change with encryption. On the other hand, it forces the encryption to be deterministic when data is being overwritten and it disallows integrity mechanisms, thus lowering security guarantees. Moreover, because the most widely used standard encryption methods (like AES-XTS) work at small sub-blocks of no more than 32 bytes, deterministic overwrites form an even greater security risk. Overall, today’s standard practice forfeits some security for ease of management and performance considerations. This shortcoming is further amplified in a virtual disk setting that supports versioning and snapshots so that overwritten data remains accessible.

In this work, we address these concerns and stipulate that especially with virtual disks, there is motivation and potential to improve security at the expense of a small performance overhead. Specifically, adding per-sector metadata to a virtual disk allows running encryption with a random initialization vector (IV) as well as potentially adding integrity mechanisms. We explore how best to implement additional per-sector information in Ceph RBD, a popular open-source distributed block storage with client-side encryption. We implement and evaluate several approaches and show that one can run AES-XTS encryption with a random IV at a manageable overhead ranging from 1%–22%, depending on the IO size.

1 INTRODUCTION

Disk Encryption: Data-at-rest disk encryption is at the foundation of storage security and has been a central requirement for persistent storage over the years. It requires that data is encrypted before being written to disk so that if the disk is stolen or illegally accessed, attackers would not be able to make sense of the data (as long as they do not hold the encryption key).

When encrypting a disk one must take into account its structure and access patterns. Disks are accessed at a sector granularity and as such, encryption is done at a sector-by-sector granularity. Originally, disk sectors were 512 bytes each, and today they are typically 4096 bytes. As such, disk encryption encrypts each sector separately. Moreover, in a disk, each sector is addressed by the Logical Block Address (or LBA) and to simplify the integration of encryption, this mapping is kept intact when data is encrypted. This implies that the encryption of a sector should have the same length as the sector.

Several issues arise when the length of the output cannot grow. Mainly:

1. Deterministic encryption: To achieve Semantically secure encryption, the encryption must not be deterministic [7]. In particular, if a sector is overwritten, an adversary must not be able to determine whether the contents of the sectors have changed during the overwrite. Yet if the encryption is deterministic, this information is obvious since the same plaintext would yield the same ciphertext. The common mechanism to avoid determinism in encryption is to add a nonce as an input to the encryption. This nonce, usually called the Initialization Vector (IV), is a string of bits that is guaranteed not to repeat.
itself between instances of encryption, hence avoiding the
determinism of the encryption function (note that
the IV, unlike the encryption key, can be made public).
The IV is required in order to decrypt the data and hence
must be stored alongside the encrypted data and read for
the decryption process. The problem is that with stan-
dard disk encryption, there is no room left to store the
IV alongside the encrypted sectors.

(2) Authentication of encryption: In length preserving encryp-
tion, changing a part of the cipher of a sector generates
a new legal encryption pattern (of a different plaintext).
This means that one cannot detect changes to the ci-
phertext, whether malicious or accidental. The common
approach to handle authentication of encrypted data is to
hold an additional Message Authentication Code (MAC)
that can later be used to verify that the encrypted sector
has not changed. In traditional disk encryption, there is
no room to store a MAC associated with each sector.

In short, since the length of the output cannot grow, it is
possible to identify which sections have changed between
writes and also possible to revert a sector to an older version.

**Disk Encryption Today:** Given the length preserving limi-
tations and the lack of space for additional per-sector infor-
mation, the cryptographic and security communities resorted
to the following approach:

• Use a unique data encryption key per disk. This key is
  used to encrypt all the sectors in the disk.

• In order to avoid deterministic encryption across sectors,
  the sector number or LBA is used as an additional per
  sector input to the encryption. The sector number is used
together with the key to derive the actual IV used in each
  encryption block. Because the sector number is also known
during reads, it can be used to correctly decrypt the data.

• Devise encryption modes that will not “break” if a nonce
  is repeated with different data. Namely, the data itself
  remains unknown, and the only information divulged is
  whether the underlying plaintext has changed or not. AES-
  XTS [4, 18] is the most commonly used method today that
  was designed to remain secure under repeating IVs. ¹

¹Historically, AES-CBC was the widely used encryption method, but it was
replaced due to security attacks on this mode.

In reality, repeating the same IV even in AES-XTS is not
ideal [17], as is explained below in §2.1. However, it is a com-
promise that the community was willing to take with the
lack of a better alternative. Since data written to different
addresses uses different IVs, the only security concerns arise
with overwrites to the same address. In that sense, full disk
encryption with AES-XTS guarantees that if the disk is
physically stolen, then no data in the disk is encrypted with the
same IV since there is no record of overwrites of the data. ²
It is only when an adversary eavesdrops to the write stream
over a disk that it will encounter sectors encrypted with the
same IV due to overwrites.

**Virtual Disks:** Virtual disks change the equation in two fun-
damental ways. The first is the snapshot capabilities which
are an important feature of such disks. In the presence of
snapshots, various versions of data written to the same sec-
tor are kept and persisted one alongside the other (this holds
for every mechanism for snapshots or versioning above the
disk layer, whether in virtual disks or not). This means that
the guarantee of no repeating IV in a stolen physical disk no
longer holds. With various versions of the data encrypted
under the same IV one can, for example, manipulate the data
to contain arbitrary combinations of data from various snap-
shots (creating the encryption of a data combination that
was never actually written).

The second consideration is that while for a physical disk it
is very tempting to avoid adding a layer of virtual-to-physical
mapping, for a virtual disk this is a non-issue. A virtual disk,
your definition, already contains a virtual-to-physical mapping
layer which we can piggyback on to augment the layout and
incorporate additional per-sector information.

**Our Work:** We study the possibilities of adding per-sector
information in the context of encryption in a specific setting:
Ceph block storage [22] (also known as Ceph RBD). Specifi-
cally, we modify the built-in client-side encryption in Ceph
RBD to use a fresh random IV per each sector write. The IV
is persisted to disk to be used during read operations. We
evaluate the tradeoffs of such a design, providing improved
security at the cost of the overhead required to persist and
read the random IVs. We show that for the best implementa-
tion option we test the performance overheads are no larger
than a 22% overhead on writes and 3% on reads.

**Structure:** The rest of the paper is structured as follows: §2
provides the necessary background and related work; §3 de-
tails the implementation and results; and lastly, §4 concludes
the paper and discusses future work.

# 2 BACKGROUND

## 2.1 AES-XTS and its Shortcomings

AES-XTS is the prevalent standard used for disk encryption
to date. Among others, it is available in Android [3], Apple’s
Filevault [1], Microsoft’s BitLocker [15], and Linux’s
DMCrypt [10]. It is a specific implementation of tweakable
encryption [11] - a block encryption mode that takes as input an additional parameter (the tweak) that can be public and adds variability to an otherwise deterministic encryption function. AES-XTS is used in disk encryption by setting the tweak, also referred to as the IV (Initialization Vector), to be the sector number, also referred to as the LBA (Logical Block Address). Therefore, if the same data is written to different sectors they will result in totally different ciphertext as they will use different IVs. A critical security property required of tweakable encryption is that if different plaintexts are encrypted with the same IV, still no information can be deduced about the encrypted data. AES-XTS only achieves this to a certain extent.

In an ideal block cipher, even if it is deterministic, changing a single bit in the plaintext of a sector will result in an entirely different, (random-looking) ciphertext sector. However, AES-XTS falls short of this (as do many other AES-based encryption modes). In AES-XTS, changing a single bit in the sector (without changing the key or IV) will yield the expected change only to the sub-block in the cipher to which this bit belongs. The sub-blocks are the same size as the encryption key - either 32 bytes (AES-256) or 16 bytes (AES-128) and stem from the way AES-XTS is built on top of the AES primitive - a building block that works on small 16/32 byte blocks. Such ciphers are referred to as narrow-block encryption. This means that during an overwrite of a sector (using the same LBA and thus the same IV), an adversary can detect exactly which of the sub-blocks has changed and which have remained the same. Moreover, one can manipulate ciphertexts at a sub-block level. For example, given two versions of ciphertexts written to the same LBA, one can generate a new ciphertext of this sector that combines sub-blocks from both versions. The resulting ciphertext is legal and the manipulation cannot be detected. So encrypting different plaintexts with the same IV provides very good security guarantees at a granularity of a single sub-block, yet leaks some information about the relation between the plaintexts at a sector granularity. Still, due to the practicality of AES-XTS for disk encryption, it is widely used.

Similar shortcomings also exist in other popular block cipher modes. For example, in AES-CBC [5] one can detect the first sub-block in which a bit has changed. Note that other methods like AES-GCM [12, 14] are completely insecure if the same key and IV are used and may leak information about the plaintext. Hence such modes can only work with a true nonce as an IV (one that never repeats).

### 2.2 Possible Mitigations

The approach that we take to remedy the security shortcomings is to use a random IV rather than use the LBA. If the random IV is chosen from a large enough range, the probability of ever repeating an IV is negligible. This in essence removes the determinism of encryption for overwriting a sector and an adversary would not be able to detect if the underlying plaintext has changed at all. However, as described in the introduction, this requires writing the per-sector IV to the disk so that the sector could be decrypted during reads. Note that one should also include the sector number as part of the IV in order to avoid replay attacks where data encrypted at one LBA is replayed at another LBA.

Using an authentication code (MAC) on the ciphertext can prevent the various manipulation attacks described above, but also requires additional space. Also, using authentication alone still exposes which parts of the plaintext have changed during an overwrite.

Another approach is using wide-block encryption [9], an encryption method in which every bit of the plaintext of a sector will influence the entire ciphertext of the sector (as opposed to methods like XTS which are narrow-block ciphers). This holds even if it is built on top of a building block like AES which works on a much smaller size than the sector. Wide-block encryption has been standardized [9], with two certified methods - XCB-AES[13] and EME2-AES [8, 9]. Yet it has not been widely adopted mainly due to lower performance, as well as implementation and patenting considerations. Using a wide-block cipher still carries the limitations of a deterministic cipher (an exact overwrite is easily identified), yet limits the attack granularity to that of a full sector.

### 2.3 Related Work

The security concerns about the commonly used methods for disk encryption have been raised and studied by the cryptographic community. This was the main motivation for studies on wide-block encryption and their standardization effort [9].

Brož et al. [2] studied adding additional per-sector metadata as part of the dm-crypt encryption framework in the Linux kernel. They do this by using an additional device-mapper called dm-integrity that can be used for storing authentication information, or in the encryption case also a random IV. To ensure consistency between the data sector and its metadata, they resort to using a journal which is shown to reduce the throughput by nearly one-half. Zhang et al. [24] integrate the AES-XTS encryption with the Flash Translation Layer (FTL) of an SSD and use the number of overwrites a sector has as a seed for its IV (hence ensuring that each overwrite gets a unique IV). This approach works well for storage-side encryption, which means that the data exists in the clear at the storage before being encrypted. Our

---

1 In a system with snapshots one can also integrate the snapshot number into the IV to avoid cross snapshot replay attacks.
work targets encryption at the client-side of a distributed storage system, ensuring that the data is always encrypted outside of the client, and attempts to piggyback the indirection layer of the distributed storage system.

Note that some storage protocols like NVMe (starting from version 1.2) [23] include the option for a per-sector metadata support. However, this is not widely implemented in existing SSDs and existing implementations typically only allow for 8 bytes of metadata per sector, which is too short for our use-case.

2.4 Ceph RBD Encryption

Ceph [22] is an open-source distributed storage platform that provides support for object storage, block storage, and file storage. In this work, we focus on the block-storage of Ceph called RBD (Rados Block Device).

The general architecture of a Ceph RBD deployment is depicted in Fig. 1. The Ceph cluster is made out of OSD nodes (Object Storage Devices) that actually store the data and its replicas, monitors that maintain maps of the cluster state and perform access control, and managers that provide additional metrics and interfaces.

In its standard deployment, Ceph RBD employs a client-side driver called libRBD at each host accessing the storage. For every virtual disk, libRBD maps each LBA to a specific OSD node by breaking the LBA space into objects (typically 4MB in size) and computing a placement algorithm for objects. The libRBD library distributes each IO to its corresponding OSD via a proprietary protocol called RADOS. The RADOS protocol supports several high-level functions such as snapshots. It also has supports transactions in which writes of several small IOs are guaranteed to be written atomically. This proved very useful in ensuring consistency between written data and per-sector metadata.

RBD supports client-side encryption [19], allowing for data to never leave the host in the clear. The encryption follows the LUKS standard for encrypted disks in which the default encryption is AES-XTS.4

Note that LUKS has 2 versions, LUKS1 [6] and LUKS2 [16]. In LUKS2, the default sector size is 4KB per block whereas in LUKS1 it is limited to 512 bytes only which makes adding per-sector information far more costly. In this work, we only consider 4KB sectors.

3 IMPLEMENTATION AND EVALUATION

3.1 Design Choices for Storing Per-Sector Information

We explore how to integrate support for additional per-sector information. We focus on the use-case of using a random IV with AES-XTS encryption, but this can be used also for storing integrity information, or using an alternative cipher like AES-GCM. We leave evaluation of these options to future research.

We implement three alternatives on where to store the IV with Ceph RBD, which are illustrated in Fig. 2.

(a) Unaligned: each IV is stored at the end of its block.
(b) Object end: All IVs stored at the end of the entire object.
(c) OMAP: IVs stored at an external key-value DB.

Figure 2: Storage options for IVs

4 Note that LUKS has 2 versions, LUKS1 [6] and LUKS2 [16]. In LUKS2, the default sector size is 4KB per block whereas in LUKS1 it is limited to 512 bytes only which makes adding per-sector information far more costly. In this work, we only consider 4KB sectors.
3.3 Results

To measure the throughput performance, we use fio [20] which has native support for Ceph RBD. We use fio version 3.1, and deploy a single client random read and write workloads, with 32 maximum parallel accesses on a full Ceph image of 64GB. There are tests for IO sizes ranging from 4KB to 4MB and each test is repeated 10 times. Sequential IO tests are not presented, but give similar results to random IO with large sizes.

Fig. 3 presents a comparison of the three approaches to the baseline which is Ceph’s LUKS2 implementation [19] with deterministic LBA based IVs that are not stored. Of the three random IV implementation options, the object end gives the best results for both reads and writes.

For the read workloads, all three approaches perform nicely, likely due to the backend’s ability to do the IV reads in parallel to the data IO. The OMAP version fares slightly worse, due to the overhead of accessing the DB. The object end approach closely mirrors the baseline where the biggest difference we measure is 3%.

For the write workloads, there is a significant difference between the three options. Fig. 4 presents the performance degradation of each method compared to the LUKS2 baseline, i.e., lower is better. For the small block sizes, the OMAP solution gives the best performance, but this briefly changes as the IO size increases and the DB fails to provide high performance. The object end option performs better for almost all IO sizes, resulting in 1%–22% performance loss, depending on the IO size.

As the IO size grows, the theoretical overheads of unaligned and object end, measured as the number of sectors that need to be read or written to disk, decrease. For example, in a 4KB write/read, a minimum of two physical disk sectors need to be accessed (one for the data and one for the IV) versus one in the baseline. Whereas a 32KB IO typically requires 9 sectors to be accessed versus 8 in the baseline. Indeed, as the IO size grows we see an improvement in the measured performance overhead (except for an unexplained degradation at 1024KB writes). In the OMAP solution, this calculation does not work and hence the overhead grows significantly with the IO size. We suspect that the unaligned solution performs worse due to unaligned operations that trigger costly read-modify-write operations (these could potentially be further optimized with intelligent buffer writes).
4 CONCLUSIONS AND LOOKING FORWARD

The purpose of this paper is to raise awareness in the storage community to the security concessions that we make in order to accommodate simpler and more efficient encryption techniques. We further wish to demonstrate that better security can be achieved by adding the proper support in the storage layer and explore the performance tradeoff associated with this. We hope to further understand the performance results that we observed and explore how much they apply to different Ceph configurations and different hardware or scale. We also ask how this design can be generalized to other systems.

We point out that working at the virtual mapping layer of the storage system creates opportunities for more efficient implementation than doing the mapping as an additional layer (like the implementation in dm-crypt [2]). We expect that similar designs can be achieved in other architectures for virtual disk other than Ceph.

In the long term, we believe that block storage systems would benefit by natively supporting per-sector metadata as part of their initial design. Could a change in the standard block storage APIs to include per-sector metadata be advisable or beneficial? This could allow simple extensions from layers above the block storage (like dm-crypt). Furthermore, we wonder what additional use cases could benefit from per-sector metadata beyond security and integrity?

ACKNOWLEDGMENTS

Oded Naor is grateful to the Azrieli Foundation for the award of an Azrieli Fellowship, and to the Technion Hiroshi Fujiwara Cyber-Security Research Center for providing a research grant. We thank Jonas Pfefferle, Nikolas Ioannou, Andreas Döring and Sanghee Gupta for their help with the evaluation environments. We also thank Jason Dillaman for enlightening design discussions and his insights on Ceph architecture.

REFERENCES

[1] Apple. [n.d.]. https://support.apple.com/en-us/HT204837 Accessed: 2022-03-20.
[2] Milan Brož, Mikulás Patocka, and Vashek Matyás. [n.d.]. Practical Cryptographic Data Integrity Protection with Full Disk Encryption. In ICT Systems Security and Privacy Protection - 33rd IFIP TC 11 International Conference, SEC 2018, Vol. 529. 79–93.
[3] Android documentation. [n.d.]. https://source.android.com/security/encryption Accessed: 2022-03-20.
[4] Morris Dworkin. 2010. Recommendation for Block Cipher Modes of Operation: the XTS-AES Mode for Confidentiality on Storage Devices - NIST SP 800-38E.
[5] William F. Ehrsam, Carl HW Meyer, John L. Smith, and Walter L. Tuchman. 1978. Message verification and transmission error detection by block chaining. US Patent 4,074,066.
[6] Clemens Fruhwirth. 2018. LUKS1 On-Disk Format Specification. https://gitlab.com/cryptsetup/cryptsetup/-/wikis/LUKS-standard/on-disk-format-pdf
[7] Shafi Goldwasser and Silvio Micali. 1984. Probabilistic Encryption. J. Comput. Syst. Sci. 28, 2 (1984), 270–299.
[8] Shai Halevi. 2004. EME*: Extending EME to Handle Arbitrarily Long Messages with Associated Data (INDOCRYPT’04). Springer-Verlag, Berlin, Heidelberg, 315–327.
[9] IEEE. 2021. IEEE Standard for Wide-Block Encryption for Shared Storage Media. IEEE Std 1619.2-2021 (Revision of IEEE Std 1619.2-2010) (2021), 1–88. https://doi.org/10.1109/IEEESTD.2021.9457235
[10] Linux. [n.d.]. https://gitlab.com/cryptsetup/cryptsetup/-/wikis/DMCrypt Accessed: 2022-03-20.
[11] Moses Liskov, Ronald L Rivest, and David Wagner. 2011. Tweakeable block ciphers. Journal of cryptography 24, 3 (2011), 588–613.
[12] David McGrew and John Viega. 2004. The Galois/counter mode of operation (GCM). submission to NIST Modes of Operation Process 20 (2004), 0278–0070.
[13] David A. McGrew and Scott R. Fluhrer. 2007. The Security of the Extended Codebook (XCB) Mode of Operation. In Selected Areas in Cryptography. 311–327.
[14] David A McGrew and John Viega. 2004. The security and performance of the Galois/Counter Mode (GCM) of operation. In International Conference on Cryptology in India. Springer, 343–355.
[15] Microsoft. [n.d.]. https://docs.microsoft.com/en-us/windows/security/ information-protection/bitlocker/bitlocker-overview Accessed: 2022-03-20.
[16] Brož Milan. 2018. LUKS2 On-Disk Format Specification. https://gitlab.com/cryptsetup/LUKS2-docs
[17] Thomas H. Ptacek. 2014. You Don’t Want XTS. https://sockpuppet.org/blog/2014/04/30/you-dont-want-xts/. (Retrieved Feb. 2021).
[18] Phillip Rogaway. 2004. Efficient Instantiations of Tweakeable Blockciphers and Refinedness to Modes OCB and PMAC. In Advances in Cryptology - ASIACRYPT 2004, Pil Joong Lee (Ed.). Springer Berlin Heidelberg, Berlin, Heidelberg, 16–31.
[19] Ceph website. [n.d.]. https://docs.ceph.com/en/latest/radosgw/encryption/ Accessed: 2022-03-20.
[20] fio website. [n.d.]. https://fio.readthedocs.io/ Accessed: 2022-03-15.
[21] RocksDB website. [n.d.]. http://rocksdb.org/ Accessed: 2022-03-15.
[22] NVM Express Workgroup. 2014. NVM Express® Base Specification revision 1.2. https://nvmexpress.org/developers/nvme-specification/
[23] Qionglu Zhang, Shijie Jia, Junlin He, Xinyi Zhao, Luning Xia, Yingjiao Niu, and Jiwu Jing. 2020. Ensuring Data Confidentiality with a Security Mode. In 2020 IEEE 5th International Conference on Cloud Computing and Big Data Analytics (ICCCBDA). 289–294. https://doi.org/10.1109/ICCCBDA49378.2020.9095700