Design and Implementation of a Windows Kernel Driver for LUKS2-encrypted Volumes

I do not know yet whether I want to have a subtitle, have a placeholder for now

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Abstract

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Contents

1 Introduction

Explain use case etc.

Note that in this thesis the terms *disk*, *drive*, *volume* and *partition* are used somewhat loosely and probably mean roughly the same.

2 Background

2.1 LUKS2 Disk Encryption

Linux Unified Key Setup 2, or short LUKS2, is the second version of a disk encryption standard. It provides a specification [1] for a on-disk format for storing the encryption metadata as well as the encrypted user data. Unlocking an encrypted disk is achieved by providing one of possibly multiple passphrases or keyfiles. The intended usage of LUKS2 is together with the Linux dm-crypt subsystem, but that is not mandatory[1].

The differences between the original LUKS and LUKS2 are minor. According to [1], LUKS2 adds "more flexible ways of storing metadata, redundant information to provide recovery in the case of corruption in a metadata area, and an interface to store externally managed metadata for integration with other tools." Practically, this means that LUKS2 has a different on-disk layout and, among other things, supports more password hashing algorithms (more precisely, password-based key derivation functions).

The reference implementation[2] is designed only for usage on Linux, which is why we developed a new Rust library for interacting with LUKS2 partitions. This is not a full equivalent, but only a cross-platform helper. Its task is to take care of all the cryptographic work needed before actually decrypting and encrypting data. Notably, it lacks the following features of the reference implementation:

- formatting new LUKS2 partitions,
- modifying or repairing existing LUKS2 partitions,
- converting a LUKS partition to a LUKS2 partition,
- actually mounting a LUKS2 partition for read/write usage (this is what our kernel driver and its userspace configuration tool is for).

Our library does provide access to the raw decrypted user data, but the practical use of this is very limited: the decrypted data is in the format of a filesystem, e.g. FAT32, btrfs, or Ext4. Therefore a filesystem driver is needed to actually access the stored files. One way of exposing the decrypted data to the system's filesystem drivers is by transparently decrypting the data directly in the kernel, which is what our driver does (see section 5).

2.1.1 On-Disk Format

Figure 1 shows the high-level layout of a LUKS2-encrypted disk.

The two binary headers have a size of exactly one sector, so that they are always written atomically. Only the first 512 bytes are actually used. The header marks the disk as following the LUKS2 specification, and contains metadata such as labels, a UUID, and a header checksum. The labels and UUID can be accessed using the `blkid`[3] command-line tool and also be used in the `udev`[4] Linux subsystem. For the detailed contents, see Figure 2. Figure 3 also contains an example hexdump of a binary header.

The sector containing the binary header is followed by the JSON area. This area arguably contains the metadata that is most relevant for decryption and encryption. Figure 4 contains an overview of the objects stored in JSON and their relationships. For

[1] As we show in this thesis, it is possible to make the combination of LUKS2 and Windows work.
[2] `https://gitlab.com/cryptsetup/cryptsetup`
[3] `https://linux.die.net/man/8/blkid`
[4] `https://linux.die.net/man/8/udev`

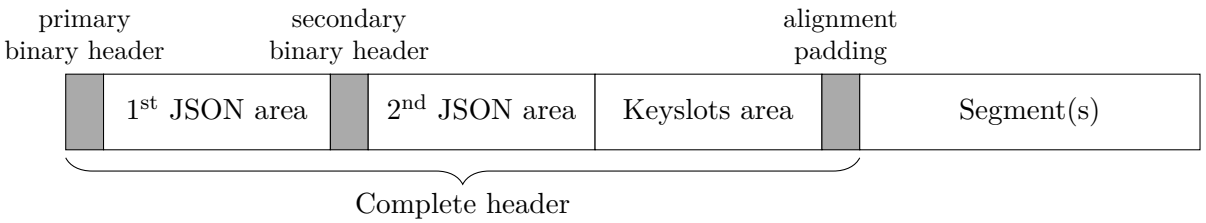

Figure 1: LUKS2 on-disk format (modified after [1]). The complete header consists of three areas: a binary header of exactly one 4096-byte sector, JSON metadata, and the binary keyslots data. A *keyslot* is an "encrypted area on disk that contains a key" [1]. For redundancy, the binary header and the JSON metadata are stored twice. After that follow one or areas containing encrypted user data. The specification calls these areas *segments*.

```c
#define MAGIC_1ST "LUKS\xba\xbe"
#define MAGIC_2ND "SKUL\xba\xbe"
#define MAGIC_L     6
#define UUID_L     40
#define LABEL_L    48
#define SALT_L     64
#define CSUM_ALG_L 32
#define CSUM_L     64

struct luks2_hdr_disk {
    char     magic[MAGIC_L];       // MAGIC_1ST or MAGIC_2ND
    uint16_t version;              // Version 2
    uint64_t hdr_size;             // size including JSON area [bytes]
    uint64_t seqid;                // sequence ID, increased on update
    char     label[LABEL_L];       // ASCII label or empty
    char     csum_alg[CSUM_ALG_L]; // checksum algorithm, "sha256"
    uint8_t  salt[SALT_L];         // salt, unique for every header
    char     uuid[UUID_L];         // UUID of device
    char     subsystem[LABEL_L];   // owner subsystem label or empty
    uint64_t hdr_offset;           // offset from device start [bytes]
    char    _padding[184];         // must be zeroed
    uint8_t  csum[CSUM_L];         // header checksum
    char    _padding4096[7*512];   // Padding, must be zeroed
} __attribute__((packed));
```

Figure 2: LUKS2 binary header structure from [1]. Integers are stored in big-endian format, and all strings have to be null-terminated. The `magic`, `version`, and `uuid` fields are also present in the LUKS1 binary header and were placed at the same offsets as there.

this thesis' brevity's sake, please refer to Chapter 3.1 in [1] for an example of a LUKS2 JSON area.

After the JSON area, the keyslots area is stored on the disk. This is space reserved for storing encrypted cryptographic keys. The metadata from the JSON keyslot objects describe the position of a key on the disk as well as information on how to decrypt it.

```
0000  4C 55 4B 53 BA BE 00 02  00 00 00 00 00 00 40 00  LUKSº¾........@.
0010  00 00 00 00 00 00 00 03  54 68 69 73 20 69 73 20  ........This is
0020  61 6E 20 41 53 43 49 49  20 6C 61 62 65 6C 00 00  an ASCII label..
0030  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
0040  00 00 00 00 00 00 00 00  73 68 61 32 35 36 00 00  ........sha256..
0050  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
0060  00 00 00 00 00 00 00 00  EB 0F D2 C6 E3 D2 8D 4B  ........ë.ÒÆãÒ.K
0070  BB 2B 8A 49 E6 2E 4E B7  04 2F A9 39 76 71 8F 8A  »+ŠIæ.N·./©9vq.Š
0080  33 E8 F3 90 FF DC 4D 3D  E8 30 7B 37 01 30 E7 5D  3èó.ÿÜM=è0{7.0ç]
0090  AD A0 57 1C 0E 63 BC D4  DD 3C EC F5 DE 67 F8 D8  ..W..c¼ÔÝ<ìõÞgøØ
00A0  F2 7E 82 CD B9 DD 77 10  65 39 33 64 63 61 66 61  ò~‚Í¹Ýw.e93dcafa
00B0  2D 65 65 30 62 2D 34 31  36 38 2D 61 61 37 63 2D  -ee0b-4168-aa7c-
00C0  66 33 30 34 37 34 38 38  36 61 32 65 00 00 00 00  f30474886a2e....
00D0  54 68 69 73 20 69 73 20  61 6E 20 6F 70 74 69 6F  This is an optio
00E0  6E 61 6C 20 73 65 63 6F  6E 64 61 72 79 20 6C 61  nal secondary la
00F0  62 65 6C 00 00 00 00 00  00 00 00 00 00 00 00 00  bel.............
0100  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
0110  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
0120  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
0130  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
0140  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
0150  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
0160  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
0170  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
0180  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
0190  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
01A0  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
01B0  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
01C0  91 A4 A9 83 03 FF FB 68  4E C2 94 6F 4C 78 71 AF  ‘¤©f.ÿûhNÂ"oLxq¯
01D0  AE 1A 91 F8 E0 2C F3 71  D5 17 CB 60 E5 2F D6 36  ®.‘øà,óqÕ.Ë‘å/Ö6
01E0  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
01F0  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
```

Figure 3: LUKS2 binary header example. The fields, as described in Figure 2, were coloured differently to be easily distinguishable. A similar header, although with different salt and hash, can be generated by executing `fallocate -l 16M luks2.img && cryptsetup luksFormat --label 'This is an ASCII label' --subsystem 'This is an optional secondary label' --uuid e93dcafa-ee0b-4168-aa7c-f30474886a2e luks2.img` in a Linux shell.

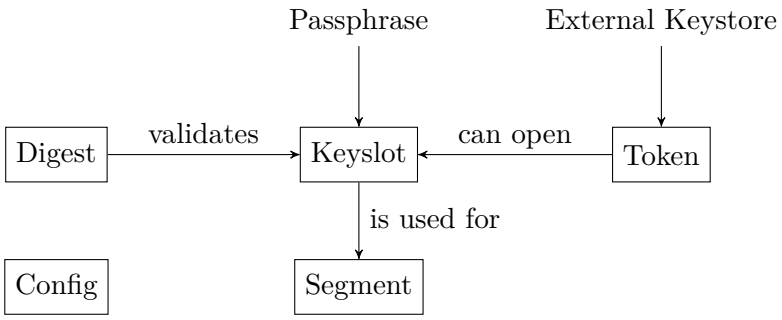

Figure 4: LUKS2 object schema from [1]. The most important objects are the following: *keyslots*, which describe the details of how cryptographic keys are stored and encrypted; *digests*, which can be used to verify that one has successfully extracted a key from a keyslot; and *segments*, which describe the disk areas where the encrypted user data is stored. Figure 1 shows where the areas described by the keyslot and segment objects actually lie on disk.

2.1.2 Unlocking a Partition

For simplicity, our LUKS2 Rust library does not support unlocking a keyslot using an external keystore defined by a token. Only unlocking via password is implemented. The library does however include support for different *password-based key derivation functions*

(PBKDFs), namely `pbkdf2` with SHA-256, `argon2i`, and `argon2id`. These are all the PBKDF algorithms that are listed in the LUKS2 specification (see [1], Table 3).

maybe [2] could be useful here?

The LUKS2 specification allows for multiple segments in one partition. To make things easier, our driver only supports unlocking one segment. Therefore, in this thesis we may speak of unlocking a partition and mean unlocking one of the partition's segments.

To unlock a segment means to derive the cryptographic key that is needed for reading decrypted or writing encrypted data. This key is called the segment's *master key*.

LUKS2 uses a process called *anti-forensic splitting* to store the master key on the disk. This method was introduced in [3]. It is used to diffuse the key's bytes into a longer sequence of bytes that has the following property: if at least one bit of the diffused sequence is changed, the key cannot be recovered. This is achieved by a clever combination of XOR and a hash function. The motivation behind this to make it easier (or possible) to dispose of an old key in such a way that it cannot be recovered from the disk. This is because it is much more feasible to partially erase a long sequence of bytes than to completely erase a short sequence. Erasing here means to overwrite the data in such a way that it cannot be recovered, which is not as trivial as one might think.

[3] calls the operation that splits data anti-forensically AFsplit and the recovery operation AFmerge. We will adhere to this convention (with slight variations).

To necessitate the need of a password to recover the key, the data is also encrypted before it gets written to the disk. The encryption key is a hash of the password obtained by a PBKDF.

The properties of anti-forensic splitting can be used when the user wants to change the password: the master key is derived using the old password and then re-encrypted with the new password. The key as it was encrypted with the old password can then be destroyed.

[3] presents two templates for storing keys, TKS1 and TKS2. The difference is whether the key is encrypted before or after splitting it. LUKS and LUKS2 use TKS2, which is schematically explained in Figure 5. The hash function used by LUKS2 for anti-forensic splitting is SHA-256. Figure 6 shows the outline of an implementation of TKS2 in Rust.

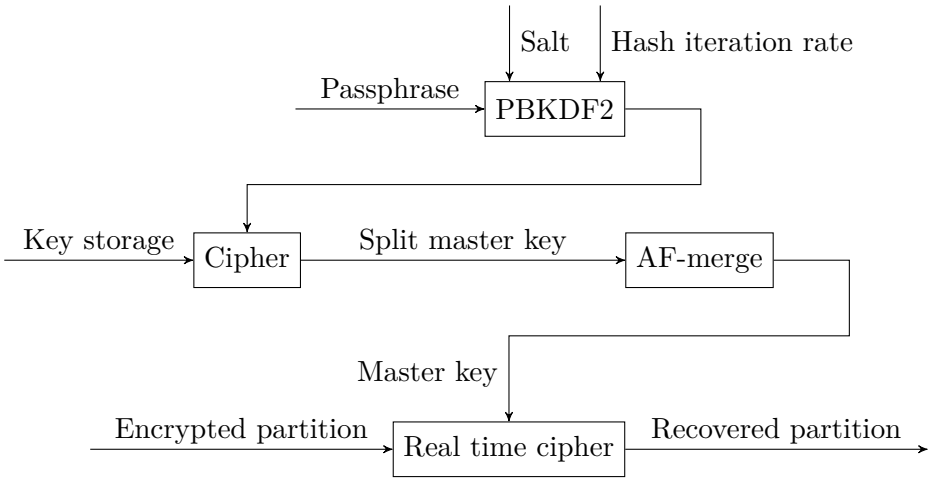

Figure 5: TKS2 scheme (modified after [3]).

The keyslots area on the disk is large enough to store multiple split and encrypted master keys. Thus one can configure a LUKS2 partition to be unlocked by different passwords. Unlocking then works as described in Figure 7.

```rust
fn decrypt_keyslot(
    password: &[u8], keyslot: &LuksKeyslot, json: &LuksJson, /* ... */
) -> Result<Vec<u8>, LuksError> {
    let mut k = vec![
        0; keyslot.key_size() as usize * keyslot.af.stripes() as usize
    ];
    // read keyslot data from disk into k...

    let mut pw_hash = vec![0; area.key_size() as usize];
    match keyslot.kdf() {
        // hash into pw_hash using pbkdf2, argon2i, or argon2id...
    }

    // decrypt keyslot area using the password hash as key
    match area.key_size() {
        32 => {
            let key1 = Aes128::new_varkey(&pw_hash[..16]).unwrap();
            let key2 = Aes128::new_varkey(&pw_hash[16..]).unwrap();
            let xts = Xts128::<Aes128>::new(key1, key2);
            xts.decrypt_area(&mut k, sector_size, 0, get_tweak_default);
        },
        // 64 byte key uses AES256 instead...
    }

    // merge and hash master key
    let master_key = af::merge(
        &k, keyslot.key_size() as usize, af.stripes() as usize
    );
    let digest_actual = base64::decode(json.digests[&0].digest())?;
    let mut digest_computed = vec![0; digest_actual.len()];
    let salt = base64::decode(json.digests[&0].salt())?;
    pbkdf2::pbkdf2::<Hmac<Sha256>>(
        &master_key, &salt, json.digests[&0].iterations(), &mut digest_computed
    );

    // compare digests
    if digest_computed == digest_actual {
        Ok(master_key)
    } else {
        Err(LuksError::InvalidPassword)
    }
}
```

Figure 6: LUKS2 master key decryption in Rust. Some values are hardcoded: only the digest with index 0 is used (lines 29, 31, 33), and it is assumed that the digest algorithm is always `pbkdf2` with SHA-256 (line 32). The latter is compliant with the specification, which lists this digest algorithm as the only option, but not optimal in the sense of input validation.

2.1.3 Using an Unlocked Partition

After a partition has been unlocked, i.e. after the master key of one of its segments has been decrypted, the partition is ready to be read from and written to. This happens using what Figure 5 calls a real time cipher. LUKS2 supports different encryption algorithms for this purpose, see Figure 8 for a selection of them. Our driver only supports the default aes-xts-plain64 encryption. Therefore we will focus on that in this section.

1. The user supplies a password.
2. One of the available keyslots is selected.
3. Using the password and keyslot, the master key is decrypted as described above.
4. The derived master key is hashed and the result compared to the corresponding digest. Which digest and what hash parameters to used is defined in the JSON section.
5. If the digests match, the master key has been successfully decrypted. Else go to step 2 and select a keyslot that has not been used yet.
6. If the master key could not be decrypted with all available keyslots, the supplied password was not correct.

Figure 7: LUKS2 master key decryption with multiple available keyslots. LUKS2 allows defining priorities that govern the order in that the available keyslots are tried. For a more detailed pseudocode see Figure 5 in [4].

Algorithm in `dm-crypt` notation	**Description**
aes-xts-plain64	AES in XTS mode with sequential IV
aes-cbc-essiv:sha256	AES in CBC mode with ESSIV IV
serpent-xts-plain64	Serpent cipher with sequential IV
twofish-xts-plain64	Twofish cipher with sequential IV

Figure 8: Selection of LUKS2 encryption algorithms (modified after [1]). The `dm-crypt` notation follows this format: cipher[:keycount]-chainmode-ivmode[:ivopts] [5]. See [6] for the CBC mode and the Serpent and Twofish ciphers, and [3] for the ESSIV IV mode.

The AES encryption algorithm is a block cipher for processing 128 bit data blocks [7]. To encrypt data longer than one block, a *block cipher mode* is needed [6]. These are encryption functions that build on a existing block cipher. When using aes-xts-plain64, LUKS2 uses the XTS block cipher mode. The defining IEEE standard [8] describes it as follows: "XTS-AES is a tweakable block cipher that acts on data units of 128 b[its] or more and uses the AES block cipher as a subroutine. The key material for XTS-AES consists of a data encryption key (used by the AES block cipher) as well as a 'tweak key' that is used to incorporate the logical position of the data block into the encryption." This tweak key is called the *initialization vector*, or IV, in the context of LUKS2. This is what the "plain64" in aes-xts-plain64 means: "the initial vector is the 64-bit little-endian version of the sector number, padded with zeros if necessary" [5]. This sector number is relative to the first sector of the segment, i.e. the first sector uses an IV of 0.

The need for an IV arises from a critical problem that occurs when encrypting each block separately with the same key: if some unencrypted blocks are identical, then so will be their encrypted counterparts. This can lead to leaked information about structure and contents of the plaintext [6].

All this theory may sound complicated, but in subsubsection 5.2.3 we will see that the

practical usage is quite simple[5].

2.2 Introduction to Windows Kernel Driver Development

This section gives an introduction on the development of Windows kernel drivers and related important concepts.

2.2.1 Structure and Hierarchy of the Windows Operating System

Roughly summarize important concepts from chapters 1 and 2 of [9]

2.2.2 The Windows Driver Model for Kernel Drivers

Also explain how it gets loaded (if not done already)

2.2.3 Communication Between Kernel and Userspace

Via ports

[5]. The implementation of cryptographic algorithms of course remains non-trivial. Implementing AES itself has been made much easier using the AES-NI CPU instruction set, though.

3 Related Work

3.1 Measuring Filesystem Driver Performance

3.2 Cryptographic Aspects of LUKS2

[3]

Search for more papers, e.g. attacks against LUKS? e.g. [2]

4 Other Approaches

4.1 Linux Kernel Implementation of LUKS2

4.2 VeraCrypt

4.3 BitLocker

[10] and [11] and [12] and [13]

5 Design and implementation of our approach

5.1 Failed Attempts

FilterManager framework

Mention KMDF / UMDF and why we didn't use that if not already done in earlier section

5.2 The Final WDM Driver

Why WDM?

5.2.1 Architecture

5.2.2 Initialization and Configuration

`luks2filterstart.exe`

5.2.3 De-/encrypting Reads and Writes

custom AES implementation

make sure this chapter and subsubsection 2.1.3 are not too similar

LUKS2 supports many encryption algorithms (see [1], Table 4), but `luks2flt` only supports `aes-xts-plain64`.

```
VOID
EncryptWriteBuffer(
    PUINT8 Buffer,
    PLUKS2_VOLUME_INFO VolInfo,
    PLUKS2_VOLUME_CRYPTO CryptoInfo,
    UINT64 OrigByteOffset,
    UINT64 Length
)
{
    UINT64 Sector = OrigByteOffset / VolInfo->SectorSize;
    UINT64 Offset = 0;
    UINT8 Tweak[16];

    while (Offset < Length) {
        ToLeBytes(Sector, Tweak);
        CryptoInfo->Encrypt(
            &CryptoInfo->Xts, Buffer + Offset,
            VolInfo->SectorSize, Tweak
        );
        Offset += VolInfo->SectorSize;
        Sector += 1;
    }
}
```

5.2.4 Handling Other Request Types

5.3 Security Considerations

How does `cryptsetup` send the master key to `dm-crypt`?

6 Performance of Our Driver

6.1 First Experiments

6.2 Final Experimental Setup

6.3 Results

7 Discussion

8 Conclusion

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