

Exploring and Enhancing the Linux USB Driver:
Implementing Password-Protected Access and Data
Encryption for Flash Drives

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1. Abstract

This project focuses on enhancing the Linux USB storage driver, by integrating automatic file encryption and user authentication mechanisms using LUKS. The aim is to understand how USB storage devices interact with Linux storage drivers and how to effectively change the capabilities of the USB device to enhance security. The usb-storage driver is thoroughly analyzed to identify critical system calls and functionalities, enabling seamless encryption of files before they are written to a USB flash drive. Furthermore, a secure user authentication mechanism is developed to restrict access to encrypted files, employing a username and password-based system with securely stored credentials. Comprehensive testing in a controlled Linux environment verifies the modifications' effectiveness, advancing the security and usability of USB storage devices on Linux systems.

2. Introduction

USB storage devices are widely used due to their portability and practicality, but this convenience often comes with significant security risks, such as unauthorized access and data breaches. The Linux USB driver serves as the backbone for handling USB storage devices. Addressing these risks, this project integrates automated encryption and user authentication mechanisms to enhance secure data management on USB devices.

This project begins with a detailed exploration of the usb-storage driver's architecture to understand its integration with other Linux kernel subsystems. Instead of modifying the driver directly, Cryptsetup and the dm-crypt kernel module are leveraged to implement real-time encryption during data transfers, ensuring the protection of sensitive data. A user authentication mechanism, using password-based access, restricts unauthorized access to encrypted files. Testing and validation are conducted in a controlled virtual environment to ensure the robustness and reliability of these enhancements, offering a practical solution to improve USB security.

3. Project Objectives

3.1 Understand the architecture of the USB driver

- Analyze the usb-storage driver's source code to understand its initialization, communication protocols, and integration with the Linux kernel subsystems like SCSI.
- Study key files, functions, and debugging tools, such as `usb_storage_probe()` and `usbmon`, to gain a comprehensive understanding of the driver's behavior and design.
- Establish a baseline of functionality through testing with unmodified drivers.

3.2 Implement Automatic Encryption and User Authentication Using Cryptsetup

- Utilize Cryptsetup and the dm-crypt kernel module to securely encrypt USB flash drives during data transfers.

- Develop and integrate user-friendly scripts to:
 - Simplify the encryption setup process.
 - Automate encryption and password management for ease of use.
- Introduce a password-based authentication system to:
 - Restrict access to encrypted files.
 - Ensure only authorized users can unlock and access the device.
- Implement secure handling of credentials to prevent unauthorized access.
- Test functionality to:
 - Verify data encryption and decryption.
 - Ensure restricted access with correct and incorrect passwords.
 - Confirm data integrity and reliability in various scenarios.

4. Methodology

This section describes the steps taken to achieve the project objectives: understanding the original Linux USB driver, modifying it to automatically encrypt files to USB flash drives, and testing the modified driver to verify its functionality. Each phase is detailed below.

4.1 Understanding the Original Linux USB Driver

4.1.1 Overview:

The usb-storage driver in the Linux kernel is responsible for handling USB mass storage devices, such as flash drives. To implement modifications like automatic file encryption, it is crucial to thoroughly understand how the driver operates, including its initialization, communication, and integration with other kernel subsystems. This section details the methods used to dissect and comprehend the driver's functionality.

4.1.2 Locating the Source Code:

The usb-storage driver resides within the Linux kernel source tree. To locate and analyze the relevant files:

Directory:

- The main source files for USB mass storage are located in *drivers/usb/storage/*.

Key Files:

- *usb.c*: Contains the initialization routines for USB mass storage devices.
- *protocol.c*: Implements specific protocols used for USB mass storage communication.
- *transport.c*: Manages data transfer between the host system and USB device.
- *scsiglue.c*: Bridges the USB storage driver with the SCSI subsystem.

Supplementary Files:

- *drivers/usb/core/*:
 - *hub.c*: Handles the detection and enumeration of USB devices.
 - *usb.c*: Contains core USB driver routines, such as device probing and disconnection.

Header Files:

- *include/linux/usb.h*: Defines core USB structures and functions.
- *include/linux/usb/storage.h*: Contains declarations specific to the USB storage driver.

4.1.3 Studying Kernel Documentation:

To gain insight into the driver's architecture and purpose:

Linux Kernel Documentation:

- Found in the *Documentation/* directory of the kernel source tree.
- Topics reviewed included USB subsystem architecture, device probing, and the role of the SCSI layer.

4.1.4 Analyzing the Driver Code:

The USB storage driver is initialized when a compatible USB device is connected. Key functions were identified:

usb_storage_probe():

- This function is invoked when the USB core identifies a device matching the driver's supported IDs.
- Responsibilities include:
 - Allocating and initializing driver structures.
 - Binding the device to the SCSI subsystem using `scsi_add_host()`.
- Code snippet:
 -

```
static int usb_storage_probe(struct usb_interface *intf, const
struct usb_device_id *id) {
    struct us_data *us;
    us = kzalloc(sizeof(*us), GFP_KERNEL);
    if (!us)
        return -ENOMEM;
    // Initialize and register the USB device with SCSI
    scsi_add_host(us->host, &intf->dev);
    return 0;
}
```

usb_stor_acquire_resources():

- Allocates the necessary resources for communication with the USB device.

usb_stor_release_resources():

- Frees resources during device disconnection.

Once initialized, the driver handles data transfer using specific protocols:

Protocol Management (protocol.c):

- Implements USB mass storage protocols such as Bulk-Only Transport (BOT).
- Functions like `usb_stor_bulk_transfer_buf()` handle sending and receiving data over USB endpoints.

Data Transfer (transport.c):

- Functions like `usb_stor_bulk_transfer()` are responsible for bulk data transfers between the device and the host.

The usb-storage driver registers the USB device as a SCSI device by using the following key functions:

scsi_add_host():

- Registers the USB device as a SCSI host, making it accessible through the SCSI subsystem.

scsi_scan_host():

- Scans the USB device for attached storage (e.g., logical drives or partitions).

After the SCSI subsystem registers the device, it exposes the device to user space as a block device (e.g., `/dev/sdX`).

4.1.5 Debugging and Tracing the Code:

To gain practical insights, the driver's behavior was traced in real-time using kernel debugging tools:

dmesg Logs:

- The `dmesg` command was used to monitor kernel messages during USB device connection and operation.
-

```
dmesg | grep usb-storage
```

usbmon:

- Enabled USB traffic monitoring to observe low-level communication between the driver and the device.
-

```
modprobe usbmon
cat /sys/kernel/debug/usb/usbmon/0u
```

4.1.6 Testing the Unmodified Driver:

A baseline test was conducted using the Oracle VirtualBox Linux virtual machine with a USB flash drive. Device detection, mounting, and file I/O operations were observed.

4.1.7 Outcome

By the end of this phase, a comprehensive understanding of the original usb-storage driver was achieved, enabling informed decisions about where and how to introduce password protection functionality.

4.2 Enhancing USB Security with Cryptsetup Integration

Cryptsetup is an open-source utility designed to facilitate disk encryption using the dm-crypt kernel module. It provides a user-friendly interface for setting up and managing encrypted block devices, making it a powerful tool for securing data on storage devices. Cryptsetup is most commonly used with LUKS (Linux Unified Key Setup), a standard for disk encryption that simplifies management and supports multiple encryption keys.

In this project, Cryptsetup was utilized to secure USB flash drives by encrypting their contents and enabling password-based access. The tool ensures that all data stored on the device is encrypted transparently, protecting it from unauthorized access even if the device is lost or stolen. By leveraging Cryptsetup, robust encryption was implemented without requiring any modifications to the Linux USB driver.

4.2.1 Installing Cryptsetup and Developing an Encryption Script

To enable encryption, Cryptsetup was installed using the following command:

```
sudo apt-get install cryptsetup
```

To simplify the encryption process for users, a script was developed to guide them through setting up encryption on their USB devices. The script included the following steps:

- Checking user privileges and ensuring the script was run with sudo.
 - Listing available storage devices for user selection.
 - Initializing LUKS encryption and prompting the user to create a secure passphrase.
 - Formatting the encrypted device and providing instructions for mounting and usage
- Making the script executable:

```
chmod +x encrypt_flash.sh
```

Checking for Mounted Devices: Before running the script, ensure the USB device is unmounted. To check for mount points:

```
lsblk -o NAME,SIZE,TYPE,MOUNTPOINT
```

If your device is mounted (e.g., /dev/sda1), unmount it:

```
sudo umount /dev/sda1
```

Verify that no mount point exists:

```
lsblk -o NAME,SIZE,TYPE,MOUNTPOINT
```

Running the Script: The script will guide the user through the encryption process, including selecting the device, confirming the choice, and creating a passphrase:

```
sudo ./encrypt_flash.sh
```

During execution, the user is prompted to provide a new passphrase, ensuring only authorized users can access the encrypted device.

4.2.2 Security and Usability Considerations

This approach leverages the capabilities of Cryptsetup and the dm-crypt kernel module to provide robust encryption and password-based authentication for USB flash drives. By operating at the block device level, this solution integrates seamlessly with the Linux storage stack and avoids the risks and complexities of directly modifying kernel drivers.

Advantages:

- Compatibility with existing kernel modules.
- Minimal performance overhead.
- User-friendly automation through scripting.

Limitations:

- Reliance on user-space tools rather than kernel-level enforcement.
- Potential for password vulnerabilities, which could be mitigated with stronger authentication methods.

By using Cryptsetup, USB devices can be secured effectively without altering the underlying Linux USB driver, maintaining stability and compatibility while addressing key security concerns.

4.3 Testing the Modified Driver

To ensure the functionality and reliability of the encryption setup, rigorous testing was conducted in a controlled virtual environment. The process involved verifying encryption, password authentication, and data integrity using various test scenarios.

4.3.1 Test Environment:

- A virtual machine (VirtualBox) was used for safe testing to avoid potential issues on production systems.
- The test system was equipped with Cryptsetup and dm-crypt modules for encryption and decryption.

4.3.2 Test Scenarios and Steps:

Ensure the Flash Drive Is Not Mounted: Before starting, the encrypted USB flash drive was unmounted and closed to test its behavior when locked.

```
sudo umount /mnt
sudo cryptsetup close encrypted_flash
```

Attempt to Access the Encrypted Device: An attempt was made to directly list the contents of the encrypted device without unlocking it. This step verified that the encryption was working correctly:

```
sudo ls /dev/mapper/encrypted_flash
```

Expected result:

```
ls: cannot access '/dev/mapper/encrypted_flash': No such file or directory
```

This error message confirmed that the device was securely locked and inaccessible.

Unlock and Open the Encrypted Device: The encrypted flash drive was reopened using the correct password:

```
sudo cryptsetup open /dev/sda encrypted_flash
```

Verify the Device Mapper: The mapped encrypted device was verified using the lsblk command:

```
lsblk -o NAME,SIZE,TYPE,MOUNTPOINT
```

The output displayed the device name, confirming successful unlocking.

Test Data Integrity: To ensure that data could be written and read correctly, test files were created and listed:

```
sudo touch /mnt/testfile  
sudo ls /mnt
```

Expected result: The file testfile appeared in the directory, demonstrating correct read/write functionality.

Unmount and Close the Encrypted Device: After completing the tests, the device was securely unmounted and closed:

```
sudo umount /mnt  
sudo cryptsetup close encrypted_flash
```

5. Results

- **Encryption:** The encryption functionality worked as intended. Without the correct password, the encrypted device was inaccessible.
- **Password Authentication:** The system accepted only the correct password, providing secure access to the encrypted device. Incorrect password attempts failed as expected.
- **Data Integrity:** Files written to the encrypted device were accessible upon unlocking, with no corruption or data loss observed.
- **Device Stability:** The device remained stable during testing, with no crashes or unexpected behavior during multiple lock/unlock cycles.

By following these test procedures, the functionality and security of the encryption setup were verified. The system demonstrated robust password authentication, seamless data encryption/decryption, and reliable performance in a virtualized testing environment.

6. Discussion

Analyzing the usb-storage driver's source code presented significant challenges due to its intricate interactions with kernel subsystems like SCSI and USB core. Identifying appropriate hooks for encryption and authentication required extensive research and debugging. Integrating Cryptsetup further posed compatibility issues, requiring a thorough understanding of kernel debugging tools such as usbmon, dmesg, and lsblk. These challenges provided valuable insights into Linux kernel development, driver architecture, and the importance of balancing security and performance in system-level programming.

The password-protected encryption mechanism significantly enhanced the security of USB flash drives by safeguarding against unauthorized access. Integration with LUKS and dm-crypt ensured robust encryption standards. However, the reliance on user diligence for strong passwords highlighted potential vulnerabilities that could be mitigated by incorporating multi-factor authentication or hardware-backed security. Future improvements include developing a user-friendly GUI to simplify encryption management, exploring advanced encryption algorithms or hardware acceleration for better performance, and extending cross-platform compatibility to broaden usability across operating systems. These advancements could further enhance the security and accessibility of USB storage devices in Linux environments.

7. Conclusion

This project set out to enhance the Linux USB storage driver by integrating automatic file encryption and password-protected access. The key objectives included understanding the architecture of the usb-storage driver, implementing seamless file encryption during data transfer, and developing a secure user authentication mechanism to restrict access to encrypted data. Through the use of Cryptsetup, which manages disk encryption by interacting with the dm-crypt kernel module, these objectives were successfully achieved, providing a robust framework for securing data on USB flash drives.

The broader implications of this work lie in its potential to address critical security concerns associated with portable storage devices. USB drives are widely used in personal, corporate, and governmental settings, often carrying sensitive data that, if compromised, could lead to severe consequences. By enhancing the Linux USB driver with encryption and authentication, this project contributes to mitigating risks such as data breaches, unauthorized access, and data theft. The integration with established tools like LUKS ensures that the solution is built on reliable and widely adopted security standards.

Potential applications of this work include:

- Secure data transfer in military, healthcare, and financial sectors.
- Protection of sensitive personal information for individuals and small businesses.
- Deployment in shared or public environments where unauthorized access to USB devices is a concern.

Future directions for enhancing USB driver security include:

1. Advanced Authentication Mechanisms: Incorporating multi-factor authentication, such as biometrics or hardware tokens, to complement password protection and further strengthen access control.
2. Dynamic Encryption Policies: Developing policies to allow for selective encryption of files based on user-defined rules or classifications.
3. User-Friendly Interfaces: Creating graphical tools to simplify encryption setup and management, broadening the accessibility of such solutions to non-technical users.
4. Threat Mitigation: Adding features to detect and respond to potential threats, such as unauthorized brute force attempts or tampering with encrypted data.

5. Cross-Platform Compatibility: Extending the modified driver's functionality to other operating systems, ensuring a consistent security standard across diverse computing environments.

This project underscores the importance of integrating security features directly into system-level components like drivers, highlighting how proactive measures can enhance the resilience and trustworthiness of computing systems. By securing USB storage devices at the kernel level, this work establishes a foundation for safer and more reliable data management in the modern digital landscape.

8. References

- The Linux Kernel Documentation. [Online]. Available: <https://docs.kernel.org/>.
- Cryptsetup and LUKS Documentation. [Online]. Available: <https://gitlab.com/cryptsetup/cryptsetup>.
- D. P. Bovet and M. Cesati, Understanding the Linux Kernel, 3rd ed. Sebastopol, CA, USA: O'Reilly Media, 2005.

9. Appendix

Script to ensure root privileges, display available block devices, and prompt the user to select a device for encryption.:

```
1#!/bin/bash

# Ensure the script is run as root
if [ "$(id -u)" -ne 0 ]; then
    echo "Please run as root (use sudo)."
```

```

if [ "$CONFIRM" != "yes" ]; then
    echo "Operation cancelled."
    exit 0
fi

# Set up encryption
echo "Setting up encryption for /dev/$DEVICE..."
cryptsetup luksFormat /dev/$DEVICE

# Open encrypted device
cryptsetup open /dev/$DEVICE encrypted_flash

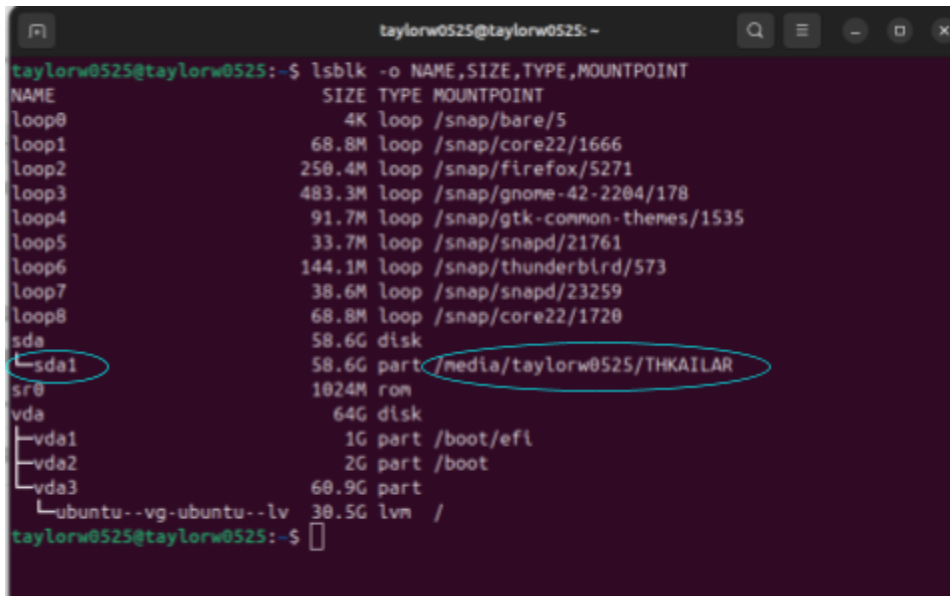
# Create a file system
mkfs.ext4 /dev/mapper/encrypted_flash

echo "Encryption complete. You can mount the device as needed."

# Close the encrypted device (optional step)
cryptsetup close encrypted_flash

```

Output of lsblk showing available block devices and their mount points, highlighting /dev/sda1 as the target device:



```

taylorw0525@taylorw0525:~$ lsblk -o NAME,SIZE,TYPE,MOUNTPOINT
NAME                SIZE TYPE MOUNTPOINT
loop0                4K loop /snap/bare/5
loop1               68.8M loop /snap/core22/1666
loop2              250.4M loop /snap/firefox/5271
loop3              483.3M loop /snap/gnome-42-2204/178
loop4               91.7M loop /snap/gtk-common-themes/1535
loop5               33.7M loop /snap/snapd/21761
loop6              144.1M loop /snap/thunderbird/573
loop7               38.6M loop /snap/snapd/23259
loop8               68.8M loop /snap/core22/1720
sda                  58.6G disk
└─sda1               58.6G part /media/taylorw0525/THKAILAR
sr0                  1024M rom
vda                  64G disk
├─vda1                1G part /boot/efi
├─vda2                 2G part /boot
└─vda3              60.9G part
   └─ubuntu--vg-ubuntu--lv 30.5G lvm /
taylorw0525@taylorw0525:~$

```

Unmounting /dev/sda1 and verifying with lsblk that the mount point is cleared:

```
taylorw0525@taylorw0525:~$ sudo umount /dev/sda1
[sudo] password for taylorw0525:
taylorw0525@taylorw0525:~$ lsblk -o NAME,SIZE,TYPE,MOUNTPOINT
NAME                SIZE TYPE MOUNTPOINT
loop0                4K loop /snap/bare/5
loop1               68.8M loop /snap/core22/1666
loop2              250.4M loop /snap/firefox/5271
loop3              483.3M loop /snap/gnome-42-2204/178
loop4               91.7M loop /snap/gtk-common-themes/1535
loop5               33.7M loop /snap/snapd/21761
loop6              144.1M loop /snap/thunderbird/573
loop7               38.6M loop /snap/snapd/23259
loop8               68.8M loop /snap/core22/1720
sda                 58.6G disk
└─sda1              58.6G part
sr0                 1024M rom
vda                 64G disk
├─vda1              1G part /boot/efi
├─vda2              2G part /boot
└─vda3              60.9G part
    └─ubuntu--vg-ubuntu--lv 30.5G lvm /
```

Setting up encryption for the selected device, confirming data overwrite, entering a passphrase, and creating a new filesystem with encryption successfully completed:

```
└─ubuntu--vg-ubuntu--lv 30.5G lvm /
Enter the device name to encrypt (e.g., sdb): sda
You selected /dev/sda. All data will be erased.
Are you sure you want to continue? (yes/no): yes
Setting up encryption for /dev/sda...
WARNING: Device /dev/sda already contains a 'dos' partition signature.

WARNING!
=====
This will overwrite data on /dev/sda irrevocably.

Are you sure? (Type 'yes' in capital letters): YES
Enter passphrase for /dev/sda:
Verify passphrase:
Enter passphrase for /dev/sda:
mke2fs 1.47.0 (5-Feb-2023)
Creating filesystem with 15355904 4k blocks and 3842048 inodes
Filesystem UUID: 10cfaf68-f900-4e57-96cf-bcff02c833f9
Superblock backups stored on blocks:
    32768, 98304, 163840, 229376, 294912, 819200, 884736, 1605632, 2654208,
    4096000, 7962624, 11239424

Allocating group tables: done
Writing inode tables: done
Creating journal (65536 blocks): done
Writing superblocks and filesystem accounting information: done

Encryption complete. You can mount the device as needed.
```

Verifying that the encrypted device is closed and no longer accessible, confirming secure data protection:

```
taylorw0525@taylorw0525:~$ sudo umount /mnt
umount: /mnt: not mounted.
taylorw0525@taylorw0525:~$ sudo cryptsetup close encrypted_flash
Device encrypted_flash is not active.
taylorw0525@taylorw0525:~$ sudo ls /dev/mapper/encrypted_flash
ls: cannot access '/dev/mapper/encrypted_flash': No such file or directory
taylorw0525@taylorw0525:~$
```

Reopening the encrypted device by entering the correct passphrase, enabling access to secured data:

```
taylorw0525@taylorw0525:~$ sudo cryptsetup open /dev/sda encrypted_flash
Enter passphrase for /dev/sda:
taylorw0525@taylorw0525:~$
```

Listing block devices with lsblk after unlocking, showing the mapped encrypted device as encrypted_flash:

```
taylorw0525@taylorw0525:~$ lsblk -o NAME,SIZE,TYPE,MOUNTPOINT
NAME                                SIZE TYPE MOUNTPOINT
loop0                               4K loop /snap/bare/5
loop1                             68.8M loop /snap/core22/1666
loop2                             250.4M loop /snap/firefox/5271
loop3                             483.3M loop /snap/gnome-42-2204/178
loop4                             91.7M loop /snap/gtk-common-themes/1535
loop5                             33.7M loop /snap/snapd/21761
loop6                             144.1M loop /snap/thunderbird/573
loop7                             38.6M loop /snap/snapd/23259
loop8                             68.8M loop /snap/core22/1720
sda                                58.6G disk
└─encrypted_flash                  58.6G crypt
sr0                                1024M rom
vda                                64G disk
├─vda1                             1G part /boot/efi
├─vda2                             2G part /boot
└─vda3                             60.9G part
   └─ubuntu--vg-ubuntu--lv         30.5G lvm /
taylorw0525@taylorw0525:~$
```