

FFS: A CRYPTOGRAPHIC CLOUD-BASED DENIABLE FILESYSTEM
THROUGH EXPLOITATION OF ONLINE WEB SERVICES

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ABSTRACT

FFS: A cryptographic cloud-based deniable filesystem through exploitation of online web services

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Many Online Web Service (OWS)s today, such as Flickr and Twitter, provide users with the possibility to post images which are stored on the platform for free. This thesis explores the idea of creating a cryptographically secure filesystem which stores its data on an online web service by encoding the encrypted data as images. Images have been selected as the target as more data can usually be stored in image posts than in text posts on OWSs. The filesystem, named The Fejk Filesystem (FFS), provides users with free, deniable, and cryptographic storage by exploiting the storage provided by online web services. The thesis analyzes and compares the performance of FFS against two other filesystems and a version of FFS that does not use an OWS. While FFS has performance limitations that make it non-viable as a general-purpose filesystem, such as a substitute to the local filesystem on a computer; however, FFS provides security benefits compared to other cloud-based filesystems specifically by providing end-to-end encryption, authenticated encryption, and plausible deniability of the data. Furthermore, being a cloud-based filesystem, FFS can be mounted on any computer with the same operating system, given the correct secrets.

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Thanks to my mom, dad, and the rest of my family for their constant support.

To the people who said it could not be done.

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Chapter 1

INTRODUCTION

To keep files and data secure we often use encrypted filesystems. However, while these filesystems hide the content of the data, they often do not conceal the existence of data. For instance, using snapshots of the filesystems from different moments in time, it could be possible to notice a difference in the data stored and therefore that data exists and where it is located. Snapshots could even reveal user passwords [1].

Deniable filesystems are intended to make the data deniable, meaning that the user is able to plausibly deny the existence of data. This is often accomplished through the use of digital steganography. There are many reasons why this is important. For instance, in 2011, a Syrian man recorded videos of attacks on civilians carried out by Syrian security forces, which he wanted to share with the world [2]. By cutting his arm, he was able to hide a memory card inside the wound and smuggled it out of the country. However, if he would have used methods such as an encrypted deniable filesystem, the border control may not have been able to discover even the existence of data, even if they would have found the memory card. By only encrypting the data, the border control would have been able to see that he was trying to hide data and make him reveal the decryption key, either by legal measures or by force.

There exist multiple deniable filesystems that are designed to address this problem on digital storage devices, such as memory cards. However, even just carrying a memory card might subject you to suspicion of hiding data, no matter how the filesystem is designed. Another solution to hiding the data is therefore to hide it somewhere else, for instance online through the use of a cloud-based filesystem service, such as Google Drive. Someone searching your body and devices, at for instance an airport or border control, might not realize that you are using a cloud-based filesystem service to hide your data. Although, more thorough investigations of a person might reveal user accounts used on the service, leading to legal processes where the service is forced to disclose your data. Even if you encrypt the data you upload to such a service,

you can still be forced to reveal the decryption keys. What we want to achieve is a combination of a deniable filesystem and a cloud-based filesystem, where the data is stored using cryptographic and deniable methods but without any company or person other than the user controlling the actual data. To accomplish this, we can store the data on online social media platforms.

Social media platforms such as Twitter and Flickr have many millions of daily users that post texts and images (for example, of their cats or funny videos). According to Henna Kermani at Twitter, they processed 200 GB of image data every second in 2016 [3]. The photos posted on Twitter, as opposed to the ones stored on cloud services such as Google Drive, are stored for free on the service for the user, for what seems to be an indefinite period. There is also no specified limit on how many images or tweets one can make. Although, as stated in their terms of service, such limits can be imposed on specific users whenever Twitter wishes, and tweets can be removed at any point in time [4].

This project created a cryptographic and deniable cloud-based filesystem called FFS that takes advantage of free online web services, such as Twitter and Flickr, for the actual storage. The idea was to save the user's files by posting an encrypted version of the file as images and text posts on these web services. The intention was not to create a revolutionary fast and usable filesystem but instead explore how feasible it is to utilize the storage that Twitter and similar services provide their users for free, as a cryptographic and deniable cloud-based filesystem. Additionally, the performance and limits of this filesystem are analyzed and compared to alternative filesystems, such as Google Drive, to compare the advantages and disadvantages of the developed filesystem compared to professional filesystems. The security of the proposed filesystem is discussed and an analysis of the deniability of the developed filesystem is presented.

1.1 Problem

Current cryptographic filesystems are often based on local-disk solutions. Distributed filesystem services, such as Google Drive, might encrypt your data but it can be

considered unsafe storage as they can give out your data if as they do not always provide end-to-end encryption. A cryptographic and deniable decentralized cloud-based filesystem where the data is not controlled by any entity other than the user can be of importance, for instance for journalists in unsafe countries. Social media services often provide free storage which makes the social media service providers a potentially good host of the data for such a filesystem as they would not be able to access the unencrypted data nor have any idea how the posts are connected, and the usage of these services for data storage might even go unnoticed due to the existing heavy load of data from regular users of these services. This raises the following questions: Is it possible to use the storage offered by various social media services to create a cryptographic and deniable filesystem where the data is stored on these online web services through the use of free user accounts? What are the drawbacks of such a filesystem compared to similar filesystem solutions concerning write and read speed, storage capacity, and reliability? Are there advantages to such a filesystem regarding security and deniability?

1.2 Purpose and motivation

The purpose of this research is to explore the possibility to create a cryptographically secure and deniable cloud-based filesystem that stores data on an Online Web Service (OWS) and to compare the performance, benefits, and disadvantages of such a filesystem to existing deniable filesystems and distributed filesystem services. A distributed filesystem service, such as Google Drive, provides data storage for users which can be free or cost money. Even though Google Drive encrypts the user's data, they control the encryption and decryption keys, and the method of encryption [5]. This means that they can give out the user's files and data if faced with legal actions, such as subpoenas. Because the service providers have the decryption keys, this opens up the possibility of hackers gaining access to the files without the user having any way to prevent this access.

The idea behind FFS is to have a decentralized cloud-based filesystem where only the user has access to the unencrypted data. By encrypting and decrypting the files

locally before uploading and after downloading them to these services (end-to-end encryption), it is possible to ensure that the user is the only one who has access to the encryption and decryption keys and therefore the unencrypted data. Even if the web service would look at the data uploaded by the user, it is unreadable without the decryption key. An interesting aspect of this is that online web services, such as social media, provide users with essentially an unbounded amount of storage for free. Anyone can create any number of accounts on Twitter and Facebook without cost, and with enough accounts, one could potentially store all their data using such a filesystem. We aim to exploit the storage web services give their users for free. We also want adversaries to be unable to prove the amount of data and the existence of data, even when the images are posted publicly.

There are several deniable filesystems available but these lack certain aspects that FFS aims to solve. Some filesystems are based on the local disk of the device in use, such as the physical storage device on a computer or phone, or an external storage device connected to a computer or phone. While these filesystems have advantages compared to cloud-based solutions, such as low latency, they lack accessibility as you need to have the device to access the content on it. It also means that when you want to share or transport the data, you must physically move the device which can lead to problems, such as it could be taken from you or be destroyed. Cloud-based solutions counter this by being available from any location that has internet access to the services used. However, existing cloud-based solutions introduce other disadvantages. One example is CovertFS [6] where data is stored in images posted on web services. The data is stored using standard steganographic methods in real images, meaning that there is a limit on how much data can be stored in a steganographic fashion. CovertFS limit this to 4 kB which means that such a filesystem with a lot of data will require many images which could lead to suspicion from the owners of the web services. FFS stores as much data as possible in the images, meaning that fewer images are needed to store a file bigger than 4 kB. This also means that the images produced by FFS does not look like a normal image, but instead have seemingly randomly colored pixels. More examples of similar filesystems will be presented in Chapter 3.

1.3 Goals

The project aims to create a secure, deniable filesystem that stores its data on online web services by taking advantage of the storage provided to its users. This can be split into the following subgoals:

1. to create a mountable filesystem where files and directories can be stored, read, and deleted,
2. for the filesystem to store all the data on online web services rather than on the local disk,
3. for the system to be secure in the sense that even with access to the uploaded files and the software, the plain-text data is unreadable without the correct decryption key,
4. to provide the user of the filesystem with plausible deniability of its data in the sense that it is not possible to associate the user with an instance FFS if the filesystem is not mounted,
5. to analyze the write and read speed, storage capacity, and reliability of the filesystem and compare it to commercial cloud-based filesystems and local filesystems, and,
6. to analyze and discuss environmental and ethical aspects of the filesystem.

1.4 Research Methodology

A literature review was carried out to examine existing cryptographic, deniable, and cloud-based filesystems, as well as state-of-the-art security standards. This created a basis for the technologies and security principles used in the produced filesystem, including FUSE as the filesystem library. Furthermore, experiments were carried out to gather quantitative data used to compare the performance of the produced filesystem against other relevant filesystems.

1.5 Limitations

Due to limitations in time and as the system is only a prototype for a working filesystem and not a production filesystem, some features found in other filesystems are not implemented in FFS. The focus is to implement a subset of the POSIX standard functions, containing only crucial functions for a simple filesystem, specifically, the FUSE functions *open*, *read*, *write*, *mkdir*, *rmdir*, *readdir*, and *rename*. However, file

access control is not a necessity and will therefore not be implemented, thus functions such as *chown* and *chmod* are not going to be implemented. The reason is that the goal is to present and evaluate the *possibility* of creating a cryptographically secure and deniable filesystem with a storage medium based on online web services and thus FFS only aims to implement a minimal filesystem.

1.6 Structure of the thesis

Chapter 2 presents theoretical background information of filesystems and the basis of FFS while Chapter 3 mentions and analyzes related work. Chapter 4 describes the implementation and the design choices made for the system, along with the analysis methodology. Chapter 5 presents the results of the analysis and Chapter 6 discusses the findings and other aspects of the work. Lastly, Chapter 7 will finalize the conclusion of the thesis and discuss potential future work.

Chapter 2

BACKGROUND

This chapter presents concepts and information that is relevant for understanding, implementing, and evaluating FFS. We first present the idea of inode-based filesystems and how data is stored in a filesystem. Following is the introduction of FUSE which will be used to implement FFS. Later sections present background information about Twitter and the potential threat adversaries of FFS.

2.1 Filesystems and data storage

This section presents how certain filesystems used today are structured. We present the idea of inode-based filesystems and distributed filesystems. Following, we describe how data is stored in a storage system and how this information can be used in FFS.

2.1.1 Unix-like filesystems

A Unix-like filesystem uses a data structure called an *inode*. The inodes are found in an inode table and each inode keeps track of the size, blocks used for the file's data, and metadata for the files in the filesystem. A directory simply contains a mapping between filenames and inodes for the files and directories in the directory. The filesystem can with an inode find information about the file or directory using the inode table. Each inode can contain any metadata that might be relevant for the filesystem, such as creation time and last update time.

Figure 2.1 shows an example inode filesystem and how it can be visualized. The blocks of an inode entry are where in the storage device the data is stored, each block is often defined as a certain number of bytes. Listing 2.1 describes a simple implementation of an inode, an inode table, and directory entries.

Inode table

Inode	Blocks	Length	Metadata attributes
1	2	3415	...
2	1,3	2012	...
3	4,6	9861	...
4	5	10	...

Directory tables

/		/fizz		/fizz/buzz	
Name	Inode	Name	Inode	Name	Inode
./	1	./	5	./	4
../	1	../	1	../	5
fizz/	3	buzz/	2	baz.ipa	6
foo.png	5	bar.pdf	4		

Directory structure



Figure 2.1: Basic structure of inode-based filesystem

Listing 2.1: Pseudocode of a minimalistic inode filesystem structure

```
struct inode_entry {
    int length
    int [] blocks
    // Metadata attributes are defined here
}

struct directory_entry {
    char* filename
    int inode
}

// Maps inode_id to an inode_entry
map<int , inode_entry> inode_table
```

Different filesystems provide different features and limitations. The Extended Filesystem (ext) exists in four different versions: ext, ext2, ext3, and ext4. This filesystem is often used on Linux operating systems. Each iteration brings new features and changes the limitations. For instance, comparing the two latest iterations, ext3 and ext4, ext4 can theoretically store files up to 16 TiB while ext3 can store files up to 2 TiB [7]. Additionally, ext4 supports timestamps in units of nanoseconds while ext3 only supports timestamps with a resolution of one second. Additionally, ext4 natively supports encryption at the directory level through the use of the fscrypt API [8].

APFS is a modern filesystem that is used on iPhones and Macs and can store files with a size up to 9 EB [9]. It supports timestamps in units of nanoseconds and is built to be used on Solid-State drive (SSD) [10]. It also supports modern features that its predecessor Mac OS Extended (HFS+) does not support, such as Snapshots and Space Sharing. APFS natively supports encryption of the filesystem volume [11].

2.1.2 Distributed filesystems

Filesystems are used to store data, for instance locally on a hard drive of a computer, or in the cloud. Google Drive is an example of a filesystem that enables users to save their data online with up to 15 GB for free [12] using Google's clusters of distributed storage devices, meaning that the data is saved on Google's servers which can be located wherever they have data centers [13]. Paying customers can have a greater amount of storage using the service. Apple's iCloud and Microsoft's OneDrive are two additional examples of distributed filesystems where users have the option of free-tier and paid-tier storage.

Cloud-based filesystems, as opposed to a filesystem on a physical disk, are accessible from multiple computers and devices without requiring the user to connect a physical disk to the computer. Thus, even if the user would lose their computer or if it would malfunction, the data on the cloud-based filesystem can still be accessed which means that the data could still be recovered. These filesystems are often owned by companies, such as Google Drive and Apple's iCloud, as they are big companies that can provide reliable storage. This also means that they have their own agenda

and policies, and as they are hosting the data they have the possibility of accessing your data. The data can be encrypted on the filesystem, for instance by the service provider, but in the case of Google Drive, they have access and control of the encryption and decryption keys which in turn means that they have access and control of the data stored [5]. While they mention in their Terms of Service that the user retains ownership of the data [14], they also mention that they can disclose your data for legal reasons and that they retain the right to review the content uploaded by users [15]. Controlling the encryption and decryption keys also enables the possibility of hackers gaining access to your data by attacking Google. iCloud allows users to enable end-to-end encryption for some parts of the service, but not for the whole suite [16]. For instance, backup data and iCloud drive can be end-to-end encrypted while contacts and iCloud mail cannot.

2.1.3 Data storage and encoding

Different file types have different formats that describe of how they should be encoded and decoded, for instance, a JPEG and a PNG file can be used to display visually similar images but the data they store is different. At the lowest level, storage devices often represent files as a string of binary digits no matter the file type (however, there are non-binary storage devices [17], but this is outside the scope of this thesis).

A file as (string of bytes) can be encoded into text or as an image by representing the bytes as pixel color data and adding a suitable image header for a given image format. This image can in turn be posted on, for instance, social media. However, there is a possibility that the social media services compress the uploaded images which could lead to data loss in the image, which would mean that the decoded data would be different from the encoded data. In this case, we would not be able to retrieve the original data that was stored unless we use methods such as error-correcting codes. The error-correcting codes would have to be stored in an ensured lossless format. For instance, text posts on the OWS can be used as long as the posts are not removed or the text is modified.

2.2 FUSE

FUSE is a library that provides an interface to create filesystems in userspace rather than in kernel space which is otherwise often considered the standard when writing commercial filesystems [18]. The reason to implement a filesystem in kernel space is that it leads to faster system calls than when writing a filesystem in userspace. However, while filesystems using FUSE are generally slower than kernel-based filesystems, using FUSE simplifies the process of creating filesystems. macFUSE is a port of FUSE that operates on Apple’s macOS operating system and it extends the FUSE API [19]. macFUSE provides an API for C and Objective C. During the research, experiments were not conducted to see if filesystems developed using macFUSE can be mounted on non-macOS operating systems. As macFUSE is an extension of the FUSE library, there is a possibility that it is easy to port the macFUSE filesystems to the normal FUSE glsAPI and mount them on, for instance, a Linux operating system. However, information about this has not been found.

Figure 2.2 presents an overview how FUSE works. FUSE consists of a kernel space part and a userspace part that perform different tasks [20]. The kernel part of FUSE operates with the Virtual Filesystem (VFS) which is a layer in both the Linux kernel and the macOS kernel that exposes a filesystem interface for userspace applications [21, 22]. The VFS interface is independent of the underlying filesystem and is an abstraction of the underlying filesystem operations which can be used on any filesystem the VFS supports. The userspace part of FUSE communicates with the kernel space part through a block device. Operations on a mounted FUSE filesystem are sent to the VFS from the user application, which is then sent to the kernel part of FUSE. If needed, the operations are transmitted to the userspace part of FUSE where the operation is handled and a response is sent back to the VFS and the user application through the FUSE kernel module. However, some actions can be handled by the FUSE kernel module directly, such as if the file is cached in the kernel part of FUSE [20]. The response is then sent back to the user application from the kernel module through the VFS.

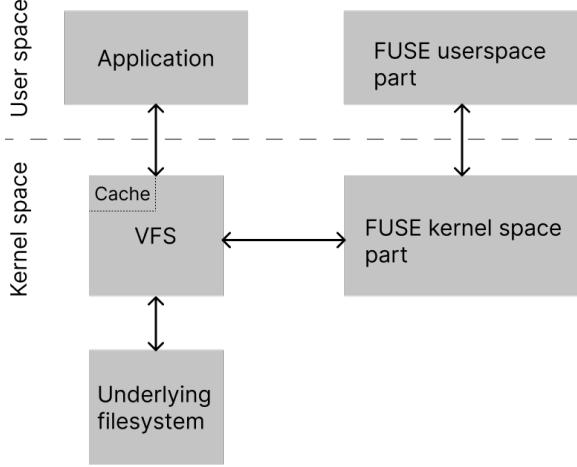


Figure 2.2: Simple visualization of how FUSE operations are executed

Figure 2.2 also visualizes the kernel cache. The data stored in a macFUSE filesystem can be cached by the kernel to provide faster filesystem operations [20, 23, 24]. This can be disabled, for instance, when the filesystem can be modified independently of filesystem operations on the computer, such as for a distributed filesystem where changes can be made by another user at any time. While FFS is a cloud-based filesystem where, potentially, the filesystem state could change even though no filesystem operations have been performed (due to, for instance, FFS being mounted on another machine at the same time), multi-user support for FFS is not covered by the scope of this thesis.

FUSE allows large files in the filesystems. The file operation offset, used to read or write at a byte location inside a file, is an unsigned 64 bit integer, meaning the filesystem operations can read and write to files as large as $1.8e^{19}$ bytes.

2.3 Online web services

This section presents two OWSs, Twitter and Flickr, where one can create free-tier accounts. On both of these OWSs, free-tier accounts can make numerous posts for free. The OWSs each provide a free-to-use API for non-commercial development.

2.3.1 Twitter

Twitter is a micro-blog online where users can sign up for a free account and create public posts (tweets) using text, images, and videos. Each post has a unique ID associated with it [25]. Text posts are limited to 280 characters while images can be up to 5 MB and videos up to 512 MB [26]. A post with images can contain up to four images in one post. There is also a possibility to send private messages to other accounts, where each message can contain up to 10 000 characters and the same limitations on files. However, direct messages older than 30 days are not possible to retrieve through Twitter's API [27]. It is possible to create threads of Twitter posts where multiple tweets can be associated in chronological order.

Twitter's API defines technical limits of how many times certain actions can be executed by a user [28]. A maximum of 2 400 tweets can be sent per day, and the limit is further broken down into smaller limits at semi-hourly intervals. Hitting a limit means that the user account no longer can perform the actions that the limit represents until the time period has elapsed.

2.3.2 Flickr

Flickr is a public image and video hosting service used to store and share photos and videos. Unlike Twitter, a post on Flickr is based on an image or video. The post can, optionally, have a title, a description, or both. However, the post must have exactly one photo or video. Flickr supports multiple image- and video formats, including PNG and MP4 [29]. Size restrictions are set for each post, depending on the media type. Images uploaded to Flickr can be a maximum of 200 MB and a video can be a maximum of 1 GB. Further, free-tier accounts can only have a total of 1 000 photos or videos on their account. This corresponds to a maximum of 200 GB of storage if we are only storing images or 1 TB of storage if we store only videos. A mix of images and videos can also be uploaded, which would mean that the maximum storage capacity would be between 200 GB and 1 TB. A Flickr Pro account has unlimited storage on Flickr but is still subject to the per-item limit of 200 MB and 1 GB for images and

videos, respectively [30]. Flickr Pro costs between EUR 7.49 to EUR 5.49 per month, depending on the subscription time the user signs up for. The description of a post has a limit of 65 535 characters according to Shhexy Corin [31]. This has been verified through testing. The title of a post has also been discovered through testing to have a limit of 255 characters.

The images and videos uploaded to Flickr are stored in their original form **without any compression** and can be downloaded by the user as the same file as was uploaded [32]. Flickr also stores other formats of the file, such as thumbnails. User accounts can restrict who, other than themselves, can download the original image. Restricting who can download the file helps ensure that no-one else can read the original file data, but also requires the user to authenticate with Flickr to download the image meaning it is not possible to anonymously download the image data. Even if the original image cannot be downloaded by anonymous users when such restrictions are set by the original uploader, they can still download other versions of the image. The other versions of the image do not contain the same data as the original image but they look similarly, potentially enabling reverse engineer of the original pixel data. The original video can only be downloaded by the user [32]. Flickr does not state if it will always be possible to download the original versions of the uploaded image or video. Further, Flickr states that it retains the right to remove user content from the service at any time [33].

The Flickr API defines a query limit of 3 600 requests per hour per application across all API calls [34]. However, according to Sam Judson in 2013, this is not a hard limit [35]. Although, this source is from almost a decade ago. There is no official information from Flickr about what happens if you break the hourly request limit. The Flickr API states that the API is monitored on other factors as well [34]. If abuse is detected, Flickr reserves the right to revoke API keys.

2.4 Cryptography

The Advanced Encryption Standard (AES) is a symmetric key encryption standard established by the The U.S. National Institute of Standards and Technology (NIST),

specifying the Rijndael block cipher [36]. AES is a symmetrical cipher, meaning that the same key is used for encryption and decryption. AES is used to make the data confidential so that no one except the person with the key can access the unencrypted data. AES produces 128-bit encrypted cipher blocks and supports key sizes of 128 bits, 192 bits, or 256 bits. The security of AES has been heavily researched since its introduction in the early 2000s, and literature has found it is well resistant to quantum attacks as well [37].

While AES is a good standard for the confidentiality of the data, confidentiality is often not enough to secure the data [38]. The importance of ensuring the authenticity of the data is also high. This means that we want to know that the data has not been modified since it was encrypted. This problem can be solved by using authenticated encryption [39]. Galois/Counter Mode (GCM) is a block cipher mode of operation which provides authenticated encryption [40]. GCM can be used together with AES to provide secure, authenticated encryption of data. To encrypt using GCM, the encryption function requires a key, a randomized Initialization Vector (IV), and the data to encrypt. The output is the encrypted cipher text and an authentication tag. The decryption function of GCM requires the same key and IV as was used as input in the encryption function, as well as the authentication tag and the cipher text received as output by the encrypting function. Further, both the encryption function and the decryption support Additional authentication data (ADD) to be provided. ADD is data that should be authenticated, but not encrypted. If ADD is provided to the encryption function, it must also be provided to the decryption function.

The key used when encrypting using AES can be derived from a password that the user provides. A Password-Based Key Derivation Function (PBKDF) is a function that can be used to derive a key to be used for, for instance, AES. The input to a PBKDF is a secret, such as a password [41]. An example of a PBKDF schema is the Hashed Message Authentication Code based Key Derivation Functions (HKDF) presented by Krawczyk [42, 43] which utilizes a hashing algorithm that provide a pseudo-random key. HKDF supports multiple hashing algorithms. The security of HKDF is partially dependent on the security of the hashing algorithm used. A well-defined suit of hashing algorithms is the The Secure Hash Algorithms (SHA), which covers, among

other hash functions, SHA-256 [44]. SHA-256 is a cryptographic hash function that outputs a 256-bit pseudo-random cipher from its input, which can, for instance, be a password. Further, HKDF uses a salt to improve the security of the provided secret. The salt is random data used to further diffuse the produced key, making two keys with the same secret but different salts, different [45]. The salt does not have to be secret and is sometimes stored with the produced cipher so that the decryption function can easily re-use the salt when deriving the decryption key. If the key used for encryption and the key used for decryption are derived using different salts, the keys will differ and the cipher text cannot be decrypted.

An alternative encryption solutions is Rivest-Shamir-Adleman (RSA). RSA is an asymmetrical cipher, meaning that it uses a public key and a private key for encryption and decryption. According to Mahajan and Sachdeva, asymmetric encryption techniques are more computationally intensive than symmetrical encryption techniques and are almost 1 000 times slower than symmetrical techniques [46]. Mahajan and Sachdeva found that AES is a faster algorithm for encryption and decryption than RSA, while maintaining very good security.

2.5 Threats

To consider a filesystem secure it is important to imagine different potential adversaries who might attack the system. Considering that FFS has no real control of the data stored on the different services, all the data must be considered to be stored in an insecure system. Even if we could hide the posts made on the online web service, for instance, Twitter, by making the profile private, we must still consider that Twitter themselves could be an adversary or that they could potentially give out information, such as tweets or direct messages, to entities such as the police. Twitter's privacy policy mentions that they may share, disclose, and preserve personal information and content posted on the service, even after account deletion for up to 18 months [47]. Therefore, to achieve security the data stored must always be encrypted. We assume that an adversary has access to all knowledge about FFS, including how the data is converted, encrypted, and posted. We also assume they know which websites and

accounts could host data from the filesystem - but we assume they do **not** have the decryption key. However, even though the data is encrypted, other properties such as your IP address can be known which can expose the user's identity. The problem of these other sources of information external to FFS is not addressed in FFS but remains for future work.

Other than adversaries for FFS, we might also imagine that the underlying services might face attacks that can potentially harm the security of the system or even cause the service to go offline, potentially indefinitely. One solution is to use redundancy - by duplicating the data over multiple services, we can more confidently believe that our data will be accessible as the probability of all services going offline at the same time is lower.

The deniability of FFS is an important aspect of the filesystem. Potential threat adversaries are agents that the user is trying to hide the data from, such as governing states. For the system to be completely deniable, an adversary should not be able to gain any information about the potential data in the system, this includes even the existence of data. When FFS is unmounted there should be no trace of FFS ever being present in the device. We will assume that an adversary is competent and can analyze the software and hardware completely. We assume that the adversary can gain access to the user's computer where FFS has been mounted previously, but that they do not have access to the machine while FFS is mounted. It is assumed that the adversary might have snapshots of the user's computer before and after FFS was mounted, but that no snapshots were taken while FFS was mounted. For instance, a country's border agents might take a snapshot of the computer's storage device every time the user passes through the border, but the user might mount FFS during the time inside the country. This requires FFS to not change any state of the operating system while it is mounted, such as information about when it was last mounted. Such state changes could be noticed using snapshots of the operating system state. During the development of FFS, no traces of previously mounted FFS instances have been found, although it has not been researched fully. Future work includes analyzing potential lingering modifications to the operating system state FFS and FUSE produce while mounted.

Chapter 3

RELATED WORK

The research area of creating filesystems to improve security, reliability, and deniability is not new and has been well worked on previously. This chapter presents previous work that is related to this thesis. This includes other filesystems that share similarities with the idea of FFS, for instance with the idea of unconventional storage media and steganography.

3.1 Steganography and deniable filesystems

Steganography is the art of hiding information in plain sight and has been around for ages. Today, a major part of steganography is hiding malicious code in for instance images, called stegomalware or stegoware. Stegomalware is an increasing problem and in a sample set of examined real-life stegomalware, over 40% of the cases used images to store the malicious code [48]. While FFS will not include malicious code in its images, this stegomalware problem has fostered the development of detection techniques of steganography in for instance social media, and it is well-researched.

Twitter has been exposed to allowing steganographic images that can easily contain any type of file [49]. David Buchanan created a simple python script of only 100 lines of code that can encode zip files, mp3 files, and any file imaginable in an image of the user's choosing [50]. He presents multiple examples of this technique on his Twitter profile¹. The fact that the images are available publicly might be evidence that Twitter's steganography detection software is not perfect. However, it is also possible that Twitter has chosen to not remove these posts.

Other examples of steganographic data storage on Open Social Networks (OSNs) include the paper by Ning et al. where the authors build a system for private commu-

¹ <https://twitter.com/David3141593>

nication on public photo-sharing web services [51]. Due to the web services processing of uploaded multimedia, they first researched how the integrity of steganographic data could be maintained after being uploaded to these services. Following this, they presented an approach that ensured the integrity of the hidden messages in the uploaded images, while also maintaining a low likelihood of discovery from the steganographic analysis. Beato, De Cristofaro, and Rasmussen also explored the idea of undetectable communications over OSNs [52]. While they did not carry out an implementation, they present an idea where messages are encoded together with a cover object and a cryptographic key to produce a steganographic message which is then posted to the OSNs. They presented a web-based user interface client with a PHP server backend as the method the users would use to create and share their secret messages.

A deniable filesystem is a system that does not expose files stored on this system without credentials - neither how many files are stored, their sizes, their content, or even if there exist any files in the filesystem [53]. A rubber-hose filesystem is a filesystem where if an adversary is only given one key out of n keys in total, they cannot prove that more data exists and the filesystem is therefore deniable. This is known as a rubber-hose filesystem because of the idea behind rubber-hose cryptanalysis where an adversary beats the user with a rubber-hose to extract the encryption key. The adversary should have no way of knowing how many keys are used to encrypt the data. Steganographic methods can be used to hide the data for a deniable filesystem, and some deniable filesystems are also steganographic filesystems. However, deniability can be accomplished using other techniques than steganography. This thesis proposes a deniable filesystem that, while storing the data in images, is not steganographic as it does not hide the data in the images, but rather use the images as the storage medium.

3.2 Cryptography

Some work choose to invent their encryption methods rather than using established standards. Chuman, Sirichotedumrong, and Kiya proposed a scrambling-based encryption scheme for images that splits the picture into multiple rectangular blocks

that are randomly rotated and inverted, both horizontally and vertically, along with shuffling of the color components [54]. This is used to demonstrate the security and integrity of images sent over insecure channels. The paper uses Twitter and Facebook to exhibit this. Because of the well-proven security of AES, FFS will use AES as its encryption method.

3.3 Related filesystems

Many steganographic and deniable filesystems have been presented previously but many of these are focused on filesystems for physical storage disks to which the user has access. For instance, Peters et al. created DEFY, a deniable filesystem using a log-based structure in 2014 [55]. DEFY was built to be used exclusively on SSD found in mobile devices to provide a deniable filesystem that could be used on Android phones. Further examples of local disk-based filesystems can be found in [53, 56, 57, 1]. However, this thesis aims to create a filesystem that is not based on a physical disk but rather a cloud-based filesystem that uses images on online web services as its storage medium.

In 2007, Baliga, Kilian, and Iftode presented an idea of a covert filesystem that hides the file data in images and uploads them to web services, named CovertFS [6]. The paper lacks implementation of the filesystem but they present an implementation plan which includes using FUSE. They limit the filesystem such that each image posted will only store a maximum of 4 kB of steganographic file data and the images posted on the web services will be actual images. This is different from the idea of FFS where the images will be purely the encrypted file data and will therefore not be an image that represents anything but will instead look like random color noise. An implementation of CovertFS has been attempted by Sosa, Sutton, and Huang which also used Tor to further anonymize the users [58].

In 2016, Szczypiorski introduced the idea of StegHash - a way to hide steganographic data on by connecting multimedia files, such as images and videos, with hashtags [59]. Specifically, images were posted to Twitter and Instagram along with certain permutations of hashtags that pointed to other posts through the use of a custom-designed

secret transition generator. StegHash managed to store short messages with 10 bytes of hidden data with a 100% success rate, while longer messages with up to 400 bytes of hidden data had a success rate of 80%. Bieniasz and Szczypiorski later presented SocialStegDisc which was a filesystem application of the idea presented with StegHash [60]. Multiple posts could be required to store a single file and each post referenced the next post like a linked list, which means that you only need the root post to read all the data. This is unlike the idea of FFS where a table will be kept to keep track of which posts store a certain file, and in what order they should be concatenated, similar to the idea of an inode table. SocialStegDisc lacks actual implementation of the filesystem but similar to CovertFS presents the idea of a social media-based filesystem.

TweetFS is a filesystem created by Robert Winslow that stores the data on Twitter [61], created in 2011. It was created as a proof of concept to show that it is possible to store file data on Twitter. The filesystem uses sequential text posts to store the data. The filesystem is not mounted to the operating system, instead, the user interacts with a Python script through the command line. This makes the filesystem less convenient from a user's perspective, compared to a mounted filesystem where the files can be browsed using a user interface or command line. There are two commands available: `upload` and `download` which upload and download files or directories, respectively. Names and permissions of files and directories are maintained throughout the upload and download process. The tweets are not encrypted but are enciphered into English words which makes them look like nonsense paragraphs. This makes the filesystem less secure than an encrypted version as it can be read by anyone with access to the decoder. However, it does introduce a steganographic element to the filesystem.

In 2006, Jones created GmailFS - a mountable filesystem that uses Google's Gmail to store the data [62, 63]. The filesystem was written in Python using FUSE and was presented well before the introduction of Google Drive in 2012. It does not support encryption as the plain file data is stored in emails. Today, Gmail and Google Drive share their storage quota and GmailFS has since become redundant as Google Drive is an easier filesystem to use. GMail Drive is another example of a Gmail-based

filesystem and it was influenced by GmailFS [64]. GMail Drive has been declared dead by its author since 2015.

Google Conduce Sistem de Fișiere (GCSF) is a filesystem that stores its data on Google Drive, built using FUSE [65, 66]. Google Drive provides a desktop application [67] that presents a mounted volume in the local filesystem, representing the user's Google Drive filesystem. The mountable volume provided by the desktop application does not always sync the stored data directly, but might instead store it locally until a later time. To enable direct synchronization of the data to Google Drive, GCSF interacts with the Google Drive REST API rather than the mounted filesystem volume. One benefit of always synchronizing the data with Google Drive is that the duration of a filesystem operation can be measured easily. For instance, a write operation on a file in GCSF will not complete before the new file data has been completely stored on Google Drive. Therefore, the duration from the start of the filesystem operation until its end includes the time it takes to upload the file. In contrast, the duration of a filesystem operation on the mountable volume provided by the Google Drive Desktop application does not always include the time it takes to upload the file, as this upload can occur at a later time. One difference between GCSF and the idea of FFS is that GCSF does not encrypt the data stored in the filesystem. While the data is, as mentioned previously, encrypted by Google Drive, the encryption keys are controlled by Google Drive, not the user of GCSF. The data stored on GCSF is also stored as its original files in Google Drive, not as images as FFS intends to store the data. The Google Drive filesystem architecture is utilized by GCSF, for instance by using its directory hierarchy structure. This allows GCSF to avoid creating its own inode table and directory structures, as Google Drive provides the functionality these structures similarly provide FFS, through the Google Drive API. The development of GCSF started in 2018 [66], and the repository in GitHub has around 2300 stars as the time of writing this thesis.

Another Google Drive-based filesystem is google-drive-ocamlfuse [68], developed for Linux using FUSE. The project has been well received online. The repository has around 6700 stars on GitHub at the time of writing this thesis and there are multiple articles online about the project [69, 70, 71]. The filesystem is well developed and

well maintained. The filesystem supports filesystem operations such as symbolic links, Unix ownership, and multiple account support. According to the author of GCSF, GCSF tends to be faster than google-drive-ocamlfuse for certain operations, including reading cached files [72, 73]. google-drive-ocamlfuse has no native support for macOS but is focused on Linux.

Zadok, Badulescu, and Shender created Cryptfs, a stackable Vnode filesystem that encrypted the underlying, potentially unencrypted, filesystem [74]. By making the filesystem stackable, any layer can be added on top of any other, and the abstraction occurs by each Vnode layer communicating with the one beneath. There is a potential to further stack additional layers by using tools such as FiST [75]. This approach enables one to create not only an encrypted filesystem but also to provide redundancy by replicating data to different underlying filesystems. If these filesystems are independent, then this potentially increases availability and reliability. FFS aims to achieve stackability through the use of FUSE.

3.4 Filesystem benchmarking

IOzone is a filesystem benchmarking tool that is used to measure performance and analyze a filesystem [76]. It is built for, among other platforms, Apple’s macOS where FFS will be built, run, and tested. However, filesystem benchmarking is more complicated than one might imagine. Different filesystems might perform differently on small and big file sizes among other things, which means that we can never compare benchmarking outputs as just single numbers. We must instead compare different aspects of the filesystems. In 2011 Tarasov et al. presented a paper where they criticize several papers due to their lack of scientific and honest filesystem benchmarking [77]. The problem with benchmarking a filesystem is all the different components that are involved when interacting with a filesystem. For instance, they mention how benchmarking the In- and output (I/O) of the filesystem, such as bandwidth and latency, is different from benchmarking on-disk operations, such as the performance of file read and write operations. The benchmarking tools can for instance rarely affect or determine how the filesystem handles caching and pre-fetching. This means

that benchmarking the read and write performance of different filesystems can be misleading as they might handle this differently, meaning that the result could be different depending on for instance the distance between the files on the disk. Two files could be adjacent on the disk on one filesystem and therefore one could be pre-fetched into the cache when the other one is read. Considerations of such factors must be done when analyzing the results of the benchmarking.

Tarasov et al. also lists several different filesystem benchmarking tools available and used by the papers they reviewed, and how well the tools can analyze certain aspects of a filesystem [77]. IOZone is listed as being compatible with multiple different benchmarking types and it is simpler to use [78] and still maintained. Due to these factors, IOZone was chosen as the benchmarking tool for FFS.

3.5 Summary

As presented in this chapter, different filesystems provide different features and drawbacks. Table 3.1 gives a summary of characteristics and features of some of the filesystems mentioned above and how they compare to FFS. As can be seen, FFS mainly lacks certain filesystem operations which are not the focus of FFS as FFS is a proof-of-concept deniable filesystem storing data on OWSs.

Table 3.1: Comparison between features present in related filesystems and FFS. X means that the feature is supported and - means that it is not supported

	ext4	Google Drive	DEFY	TweetFS	FFS
Mountable	X	X	X	-	X
Read/Write/Remove file	X	X	X	X	X
Read/Write/Remove directory	X	X	X	X	X
Hard links	X	-	X	-	-
Soft links	X	-	X	-	-
File and directory access control	X	X	-	X	-
Encrypted	X	X*	X	-	X
Deniable	-	-	X	X	X
Cloud-based	-	X	-	X	X

*As mentioned, the user has no control over this encryption

Chapter 4

METHOD

This chapter presents the methodology of implementing FFS and the specifications of the development environment. We also present the benchmarking tools and methodology used to acquire quantitative data for the evaluation of the filesystem.

4.1 Development environment specification

Development of FFS was done on a 15-inch 2016 year model Macbook Pro laptop with a 2.6 GHz Quad-Core Intel Core i7 processor and 16 GB 2133 MHz LPDDR3 memory. The storage device of the computer was a 250 GB SSD running an encrypted APFS partition as the filesystem. Apple claims that the SSD has a read speed of 3.1 GB/s and a write speed of 2.2 GB/s [79]. The computer used to develop FFS was running macOS.

Table 4.1 presents the version of the libraries, APIs, operating systems, and tools used by FFS. FFS was developed using C++ and compiled using Apple clang. FFS uses the ImageMagick Magick++ library [80] for image processing. macFUSE [19] is used by FFS to use the FUSE API. cURLpp [81] is a cURL [82] C++ wrapper used by FFS to make HTTP requests. libOauth [83] is used by FFS to sign and encode HTTP requests according to the OAuth [81] standard. Flickrcurl [84] is a C library used by FFS to communicate with parts of the Flickr API. Crypto++ [85] is a C++ library providing cryptographic schemes. FFS uses Crypto++ to encrypt and decrypt the data stored in FFS, and to derive the keys used in the encryption and decryption algorithm.

FFS was developed for use on a single computer for simplicity, and the versions of the operating system, libraries, and tools were the most recent up-to-date versions when the development of the filesystem started (January 2022). To avoid re-writing the

source code to handle new API designs, these versions remained the same throughout the development process.

Table 4.1: The versions of the libraries, APIs, operating system, and tools used by FFS

Library, API, or tool	Version
C++	20
Apple clang	13.0.0
Apple clang target	x86_64appledarwin21.4.0
ImageMagick Magick++	7.1.029
macFUSE	4.2.5
FUSE API	26
cURLpp	0.8.1
libOauth	1.0.3
Flickcurl	1.26
Crypto++	8.6
macOS Monterey	12.5

4.2 FFS

The artifact that was developed as a result of this degree project is the Fejk Filesystem (FFS). It uses an OWS to store the data and behaves as a mountable filesystem for the users. As mentioned in Section 1.5 the filesystem is a proof-of-concept and does not support all functionalities that other filesystems do, such as links or access permissions. The reasoning is that these behaviors are not required for a usable system. Additionally, when comparing FFS to distributed filesystems such as Google Drive, many of these other filesystems also do not support functionality such as links.

This section presents the implementation details of FFS. General overview of the filesystem and its internal structures are presented in Section 4.2.1. Following, the different caches of the filesystems are presented in Section 4.2.2. The encoding and encryption methods are presented in Section 4.2.3. Section 4.2.4 presents Flickr as the OWS used by FFS and why Twitter could not be used as the OWS. Following, Section 4.2.5 presents the implementation details of each FUSE filesystem operation implemented by FFS. Finally, Section 4.2.6 presents the limitations of the filesystem.

4.2.1 Design overview

FFS uses images to store the data of files, directories, and the inode table of the filesystem. These images are uploaded to an OWS, such as Flickr, as image posts. As mentioned in Section 2.3, there can be limitations on the size of these posts for certain OWSs. To support files larger than these limitations, these files will be split into multiple posts, requiring FFS to keep track of a list of posts. Figure 4.1 presents the basic outline of FFS and an example content of the filesystem. FFS is based on the idea of inode filesystems and uses an inode table to store information about the files and directories in the filesystem. However, instead of an inode pointing to specific blocks in a disk, the inode table of FFS instead keeps track of the IDs of the posts (i.e. post ID) on the OWS where the file or directory is located. The inode table entry for each file or directory will also contain metadata about the entry, such as its size and a boolean indicating if the entry is a directory or not.

Inode table

Inode	Post IDs	Length	...
1	923	3415	
2	312	2012	
3	341, 991	9861	
4	481	10	

Directory entry

Name	Inode
..	2
bar.pdf	4
fizz.jpeg	3
buzz/	9

Online Web Serve posts

Figure 4.1: Basic structure of FFS inode-based structure

The directories and inode table are represented as classes in C++. Appendix A visualizes the main attributes of the `Directory`, `InodeTable`, and `InodeEntry` classes. There can be multiple `Directory` and `InodeEntry` objects in the computers' memory and the filesystem, but there will only exist one relevant `InodeTable` instance. The `Directory` class is a data structure that stores mappings between filenames and the

files' and directories' inode, for all files and directories stored in that directory. The `InodeEntry` is a data structure that keeps track of a file's or directory's information, such as where the data is stored and its metadata, such as size and creation timestamp. The `InodeTable` stores a mapping between an inode and the file's `InodeEntry`. The `InodeTable` has always at least one entry for the root directory. This entry has a constant inode value of 0 for simplicity to look up the root directory. With the help of the root directory, all the files lower in the directory hierarchy can be found. The inode of all files and directories other than the root directory has a unique inode greater than 0. The `InodeTable` is always the most recent image saved on the OWS, making it easy to find it on the OWS. The other images stored on the OWS can be images stored in FFS, or images posted by the user that does not contain FFS data as long as the most recent image saved on the OWS is the inode table. The inode table will keep track of which images are stored in the filesystem, and ignore all the other files.

To read the content of a known filename in a directory has three steps using these data structures:

1. The `Directory` object of the directory provides the inode of the given filename.
2. The inode is used to get the `InodeEntry` from the `InodeTable`.
3. Using the inode entry, the file can be located.

The location of a file or directory is an ordered list of unique IDs of the image posts on the OWS. The data received by downloading these images, decoding them (as described in Section 4.2.3), and concatenating them, can be read as a file or represented as a `Directory` object, depending on whether the `InodeEntry` is marked as a file or a directory.

As directories only know the filename's inode, the `Directory` object does not have to be updated (and thus uploaded) when a file or directory in it is edited, for instance adding data. Only the `InodeEntry`, and thus the `InodeTable`, needs to be updated with the new post IDs of the new file or directory. This saves execution time as every request to the OWS takes time. However, if the filename is changed or the file or directory is moved to another location, the parent directory of the file or directory would have to be updated, and thus its corresponding `Directory` object has to be updated.

When a new file or directory is created, it is saved in its parent directory with its filename and an inode. The same inode is used in the inode table to keep track of the file's or directory's inode entry. The inode is represented as an unsigned 32-bit integer (as shown in Appendix A). The inode is calculated by adding one to the currently greatest inode. This means that new files and directories will always receive a greater inode value than those currently in the inode table. This naïve approach to inode generation does not take into account that there might be an available inode less than the greatest inode in the inode table (for instance, due to the deletion of a previously created file). However, this inode generation approach is fast and will not be a problem until the integer overflows. As the inode is represented using a 32-bit unsigned integer, FFS would need to have saved more than four billion files and directories before the inode value would overflow. This scenario is outside the scope of this proof-of-concept filesystem.

FFS does not support all filesystem operations that are implementable through FUSE, instead, FFS implements the subset of them shown in Table 4.2. The implemented operations are the most essential operations required for a working filesystem [86]. Operations such as `chown` provide extended capabilities of the filesystem but these are not required for a proof-of-concept filesystem. The functionality of the filesystem operations implemented by FFS and their implementation details are described in Section 4.2.5.

Table 4.2: Filesystem operations implementable through the FUSE API, and whether or not FFS implements them

Filesystem operations implemented by FFS	Filesystem operations <i>not</i> implemented by FFS
<code>open</code>	<code>readlink</code>
<code>opendir</code>	<code>symlink</code>
<code>release</code>	<code>link</code>
<code>releasedir</code>	<code>chmod</code>
<code>create</code>	<code>chown</code>
<code>mkdir</code>	<code>fsync</code>
<code>read</code>	<code>fsyncdir</code>
<code>readdir</code>	<code>lock</code>
<code>write</code>	<code>bmap</code>
<code>rename</code>	<code>setxattr</code>
<code>truncate</code>	<code>getxattr</code>
<code>ftruncate</code>	<code>listxattr</code>
<code>unlink</code>	<code>ioctl</code>
<code>rmdir</code>	<code>flush</code>
<code>getattr</code>	<code>poll</code>
<code>fgetattr</code>	
<code>statfs</code>	
<code>access</code>	
<code>utimens</code>	

A file, a **Directory**, or the **Inode Table** has to be uploaded to the OWS when it is modified to save its current information. As it takes time to make requests to the OWS, FFS is designed to make as few requests as possible while still saving the required data. Therefore, only the directory or file that is affected by a change is uploaded to the system, while those files and directories unaffected can remain the same. The inode table has to be updated with every change of a file or directory as the inode table contains the location of the file or directory.

FFS can be mounted to the local filesystem using FUSE, similar to mounting a network drive or a File Transfer Protocol (FTP) server. The mounted FFS volume operates similarly to any other drive and can be accessed using, for instance, Mac's Finder or a shell terminal.

4.2.2 Cache

FFS implements a simple in-memory Least Recently Used (LRU) cache for the downloaded content. The cache consists of two data structures:

Cache Map a mapping between a post ID and its image data, and

Cache Queue a queue keeping track of the cached post IDs.

The cache stores a maximum of 20 image posts. The data stored in the cache is the encrypted image data. To avoid FFS using too much memory, the cache is configured so that images greater than 5 MB are not cached. As a result the cache can store a maximum of $20 * 5 \text{ MB} = 100 \text{ MB}$ of encrypted image data. Each time an image is uploaded or downloaded, it is added to the Cache Map with its post ID as the key. The post ID is also added to the beginning of the Cache Queue. If the Cache Queue exceeds 20 elements, the last element of the queue is removed, and the corresponding entry in the Cache Map is erased, thus the entry is fully erased from the cache. The queue ensures that the cache is limited to 20 entries, and by using the First In First Out (FIFO) valuation method, the queue ensures that the oldest element in the cache is removed when the cache exceeds the limit. When a file or directory is removed from the filesystem, all its data is also removed from the cache, if it is stored there.

Before a post with a specified post ID is downloaded from the OWS, the cache is checked to see if the cache is currently storing this post ID. If so, the stored image is returned. Otherwise, the process continues by downloading the image from the OWS and then adding it to the cache. When the thesis states that a file or directory is downloaded, it is implied that the cache is also checked and the data is possibly returned by the cache instead of requiring a download of the data from the OWS.

FFS separately caches both the root directory and the inode table. As both of these data structures are used in many of the filesystem operations, it is important that they can be accessed quickly and not be removed from the cache. Their cache entries are updated when the files are uploaded to the OWS. They are stored as an instance of an `InodeTable` object and an instance of a `Directory` object.

FFS separately also caches the inode of open files and the inode of the open file's parent directory. The open file's data is also cached in memory if it has been read or written to while it is open. A file is opened with the use of the `open` or `create` filesystem operation, as described further in Section 4.2.5. When a file is opened it is associated with a file handle identifier that is used for subsequent filesystem operations to refer to the file rather than using the path to the file in the filesystem. When a user is reading or writing data to a file, multiple `read` or `write` file operations might be executed. For instance, when writing a 100 B file two `write` operations might be executed:

- One with `offset = 0` and with a buffer size of 50 B bytes, and
- One with `offset = 50` and with a buffer size of 50 B.

The number of `read` or `write` operations required to read or write data depends on the amount of data to read or write, and the buffer size used by the file operation which depends on the buffer sizes supported by the filesystem. macFUSE can be mounted with a maximum buffer size of 32 MB [23]. To save computation time by not having to download the file from the OWS, or even decrypt the image data found in FFS's regular cache, FFS stores the file data separately in memory. When a file with a file handle is modified or read, FFS checks if the file handle has any cached data associated with it, before checking the regular cache for the post ID. If there is data associated with the file handle, then this data is used for the file operation. If the file operation was a modifying operation, such as a `write` operation, the new data is associated with the file handle and stored in memory. When the file is closed with a subsequent `close` file operation, the modified data is encoded, encrypted and uploaded to the OWS. FFS does not limit to how many files can be open in the filesystem at the same time, nor how much modified data can be associated with a file handle. However, such limits can be imposed by the operating system. If a file

in FFS is not closed, the associated data is not disassociated with the file handle and is kept in the memory until the filesystem is shut down. Implications of this are discussed in Section 4.2.6.

Furthermore, an additional filesystem cache is provided by the operating system kernel [23, 24]. FFS can not control the kernel cache other than disabling the cache when it is mounted. However, as this operating system provided cache provides faster filesystem operations, it is beneficial for FFS to use this. While this could be a problem if another user modifies the state of the filesystem on the OWS while FFS is mounted, multi-user support is not within the scope of this thesis. The size of the kernel cache has not been found during this research.

4.2.3 Encoding and decoding objects

Entities that FFS stores on the OWS, and therefore also encodes and decodes, are: files, `Directory` objects, and the `Inode Table` object. All of these entities are stored on the OWS using PNG images with 16-bit Red Green Blue (RGB) color depth, without an alpha channel. The inode table and the directories are represented as C++ objects in memory during runtime but are serialized into a binary representation before they are encoded into images. The files saved to FFS are read into memory in a binary format before being encoded into images. All the data encoded into images are encoded similarly, and a detailed description of the binary structures can be found in Appendix B.

The input to the image encoder is the binary data to encode as an image. A header (FFS header) is prepended to the binary data, containing among other things, the size of the data and a timestamp of when the data was encoded. The FFS header and the input data are encrypted using authenticated encryption, utilizing GCM and AES. The key used for the encryption is derived using the HKDF function utilizing the SHA-256 hashing algorithm, along with a random 64 B salt vector, re-generated every time new data is encrypted. The salt is stored with the cipher to ensure that the decryption algorithm uses the same salt to derive the decryption key. The secret used in the HKDF is a password provided by the user. HKDF also uses a random

IV, re-generated every time new data is encrypted. The length of the IV is set to 12 bytes. The resulting data from the encryption is the salt, the IV, and the encrypted cipher (including the authentication tag). These three data points are concatenated into a string of bytes. This string of bytes is referred to as the Complete Encrypted Data (CED).

The dimensions of an FFS image is based on the number of bytes stored, as described in Section 2.1.3. The stored data is the CED, prepended with the Length of the CED (the Length of Complete Encrypted Data (LCED)) using four bytes. For an image of $X = \lceil \frac{4+LCED}{6} \rceil$ ¹ pixels, FFS will set the width w of the image as $w = \lceil \sqrt{X} \rceil$. Further, the height h of the image is set as $h = \lceil \frac{X}{w} \rceil$. This will require $(w * h) - X$ filler bytes and will create an image with a similar height and width. For certain values of X , h will be equal to w . For other values of X , $h = w - 1$. The resulting data encoded as pixels in the image is, in order:

- four bytes representing the LCED,
- the CED data, and
- filler bytes.

The content of the filler bytes are randomized.

The data consisting of the LCED, CED, and filler bytes are encoded into PCD for a PNG with 16 RGB bit color depth using the Magick++ library. The result is an image with a high probability of what looks like randomized colors for each pixel. This is because most pixels are encrypted data and therefore the bytes representing this data are seemingly random.

To decode an FFS image, the decoder first interprets the four first bytes as the LCED. The salt and IV are retrieved from the CED as they are of known length. The decryption key is derived using the IV and salt and results in the same key as the encryption key because AES is a symmetric cipher algorithm. The remaining bytes of the CED ($LCED - len(IV) - len(salt)$ bytes) are decrypted using the decryption key. The decrypted data consists of the FFS header concatenated with the original stored data. The FFS header is asserted to be in the correct format before the original binary

¹ $\lceil x \rceil$ is the `ceil` function, rounding x up to the closest integer

data is returned from the decryption function. Figure 4.2 visualizes the encoder and decoder for all data saved in FFS.

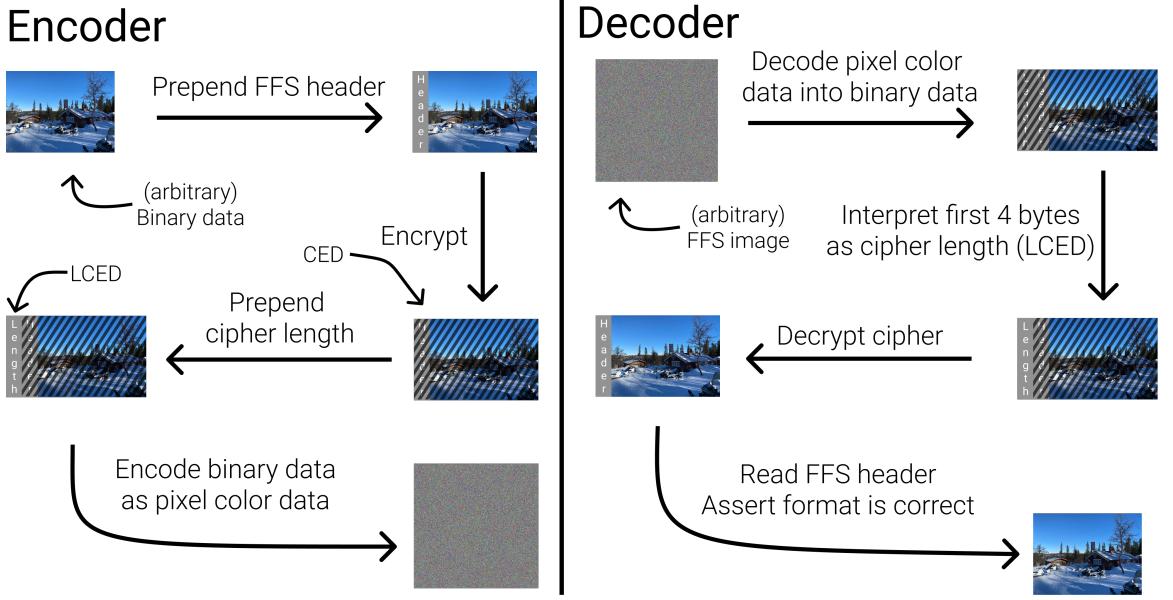


Figure 4.2: Simple visualization of the encoder and decoder of FFS. The input of the encoder is the binary data to store in FFS, eg. a file, and the output is the FFS image to upload to the OWS. The input to the decoder is an FFS image, and the output is the binary data stored on FFS, eg. a file

The encryption and decryption methods used are state-of-the-art solutions as defined and implemented by Crypto++ [85]. Crypto++ is a widely-used and well-maintained C++ library for cryptography, and as of writing has no reported CVE security vulnerabilities for the functionality used by FFS [87].

An FFS image has an upper size limit, defined by the OWS used. If the data to be stored in FFS, such as a file, exceeds this limit, it is split into multiple data arrays of sizes less than this limit. Each data array is encrypted and encoded as images independently of each other, and will be encrypted using different salts and IVs. Only the inode table stores the different post IDs in the order they were encoded. While files and directories stored in FFS can be separated into multiple images, the inode table is limited to only one image for simplicity when interacting with the OWS. This introduces a size limit for the inode table, limiting the filesystem. More details about the limits of FFS are found in Section 4.2.6.

4.2.4 Online web services

As FFS is a proof-of-concept filesystem, it only uses one OWS as its storage medium. However, for a production filesystem, using multiple OWSs could be beneficial. This would enable features such as redundancy by using replication over multiple OWSs, such redundancy could be useful in case one OWS would stop working.

The initial intention of FFS was to use Twitter as the OWS. Initial research for the thesis found that it was possible to upload a file and download the same file without any data loss. However, it was later found that this was not a reliable conclusion. Some images uploaded to Twitter were converted to another image format when they were stored by Twitter, which meant that the decoder could not decode the data as it expected another image format. Other images were compressed or re-coded which led to data loss when downloading the image. As the decoder of FFS images rely on a specific binary representation within the image, this meant that the images could not be decoded into the previously uploaded data. Twitter has previously publicly announced changes to the way they store images [88] and even suggested workarounds [89] for users who are concerned about the potential data loss. However, during research for the thesis, it was concluded that the workarounds mentioned in [89] no longer work on Twitter. For instance, some PNG images less than 900x900px that have been uploaded to Twitter, could not be downloaded as the same image, which contradicts the workaround mentioned in [89] by the Twitter employee. Further changes may have been made to the data management of images on Twitter since the initial research for the thesis; however, an official announcement has not been found.

Flickr saves the original version of the uploaded image and thus it can be used to download the same image as was uploaded. This also means that data that is encoded into an FFS-encoded image can be uploaded, downloaded, and decoded into the same data as before. While they do not assure that they will always support original images, they have not indicated that this would change. Therefore, Flickr can be used at this moment for FFS. A free-tier Flickr account is therefore used for FFS. Restrictions can be set on the Flickr account to enable or disable unauthenticated Flickr visitors to download the originally uploaded image. The advantage or enabling unauthenticated

Flickr visitors to download the images is that we can read the content of FFS even if we do not authenticate with Flickr, and the data can be shared with others using only the password used for encrypting the data in FFS. The disadvantage is that adversaries can also download these images and potentially gain information about the data stored in FFS even if they do not have the encryption password for FFS. However, even if restricting downloading of the original images, adversaries can still access the original images, for instance if Flickr provides them. Therefore, the Flickr account is set to allow unauthenticated visitors of Flickr to download the original versions of the images.

Flickr provides an extensive free REST API for non-commercial use. A user can create applications and generate access tokens for the application. These application tokens are later used to request tokens from users who authenticate using Flickr's web interface and allow the application to do requests for the user. The application will then receive access tokens for the user, which are used to authenticate with the API for the API calls that require authentication.

Flickr provides the ability to search for all the images posted by a user and to sort these results by the time of posting. In FFS, every time an image is uploaded to Flickr, it is due to some modification in the filesystem, for instance, a write operation to a file or a creation of a new directory. For every modification in the filesystem, the inode table will have to be updated. Therefore, we can ensure that the inode table is always the most recently uploaded image to Flickr by configuring FFS to upload all other images first, for instance, the newly written file. This provides FFS with a simple way of querying the inode table from Flickr - by simply requesting the most recently uploaded image on the Flickr account.

While the Flickr API is extensive in its functionality, FFS only uses a few of the provided capabilities; specifically FFS uses:

- Upload an image and return the post ID,
- Query the most recent image by a user, and return the URL and post ID of the original uploaded image,
- Get the URL to the original uploaded image given a post ID,
- Remove an image given a post ID, and,
- Get the image data of the image given its URL.

For instance, to download the original image given a post ID, two requests are required:

1. Get the URL to the original uploaded image given a post ID,
2. Get the image data of the image given its URL.

For benchmarking purposes, a fake variant of FFS, The Fejk Fejk Filesystem (FFFS), has also been developed. FFFS uses a Fake Online Web Service (FOWS), which stores the data on the local APFS filesystem. The FOWS is used by FFFS just as Flickr is used by FFS, by storing encoded images on it. By storing the images on the local filesystem, the filesystem operation's duration is shorter as the local filesystem operations are in general faster than network requests. This allows us to analyze the theoretical performance limit of FFS, and how it would perform if the OWS used had very low latency and the network connection to the OWS had very high bandwidth and low delay. By analyzing FFFS, we can also estimate how much of the filesystem operation time is affected by the time of the network requests. The time T of an FFS filesystem operation can be modeled like:

$$T = t_{\text{ffs}} + t_{\text{ows}}$$

where t_{ffs} is the time that FFS takes, for example for a read operation on a file associated with a file handle;

- to find the file in the inode table,
- decode and decrypt the image data,
- read the specified amount of data, and,
- to output the data.

This time will be approximately consistent for the same request for the same file size. However, memory cache misses/hits and process scheduling, among other factors, can fluctuate the value of t_{ffs} . In contrast, t_{ows} is the total time required to complete all requests to the OWS for a filesystem operation. For instance, for a similar read operation as above this consists of:

- to download all the directories in the file path,
- query the Flickr API for the URL pointing to the most recently uploaded image, and,
- to download the images representing the file to read.

Depending on the OWS, the latency and bandwidth of the internet connection between the user's machine and the OWS's server can differ a lot. Duplicate requests to the same OWS can also differ significantly due to, for instance, server load balancing and a difference in the number of requests from other users at the time of the requests. Further, the request could be replaced by a fast cache hit in the FFS cache. However, for a FOWS, t_{ows} can be replaced by t_{fows} which will have approximately consistent values for duplicate operations, because the local filesystem is not affected by the network connection or the current traffic by other users of the OWS. The local filesystem requests by other applications on the machine can also be minimized by not using other applications on the machine while running the benchmarking tool to ensure filesystem requests by the FOWS can be handled quickly by the operating system. However, t_{fows} is affected by, among other things, the underlying storage device of the local filesystem, process scheduling, and FFS cache hits/misses which can still affect the value of t_{fows} .

Due to limitations in the library `Flickcurl` used for uploading images to Flickr, the image to be uploaded to Flickr first has to be saved to the local filesystem. `Flickcurl` reads the image from the disk, before uploading it. Therefore, FFS saves a temporary

file on the local filesystem when data is uploaded to Flickr. This temporary file is stored in the `/tmp` directory of the local filesystem and is removed by FFS immediately after the file has been uploaded. However, it is not certain that the operating system removes or overwrites the file data on the storage device, and thus there are ways to recover the deleted data, by for instance adversaries [90, 91, 92]. Although, these methods require you to decrypt the APFS volume, requiring the decryption password. Without this password, the data cannot be recovered. Even with the decryption password, it is not certain that the data is recoverable. If an adversary obtains proof that an FFS image has been present in the `/tmp` directory, they could conclude that FFS has been used to store data, reducing the deniability of the filesystem.

4.2.5 Implemented filesystem operations

This section gives a detailed description of all the FUSE operations implemented by FFS, and how they are implemented by FFS. Further explanations about the intended functionality of the operations can be found in Kuenning’s report [86].

The path of a file is sometimes provided for the filesystem operation and traversed by FFS to understand the requested location. An example path is `/foo/bar/buz.txt` or `/foo/bar/baz/`. A path is traversed with the pseudo-code shown in Listing 4.1.

When traversing a path, FFS has to fetch all parent directories in the hierarchy. The file or directory with the filename is not fetched while traversing the path, as it might not be necessary for the operation. All operations that rely on the path of a file or directory have to download all parent directories of the path. However, the directories in the path could be cached and therefore would not be required to be downloaded from the OWS. Furthermore, the `open`, `opendir`, and `create` operations associate a file handle with a file or directory. This enables certain subsequent filesystem operations to use the file handle instead of traversing the string path. This saves time because the path traversing only occurs once for potentially multiple filesystem operations, and the result is saved in the filesystem state.

Listing 4.1: Pseudocode of traversing a given path, returning the Directory and the filename

```
# Traverse a given path and return the parent directory object
# and filename of the path
traverse_path(path) -> (Directory, string):
    # Fetches inode table from the cache
    inode_table := get_inode_table()

    split_path := path.split("/")
    # The filename could be either the name of a file
    # or the name of a directory
    filename := split_path.last
    dirs := split_path.remove_last()

    # Get the root dir from the cache
    curr_dir = cache.get_root_dir()

    # While there are still directories to traverse,
    # get the next directory in the list from the
    # current directory
    while(!dirs.empty())
        dir_name := dirs.pop_first()
        inode := curr_dir.inode_of(filename=dir_name)
        inode_entry = inode_table.entry_of(inode=inode)
        # Download the image posts defined by the
        # post IDs in the inode entry
        curr_dir = download_as_dir(inode_entry)

    return (curr_dir, filename)
```

After every operation that modifies the inode table, the inode table is uploaded to the OWS and cached. Therefore, it is assumed that the inode table is always up to date in memory and on the OWS. This will be true as long as there are not multiple FFS instances working with the same OWS account at the same time. This multiuse scenario has undefined behavior as there is no locking implemented for FFS.

All filesystem operations are synchronous unless specified. Further, FUSE is running in single-thread mode meaning that a filesystem operation call must complete before another can begin. This helps limit the risk of data races as two processes cannot call different operations that, for instance, modify the inode table at the same time.

4.2.5.1 `open`

Given a path to a file, the file is associated with a file handle. The file handle is used in subsequent operations to avoid traversing the file path multiple times. The file is not downloaded from the OWS, only the parent directories are downloaded during the path traversing as explained above. An `open` call must, eventually, be followed by a `release` call. Although, multiple other operation calls can occur between these events.

4.2.5.2 `create`

This operation creates an empty file in the filesystem given a path and associates a file handle with the file, similar to `open`. The empty file will not be uploaded to the OWS as it has no data associated with it. A new entry is added to the parent directory with the filename and a generated inode, and the parent directory is updated in the OWS. The new posts representing the parent directory in the OWS are associated with the inode entry of the parent directory in the inode table, and the old posts are deleted in the OWS. A new inode entry is also created in the inode table, representing the new, empty, file. The inode table is updated in the OWS, and the old inode table is removed.

4.2.5.3 release

Given a file handle, this operation closes the file in the filesystem, disassociating the file handle from the file. The current states of the file and the inode table are saved to the OWS, and the previous versions of the file and inode table are deleted from the OWS. Subsequent operations for the file will require path traversing as the file handle can no longer be used.

The file must have a file handle associated with it before `release` is called. This requires a preceding `open` or `create` call for the file.

4.2.5.4 opendir

Given a path to a directory, the directory is associated with a file handle. The file handle is used in subsequent operations to avoid traversing the file path multiple times. The directory is not downloaded from the OWS, only the parent directories are downloaded during the path traversing as explained above. An `opendir` call must, eventually, be followed by a `releasedir` call. Although, multiple other operation calls can occur between these events.

4.2.5.5 releasedir

Given a file handle, this operation closes the directory in the filesystem, disassociating the file handle from the directory. The current states of the directory and the inode table are saved to the OWS, and the previous versions of the directory and inode table are deleted from the OWS. Subsequent operations for the directory will require path traversing as the file handle can no longer be used.

The directory must have a file handle associated with it before `releasedir` is called. This requires a preceding `opendir` call.

4.2.5.6 mkdir

This operation creates an empty directory in the filesystem given a path. The directory is not uploaded to the OWS as it has no data associated with it. The parent directory is modified and updated in the OWS, and the old versions of the parent directory are deleted in the OWS. The parent directory entry in the inode table is modified with the new posts, and a new entry is created for the new directory. The inode table is updated in the OWS, and the old version of the table is removed from the OWS.

As opposed to `create` for files, this operation does not associate a file handle with the directory.

4.2.5.7 read

This operation reads s bytes into a data buffer a , starting at the provided offset o , from an open file with the provided file handle. If the file has not been read or written to since it was opened, the full file is downloaded and read into memory, even if just a small part of the file is requested. The file data is also cached and the cached data is associated with its file handle so that subsequent requests for the same file while it is open are faster. If the file has been read or written to since it was opened, the file data is accessed from the cache using the file handle.

4.2.5.8 readdir

This operation reads the filenames inside the directory specified by a file handle. The result includes all filenames in the directory, and the special ". ." and ". ." directories.

4.2.5.9 write

This operation writes s bytes from a data buffer a , starting at the provided offset o , to the existing and open file with the provided file handle. All the data of the current file is read into memory. Starting from the offset, the new data from a overwrites the current data of the file, until s bytes have been written. If $o + s$ is greater than the file's size, the file size is set to $o + s$. If $o + s$ is less than the file's size, the data from position $o + s$ and forward remains the same, and the file size is not modified. See Figure 4.3 for a visualization of the result of a `write` operation given different offsets. The parent directory does not have to be modified.

The file and inode table are not updated on the OWS, this occurs instead in the subsequent `release` call. However, the data is associated with the file handle so that subsequent filesystem calls use this new file data.

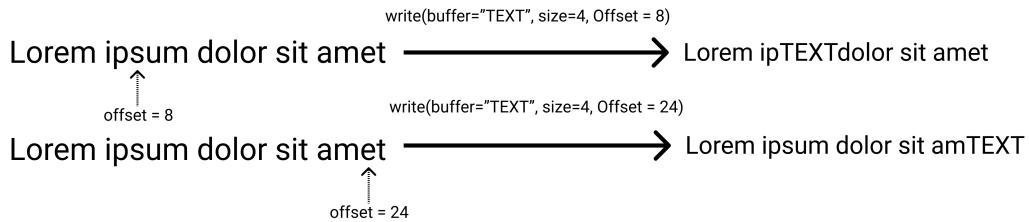


Figure 4.3: Visualization of how the `write` operation handles different offsets.

4.2.5.10 rename

This operation renames a file or directory to a new path. Both the old path and the new path have to be traversed to locate the parent directories and the file or directory to rename. The file or directory entry in the old parent directory is removed, and the old parent directory is updated to the OWS. A new entry is created in the new parent directory, with the new filename. The new parent directory is updated to the OWS. The inode entry of the renamed file or directory does not have to be modified. However, as both the old parent directories and the new parent directory are updated in the OWS, their inode entries need to be updated with the new posts. The inode

table is updated to the OWS and the old table is removed from the OWS. The old posts associated with the old parent directory and the new parent directory are removed from the OWS.

The new path could be in the same directory as the file or directory currently is in. This will not affect the process mentioned above; however, the path will only have to be traversed once, and the parent directory will only be removed and updated once. If the new path is the path of an existing file, the existing file is removed from the filesystem and the OWS.

4.2.5.11 `truncate`

This operation truncates or extends the file in the given path, to the provided size s . The full current file is downloaded into memory. The data of the current file is written to a new buffer until either the file is fully written, or until s bytes have been written. If the current file's size is smaller than s , the remaining bytes are written as the NULL character. The new file data is uploaded to the OWS, and the old data is removed from the OWS. The inode table entry is updated with the new posts and uploaded to the OWS. The old inode table is removed from the OWS.

4.2.5.12 `ftruncate`

This operation is similar to `truncate`, but is called from a user context which means it has a file handle associated with it. The operation truncates or extends the file in the given file handle, to the provided integer s . The full current file is read into memory, either from the OWS or from the cache. The data of the current file is written to a new buffer until either the file is fully written, or until s bytes have been written. If the current file's size is smaller than s , the remaining bytes are written as the NULL character.

The file and inode table are not updated to the OWS, this occurs instead in the subsequent `release` call. However, the data is associated with the file handle so that subsequent filesystem calls use this new file data.

4.2.5.13 `unlink`

This operation removes a file given the file path. The file is removed from the parent directory, and the parent directory is updated to the OWS. The old parent directory data is removed on the OWS. The removed file's entry in the inode table is also removed, and the inode table updates the entry for the parent directory with its new posts. The inode table is then updated on the OWS and the old inode table is removed on the OWS. Finally, the data of the removed file is removed from the OWS. The last step is not necessary for a working filesystem; however, to save space on the OWS, this is done. If the OWS permits unlimited images and total storage, this step could be omitted to save time.

4.2.5.14 `rmdir`

Similar to `unlink`, this operation removes the directory at the given path. The directory and all its subdirectories are traversed, and the post IDs of these files and directories are recorded for deletion later. Following this, the entry of the removed directory is removed from the parent directory. The inode entry for the removed directory is removed. The parent directory is updated to the OWS, and the inode table is updated with the new posts of the parent directory. Following this, the inode table is updated to the OWS. The old parent directory and the old inode table are removed from the OWS.

The operation also starts a new thread, where all the posts of files and subdirectories inside the removed directory, are removed from the OWS. They are removed to save space on the OWS, and a separate thread is used to minimize the delay for subsequent file operations. There is no data race involved as the API is thread-safe, and the posts are no longer associated with any data structures in the main thread and thus could

not be accessed there. This also means that this thread can be run with a lower priority.

4.2.5.15 `getattr`

This operation returns attributes about a file or directory given a path. This includes permissions, the number of entries (if the provided path points to a directory), timestamps of creation, timestamps of last access, and timestamps of last modification. However, as mentioned previously, FFS does not implement all features, such as permissions. Instead of keeping track of a file's or directory's permissions, all calls to a valid path will return full read, write, and execute permissions for everyone. However, the timestamps are stored in the inode table of FFS. The file or directory pointed to by the path does not need to be downloaded, all the metadata that FFS stores is accessible through the inode entry in the inode table, and the inode table is always cached.

4.2.5.16 `fgetattr`

This operation is similar to `getattr` but is called from a user program context meaning that the file has a file handle associated with it. Other than skipping the path traverse step, this operation returns the equivalent information as `getattr`.

4.2.5.17 `statfs`

This operation returns metadata information about FFS. This includes, among other things, the maximum filename size and the filesystem ID. The operation has a short computation time as it does not have to download or upload any files. The only variable information is read from the inode table that is stored in memory and thus does not have to be downloaded from the OWS.

4.2.5.18 access

This operation, given a path, returns whether or not the path can be accessed. As long as the path is valid, this always returns true.

4.2.5.19 utimens

This operation, provided new timestamps, updates the last access timestamp, the last modified timestamp, or both, of the file or directory at the given path. The file or directory does not have to be downloaded. However, the inode entry for the file's or directory's inode is updated with the new timestamps if they are newer than the previous timestamps but not greater than the current time since epoch. The new state of the inode table is updated to the OWS, and the old version is removed from the OWS.

4.2.6 FFS limitations

FFS has numerous limitations due to both implementation decisions and OWS limits. As Flickr allows a free-tier user account to store up to 1 000 images of up to 200 MB per image, this allows storage of up to 200 GB of images per account on Flickr. However, as the inode table is required to be stored on the filesystem, a maximum of 999 images can be used to save file and directory data. This limits the filesystem to a maximum of 999 files and directories when utilizing one free-tier account on Flickr, which also limits the maximum storage of file- and directory images to 199.8 GB.

While Flickr supports each image to be up to 200 MB, it is not possible to use the full 200 MB to store the file or directory data. Each image includes, among other things, a PNG header, other PNG attributes, and the CED which in total is of greater size than the unencrypted data. To ensure that the PCD along with the PNG header and other PNG attributes do not exceed the limit of 200 MB, FFS limits the PCD size to allow at least 10 MB for the PNG header and other PNG attributes, meaning that the PCD can be a maximum of 190 MB. The cryptographic variables

IV, salt, and the authentication tag are stored in the CED using 12, 16, and 64 bytes respectively, for a total of 92 bytes. The size limit means that these 92 bytes, along with the encrypted cipher text, cannot exceed 190 MB, meaning that the encrypted cipher text cannot exceed $190\ 000\ 000 - 92 = 189\ 999\ 908$ bytes. However, as AES is a block cipher producing cipher blocks of 16 bytes, the resulting cipher text must be divisible by 16. The largest encrypted cipher text that FFS allows is therefore $\lfloor \frac{189\ 999\ 906}{16} \rfloor * 16 = 189\ 999\ 904^1$ bytes. Due to plain text padding, the unencrypted plain text can be a maximum of one byte less than this value [93], meaning that the plain text can be a maximum of 189 999 903 B. For simplicity, this is rounded down to 189 MB, leaving almost 11 MB in total for the PNG header and other PNG attributes. Therefore, 189 MB is set as the maximum amount of data FFS will store per image. Data greater than 189 MB in size is split into multiple encoded images. For instance, a file of 200 MB will be stored as 189 MB in one image, and 11 MB in another.

189 MB of usable data per image gives FFS a maximum storage capacity of 188.811 GB using 999 files and directories on one free-tier account on Flickr. Each file with data requires at least one image, thus there can be a maximum of 998 non-empty files and directories in the filesystem, excluding the root directory. However, there could also be just one single entry of 188.811 GB stored in the filesystem, which would represent the root directory.

The inode table keeps the information about empty files and directories even though they store no data on the OWS. The inode of a file or directory is an unsigned 32-bit integer, meaning that the inode table could theoretically store more than four billion files and directories. However, due to the constraints mentioned above, most of these files and directories would have to be empty as Flickr limits the number of images stored. An empty file requires 37 B in the inode table, consisting of the inode, length, and other variables that must exist for an inode entry. As the inode table is limited to one single image on the OWS, the inode table is limited to a maximum size of 189 MB. Further, the size of the inode table is 4 B plus the size of each entry, and one of these entries is the root directory. Even if a file is empty, it is still stored with its filename and inode in its parent directory. A non-empty file or directory in the inode

¹ $\lfloor x \rfloor$ is the **floor** function, rounding x down to the closest integer

table requires 37 B plus approximately (depending on the post ID length generated by the OWS) 12 more bytes per post ID representing the file or directory on the OWS. Assuming only one non-empty directory which stores empty files and directories and only uses one post ID of 12 B, the maximum number of files and directories X that the inode table can store is:

$$X = \left\lfloor \frac{189\,000\,000 - 4 - (12 + 37)}{37} \right\rfloor + 1 \iff X = 5\,108\,107$$

The additional directory is the root directory. Thus, the maximum number of files and directories that the inode table can store is more than five million; however, this requires all files and directories, except the root directory, to be empty. Otherwise, the entries in the inode table will require more space due to the post IDs. These calculations are based on a single free-tier Flickr account. However, future work of FFS could include multiple user accounts and multiple services. This could increase the limits on the filesystem at the cost of increasing the information stored in the inode table as it would need to keep information about the OWS of each post ID.

A directory is encoded as four bytes to represent the number of entries in the directory, plus a directory entry for each file or directory in the directory. A directory entry consists of four bytes representing the inode, followed by the bytes representing the filename followed by the NULL character. The filename is limited to 128 characters, meaning that each directory entry can take up to $4 + 128 + 1 = 133$ bytes. While a directory is not limited to one image in the implementation, it is interesting to calculate how many entries a directory can have using only one image. With 4 B for the number of entries and 133 B per entry, and a maximum size of 189 000 000 B, we get the equation:

$$4 + 133 * x < 189\,000\,000 \iff x < 1\,421\,052.60$$

Meaning that there can be a maximum of 1 421 052 entries using the full file-name limit using only one image, and that the directory can store at least that many files without exceeding the image size limit. With shorter filenames, more entries can be kept in the directory. The maximum number of files and directories one directory can

store due to the inode table limitations mentioned above is 5 108 106, one less than the maximum number of files and directories the inode table can store. These files and directories must be empty as the inode table size limit would be exceeded otherwise. If the directory stores 5 108 106 empty files and directories, and the inode table uses one image, the directory can use up to 999 images on Flickr before the account exceeds the maximum number of images. However, these 5 108 106 empty files and directories can also fit in just one image representing the directory. This requires the filenames to be small enough that the directory does not exceed the maximum image limit of 189 MB. For instance, using filenames of four letters, and using both uppercase and lowercase letters, we can form $(26 * 2)^4 = 7\,311\,616$ unique filenames. Assuming each file has the same three character file extension (such as pdf or png), it requires four extra bytes per file name, including the "." separator. 5 108 106 directory entries of four-letter filenames, four-byte file extension, one NULL character, and four-byte inodes requires $5\,108\,106 * (4 + 4 + 4 + 1) = 66\,405\,378$ bytes ≈ 66.5 MB. Therefore, the directories do not need more than one image to describe all the possible files with four character filenames it can contain before FFS runs out of storage; however, if the filenames are longer than four characters, or if the file extensions are longer than three characters, the directory could exceed the maximum image limit of 189 MB before reaching 5 108 106 images, requiring multiple images.

The biggest possible file that can be stored in the filesystem is 188.811 GB minus the size of a single-entry root directory and an inode table with two entries representing the root directory and the file. A single-entry directory requires four $4 + 4 + 1 + x$ bytes for the number of entries, the inode of the file, the NULL character, and x as the number of bytes in the filename. The smallest filename size is one byte, meaning that the smallest possible single-entry directory requires 10 B. The inode table with two entries, assuming the post IDs are 12 B, requires:

- 4 bytes for the number of entries,
- $37 + 12$ bytes for the directory as it only requires one image, and
- $37 + 12 * y$, where y is the number of posts required to store the file.

This means that the inode table will require $90 + 12 * y$ bytes. The maximum value of y for a free-tier Flickr account is 998 as one image is required for the inode table and one for the root directory. The directory and inode table will therefore require $10 + 90 + 12 * 998 = 12\,076$ B. As each image can use up to 189 MB, the maximum file size is $998 * 189 * 10^6 = 188.622$ GB. 188.622 GB + 12 076 B < 188.811 GB meaning a file of 188.622 GB is allowed in the filesystem.

Limits to the file sizes also depend on the machine where FFS is mounted. When a file is read or written to, the complete file is read into memory. This requires the computer to provide at least as much memory as the size of the file. Further, the cache of FFS can store up to 20 images with a size of 5 MB in memory, requiring up to 100 MB of memory. Furthermore, open files can be cached in-memory independent of their size, potentially occupying up to 188.622 GB of memory. The inode table and root directory are also cached in-memory so even more memory could be required. This is more memory than most computers are sold with today. However, if the computer has less physical memory available, more memory space can often be provided through swap on the hard disk. Apple ensures that the swapped data is securely encrypted on the hard disk [94]. However, using a swap space puts a constraint on the available storage of the hard disk used by the underlying filesystem as the available storage must be sufficient to store this data. Further, as FFS temporarily saves the data in the local filesystem before it is uploaded to Flickr, the storage device must have sufficient storage available for this as well. A file larger than the available storage on the local filesystem cannot be saved to FFS. If the local filesystem has no available storage, only a few filesystem operations can be performed on FFS as any operation that modifies the inode table requires the new inode table to be saved to the local filesystem before it is uploaded to Flickr.

FFS stores data associated with file handles of modified and open files in memory. The number of open files in FFS is unbounded by FFS, but can be limited by the kernel of the operating system. The kernel of the operating system where FFS is run

for this degree project has a limit of 61 440 open files per process and this value can be configured [95]. The amount of data FFS can store per file handle is unbounded by FFS, and FUSE allows big file sizes as mentioned in Section 2.2. The data associated with the file handle is not removed from memory until the file is closed. If many files are opened and modified without being closed, the memory of the computer could be quickly filled. The file handle associated with an open file is the inode of the file, meaning that there is no risk of collision of file handles as the inodes are assured to be unique per file. One file can only be opened once before it is closed; this, `open` calls on an open file will be ignored. If an edited file is not closed before FFS is shut down, the new file data is not updated on the OWS and the new file data is lost. When FFS is launched again, the data saved by the most recent close operation on the file will be used as this is the data saved on the OWS.

Another limitation of FFS is the rate limit imposed by the Flickr API. Flickr allows up to 3 600 API requests per hour, after which the API keys may be revoked by Flickr. 3 600 requests per hour equals 60 requests per minute, or 1 request per second. If the average request takes less than a second for constant, sequential Flickr API calls, the API keys could be revoked. Furthermore, some requests are sent concurrently to Flickr which means that FFS could reach 3 600 API calls faster. Reading a file, represented by one image that is not in the cache, stored in the root directory, requires two requests:

- Request the URL to the original image given a post ID,
- Downloading the image from Flickr.

With a maximum of one request per second, we can read 30 un-cached files per minute. If the file is in a directory that is in the root directory, and the directory is not in the cache, two similar requests are required to download the parent directory assuming that the directory is represented by one image. This would require four requests in total, limiting us to read 15 un-cached files per minute. For each level of depth in the directory, two more requests are required per directory not in the cache, assuming the directory is represented using one image.

If the file or directory is represented using more than one image, two more requests are required per extra image. Furthermore, the bandwidth of the internet connection to the OWS will affect the duration of the request significantly for big images. For instance, downloading a 200 MB file with 100 Mbit/s download bandwidth to Flickr will take 16 s. To download a 5 MB (the cache file size limit) using the same connection would take 0.4 s. The response when requesting the URL to the original image is only a few kilobytes which would take a few milliseconds for the same bandwidth. Constant read operations (including preceding open- and subsequent close operations) on a file just over 5 MB could therefore exceed the API request limit with a 100 Mbit/s bandwidth.

A limitation of FFS that impossible to overcome is the bandwidth and latency of the network connection between the user and Flickr. The bandwidth and latency of this connection can vary significantly depending on, for instance, the network load at a given moment and the geographic location of the user. For instance, given a 5 Mbit/s download bandwidth to Flickr, downloading a 5 MB image would take 8 s, and a 200 MB file would take more than 5 min. However, the API request limit would be a limitation when reading smaller files; for instance, any file of 625 kB or less takes 1 s or less to download given this same bandwidth.

4.3 Benchmarking

This section describes the methodology and execution of the different filesystem benchmarks. Two different filesystems that are relevant to FFS: (1) APFS and (2) GCSF, are compared with the result of two different instances of FFS: (1) one instance that uses Flickr as its OWS, and (2) one instance that uses a FOWS by storing the encoded images in the local filesystem on the test machine.

4.3.1 Filesystems

To analyze the performance of FFS, a filesystem benchmarking tool was used to compare FFS against other filesystems that are relevant to FFS. The filesystems FFS is compared to are:

1. An encrypted APFS partition on an SSD,
2. An instance of GCSF, and,
3. An instance of FFFS using an encrypted APFS filesystem on an SSD as its FOWS.

The encrypted APFS filesystem was used as a reference for a local filesystem without an internet connection. An encrypted APFS is the local filesystem of the development environment for FFS, it was selected as an example of a modern, well-used, and fast filesystem, and provide a baseline benchmark to which FFS and the other filesystems compared.

GCSF was selected to compare FFS against another network-based filesystem. While GCSF is not a deniable filesystem, it is a filesystem that stores its data on an OWS, namely Google Drive. The reason GCSF was used instead of, for instance, the official Google Drive mountable filesystem volume provided by the Google Drive Desktop application, is that GCSF provides instant upload of the files and directories to Google Drive using the Google Drive REST API. The instant upload provided by GCSF enables us to easily measure the duration of a file operation. For instance, a write operation on a file in GCSF will not complete before the new file data has been

completely stored on Google Drive. Another reason why GCSF was chosen is because it is a recent filesystem compared to other related filesystems. Some of the other filesystems discussed in Section 3.3 were developed many years before FFS and thus no longer work as expected, for instance, due to changes in the API, or because the OWS manages the uploaded data differently than previously.

The instance of FFFS using a FOWS of an encrypted APFS was chosen to be compared to FFS so that the duration of the FUSE filesystem operations could be further analyzed. As the filesystem operations of FFFS are similar to the ones of FFS, other than the network request being replaced by local filesystem operations, it is possible to analyze the effect of the OWS latency, the OWS internet connection bandwidth and latency, and the OWS data processing speed has on the filesystem performance. Comparing the benchmark results of FFFS and APFS allows us to analyze the FFS overhead as FFFS is dependent on the performance of APFS. Especially for file operations where FFFS must interact with the storage medium, for instance, write operations and read operations for files not in the cache, FFFS cannot outperform APFS as FFFS requires the execution time of the underlying APFS file operation as well as the internal FFS computation time. Both FFFS and FFS were mounted with a maximum buffer size of 32 MB.

4.3.2 IOZone

IOZone [76] is a filesystem benchmarking tool used to analyze the performance of filesystem file operations using different tests on a file [96]. Examples of tests that IOZone provides support for are: reading and writing, reading and writing randomly, and reading backward. Each test can be run with different file sizes and different buffer sizes for the read or write operation. Normally, multiple buffer sizes are used for each test and for each file size tested. The buffer size starts at 4 kB and increases by a multiple of two up to a buffer size equal to the file size. Multiple file sizes are often used for benchmarking tests as well, which are also increased by a multiple of two. For instance, one could run the IOZone tests with file size 1024 kB and 2048 kB, which would utilize the following values of the file size and buffer size for each test specified:

1. File size = 1024 kB, buffer size = 4 kB,
2. File size = 1024 kB, buffer size = 8 kB,
3. File size = 1024 kB, buffer size = 16 kB,
4. File size = 1024 kB, buffer size = 32 kB,
5. File size = 1024 kB, buffer size = 64 kB,
6. File size = 1024 kB, buffer size = 128 kB,
7. File size = 1024 kB, buffer size = 256 kB,
8. File size = 1024 kB, buffer size = 512 kB,
9. File size = 1024 kB, buffer size = 1024 kB,
10. File size = 2048 kB, buffer size = 4 kB,
11. File size = 2048 kB, buffer size = 8 kB,
12. File size = 2048 kB, buffer size = 16 kB,
13. File size = 2048 kB, buffer size = 32 kB,
14. File size = 2048 kB, buffer size = 64 kB,
15. File size = 2048 kB, buffer size = 128 kB,
16. File size = 2048 kB, buffer size = 256 kB,
17. File size = 2048 kB, buffer size = 512 kB,
18. File size = 2048 kB, buffer size = 1024 kB, and
19. File size = 2048 kB, buffer size = 2048 kB.

Furthermore, each test is run for each file size-buffer size pair before the buffer size or file size is increased. This means that, for the example above using the tests: Read, Write, Re-Read, Re-Write, Random Read, and Random Write, IOZone will run the following in order:

1. Write test for: File size = 1024 kB, buffer size = 4 kB,
2. Re-Write test for: File size = 1024 kB, buffer size = 4 kB,
3. Read test for: File size = 1024 kB, buffer size = 4 kB,
4. Re-Read test for: File size = 1024 kB, buffer size = 4 kB,
5. Random Read test for: File size = 1024 kB, buffer size = 4 kB,
6. Random Write test for: File size = 1024 kB, buffer size = 4 kB,
7. Write test for: File size = 1024 kB, buffer size = 8 kB,
8. Re-Write test for: File size = 1024 kB, buffer size = 8 kB, et cetera.

When IOZone reads from a file it has written to, it checks that the file content is what it wrote previously to verify that the filesystem stores the data properly. This is not documented in the IOZone documentation [96] but was discovered during testing. However, while it checks that file operations function correctly, it does not verify all aspects of the filesystem functionality. Further, as IOZone does not state that the file operations are tested, it cannot be assumed that the file operations are correct. Additionally, IOZone does not test if directory hierarchies work as expected, nor if multiple files can be stored at the same time. IOZone is a benchmarking tool used for evaluating the performance of the file operations of a filesystem, not testing the functionality of a filesystem. However, certain cases of the functionality of both FFS and GCSF were tested in order to see that they support directory hierarchies and multiple files as expected. Future work includes analyzing the functionality of FFS and GCSF. APFS is expected to have full functionality as it is a professionally developed and widely used filesystem.

While IOZone supports multiple different file operation tests, this thesis only used a subset of these for benchmarking. Among other reasons, certain tests failed when ran on GCSF. Furthermore, tests such as backward reading lack relevance as it tests a rare case of filesystem operations. The documentation of IOZone [96] claims that the software MSC Nastran uses backward-read. The documentation also mentions that only a few operating systems provide enhancements for backward reading, although many operating systems provide enhancements for forward-reading. As FFS is intended as a proof-of-concept filesystem and is not intended as a general-purpose filesystem, only relevant tests were chosen. The IOZone benchmarking tests used

in the thesis are: Forward- Read and Write, Forward- Re-Read and Re-Write, and Random- Read and Write. The *Forward* specifier will sometimes be omitted in the thesis when the tests are referenced. For instance, when mentioning the Read test, we refer to the Forward Read test. The Forward Write test is writing data to a new file, in order. The file is first created which can include overhead time. Forward Read tests reading the file in order. The Read test tests reading from the same file in-order. The Re-Write test measures the performance of writing to an existing file in-order. In general, Re-Write is faster than Write as it does not have to create the file. Re-Read measures the performance of reading a recently read file in-order. In general, Re-Read is faster than Read as the file data can be kept in the filesystem cache. The Random Write and Random Read tests measure writing and reading data from random positions in a file. Depending on filesystem implementation, this can be influenced by many factors. For instance, as FFS has to download and read the entire file into memory before accessing a specific offset, FFS might provide lower performance for these tests than a filesystem that can choose to only read a part of a file at a specific location. The official descriptions of these tests can be found in the IOZone documentation [96].

The IOZone documentation [96] states that to get the most accurate performance results from the benchmarking, the maximum file size of the tests should be set to a value bigger than the filesystem cache. While the FFS cache limit is known to be 5 MB, the cache size limit or the existence of such a limit for the other filesystems, such as GCSF¹, is unknown. The IOZone documentation states that when the cache is unknown, it should be set to be greater than the physical memory of the system. The memory of the computer where the benchmarking is run is 16 GB which is a greater value than reasonable for testing FFS and GCSF due to the execution time of the tests. Each doubled file size takes exponentially more time as both the file size and buffer size are doubled for each test. Furthermore, it was found that GCSF will crash for large file sizes (as occurred for file sizes greater than 262 144 kB). The maximum file size for the benchmarking tests was set as 262 144 kB as this is bigger than the biggest image possible to store on Flickr, requiring FFS to split the image

¹ Size limit of the cache entries of GCSF cannot be configured. However, the number of cache entries and the time-to-live per cache entry can be configured

into more than one image on the OWS. This helped us test the functionality of FFS further. The file sizes used for the IOZone tests were therefore set as:

1. 1024 kB,
2. 2048 kB,
3. 4096 kB,
4. 8192 kB,
5. 16 384 kB,
6. 32 768 kB,
7. 65 536 kB,
8. 131 072 kB, and
9. 262 144 kB

The biggest buffer size IOZone uses is 16 384 kB, therefore the buffer sizes tested were:

1. 4 kB,
2. 8 kB,
3. 16 kB,
4. 32 kB,
5. 64 kB,
6. 128 kB,
7. 256 kB,
8. 512 kB,
9. 1024 kB,
10. 2048 kB,
11. 4096 kB,
12. 8192 kB, and
13. 16 384 kB

However, the actual maximum buffer size for each file size is limited to the file size itself. For instance, for a file size of 4096 kB, IOZone will run the tests for buffer sizes up to, and including, 4096 kB. It does not make sense to run tests with a buffer size greater than 4096 kB for a file size of 4096 kB.

While GCSF does not define a maximum file size for its cache, one can configure the time-to-live of the cache entries, and the number of cache entries allowed in the cache [97]. During benchmarking, The GCSF cache was configured to store up to 20 cache entries for up to 300 seconds per cache entry. The cache entry limit is the same limit as the cache entry limit of FFS. 300 seconds time-to-live limit was set for the entries as it was the default configuration for the time-to-live.

IOZone reads and writes the same file. The file is created and removed during the tests, but there are never two files created by IOzone at the same time. When conducting the benchmarking for this thesis, the file is stored in the root directory of FFS, FFFS, and GCSF. This means the path traversal is as short as possible for these filesystems. Furthermore, as FFS and FFFS constantly cache the root directory and both have a cache limit of 20 entries, and as no other operations are performed on the filesystem at the same time as the benchmarking tests, the file can always be stored in the cache as long as the file is small enough. The cache entry of the benchmarking

file will not be removed unless the file is removed as the cache will not be filled by other entries. The file used for benchmarking APFS was in temporary directory in the root directory of the computer (`/tmp`). The reason is because the root directory of the APFS on the computer was a Read-only filesystem. Furthermore, FFFS saves its files in the same temporary directory, so the performance of saving the images for FFFS and the performance of the APFS write operation can be compared. Future work could compare benchmarking FFS, FFFS, GCSF, and APFS in different depths of directory hierarchies to analyze how the depth of a file impact the performance of the filesystem.

When benchmarking the filesystems using IOZone, an argument is passed to include the time to close a file (using the `close` filesystem operation) in the total time of a test. This is important as FFS, and potentially other filesystems, save the data to the storage medium only after the device is closed. In the case of FFS, if the time of closing the file was not included, the performance of the filesystem would appear to be higher than it is.

IOZone produces a log of the benchmarking results for the filesystem it benchmarked. This log contains a report of each test (file operation) with performance data for each file size, and for each buffer size for each file size benchmarked for the test. The performance of the filesystem is measured in kilobytes per second.

During the benchmarking of FFS and GCSF, an automatic speed test was conducted every five minutes to survey the current internet connection. The speed test uses Bredbandskollen’s command line interface tool [98] which measures the latency, upload-, and download speed of an internet connection to a measurement server in Sweden, Norway, or Denmark [99]. The benchmarking tests of FFS and GCSF were carried out in Amsterdam in The Netherlands using an ethernet connection to a fiber-connected router in a corporate office after-hours when no other devices used the internet in the office. While the internet connection to the measurement server of Bredbandskollen is not necessarily equal to the internet connection to the servers of Flickr or Google Drive, Bredbandskollen’s output was used as an estimate of the internet connection’s characteristics. Measuring the individual filesystem’s internet connection bandwidth would have been preferable. However, when researching tools that could measure

the average bandwidth over time, per application, no tools were found that could be run on macOS. As there are multiple background processes running at all times, it is important that the internet connection can be filtered based on the application. If it could be ensured that no other processes used the internet at the same time, a tool such as Wireshark [100] could be used to measure the bandwidth. In future work the measurement of the individual filesystems bandwidths could be explored further which could provide further comparisons between the filesystems.

Chapter 5

RESULTS

This section presents the results of the thesis. The resulting filesystem is presented in Section 5.1. The benchmarking data outputted from IOZone is presented in Section 5.2

5.1 FFS

The artifact developed as a result of the thesis is FFS, which uses Flickr as its OWS. The source code of FFS can be found on GitHub at github.com/GlennOlsson/FFS [101]. The source code consists of 4 184 lines of code excluding comments. The filesystem provides free cloud-based cryptographic and deniable storage as a mountable volume for a computer running macOS. The filesystem requires the user to provide their Flickr API keys and an encryption password. The API keys are used to authenticate with the Flickr API, and the password is used to derive the encryption and decryption keys. These values are passed to FFS as environment variables.

5.2 Benchmarking

This section presents the result from the IOZone benchmarking tests run on each filesystem. The output results are presented as a table for each test for each filesystem (See Appendix C starting on page 147 for the tables). Each table presents the benchmarked performance of the test for each file size and each buffer size. The benchmarking completed successfully for all file sizes for FFS, FFFS, and APFS. For the biggest file size, 262 144 kB, GCSF crashed multiple times, but it succeeded for the other file sizes. Therefore, the results for the biggest file size was omitted from the tests of GCSF. In total, six benchmarking tests were conducted on the filesystems, using nine file sizes (eight for GCSF) and up to 13 buffer sizes per file size. Each

test per filesystem produces a table with nine rows (eight rows for GCSF) and 13 columns, where each cell is the performance of the test with the specific file size and buffer size on the filesystem. Each table for FFS, FFFS, and APFS have 107 cells, while the table for GCSF has 94 cells.

The average latency of the internet connection when FFS ran was 15.3 ms, the average download speed was 90.87 Mbit/s, and the average upload speed was 92.95 Mbit/s. The average latency of the internet connection when GCSF ran was 17.29 ms, the average download speed was 89.2 Mbit/s, and the average upload speed was 91.83 Mbit/s.

Combining all the data points of one benchmark result table, we get the overall performance of a test on a filesystem. With this data we can use a box plot to present the values in the table, and combining the results from all filesystems for a specific test, we can compare their box plots in one figure. Figure 5.2 presents a box plot of the benchmarking results of the filesystems for the Read test. It can be observed that the read operation performance of FFS and GCSF are in general worse than the performance for FFFS and APFS. FFS has by far the biggest spread of values, and FFFS has also a significant spread. The median performance of FFS and GCSF are similar. In contrast, the results for GCSF and APFS have less spread. The median performance of APFS is significantly higher than the median performance of FFS, FFFS, and GCSF.

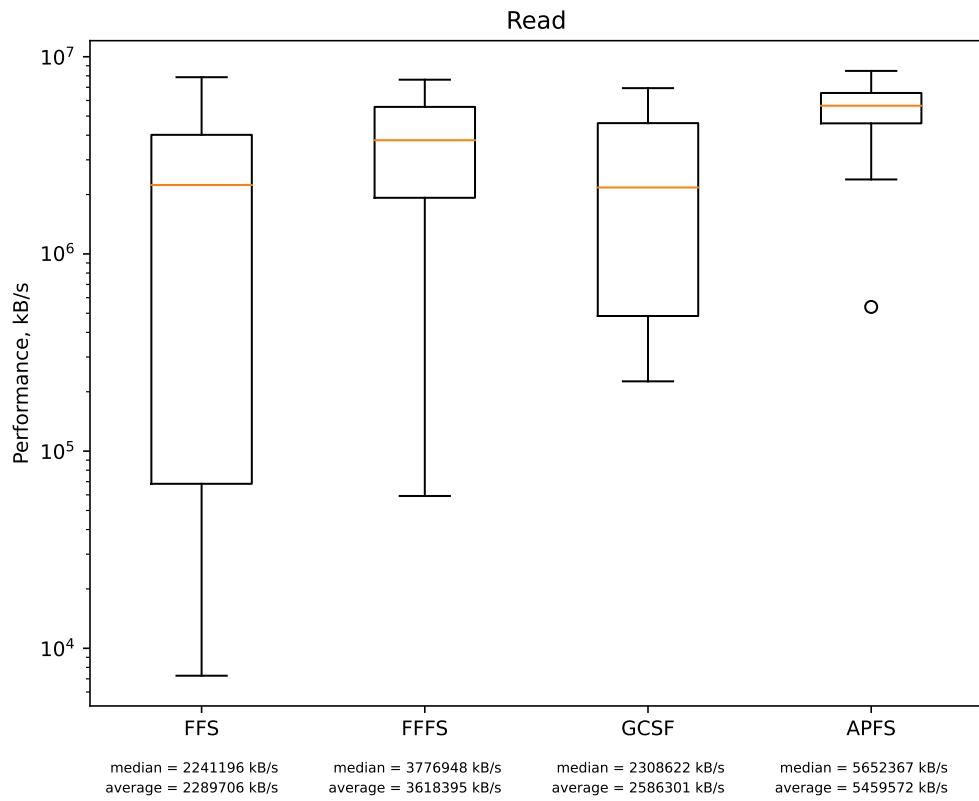


Figure 5.1: Box plot of the IOZone output for the Read test on the different filesystems

Figure 5.2 presents a box plot of the benchmarking results of the filesystems of the Write test. APFS has the best write performance of the four filesystems, followed by FFFS. In contrast, the cloud-based filesystems FFS and GCSF have the worst median write performance, with FFS having the worst performance of the filesystems. Comparing with the results of the Read test presented in Figure 5.2, it can also be noted that the write performance is significantly worse for the read operations for all filesystems. The average performance of the Write test for APFS is 9.8% of the Read performance. For FFFS, GCSF, and FFS this percentage was 0.29%, 0.17%, and 0.06%, respectively.

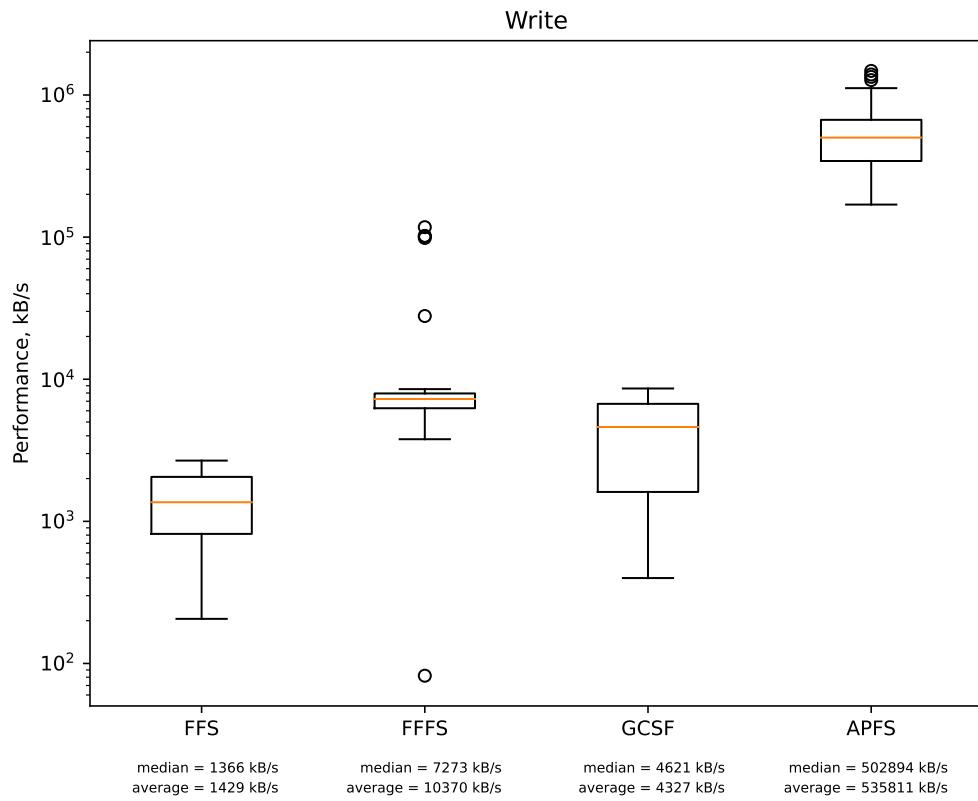


Figure 5.2: Box plot of the IOZone output for the Write test on the different filesystems

Figure 5.2 presents the result of the Re-Read test for the filesystems. The median performance of the filesystems are similar, with the performance of FFS being lowest. The spread of the values for APFS is greater than for the other filesystems but the filesystem still has the best median and average performance. While the average performance for the Re-Read test of APFS is around 5 400 000 kB/s, the lowest performance was at 422 414 kB/s, namely for `file size = 32 768 kB`, `buffer size = 8 kB`. The spread of values is higher for FFS than for FFFS and GCSF. FFFS has a higher average and median performance than GCSF.

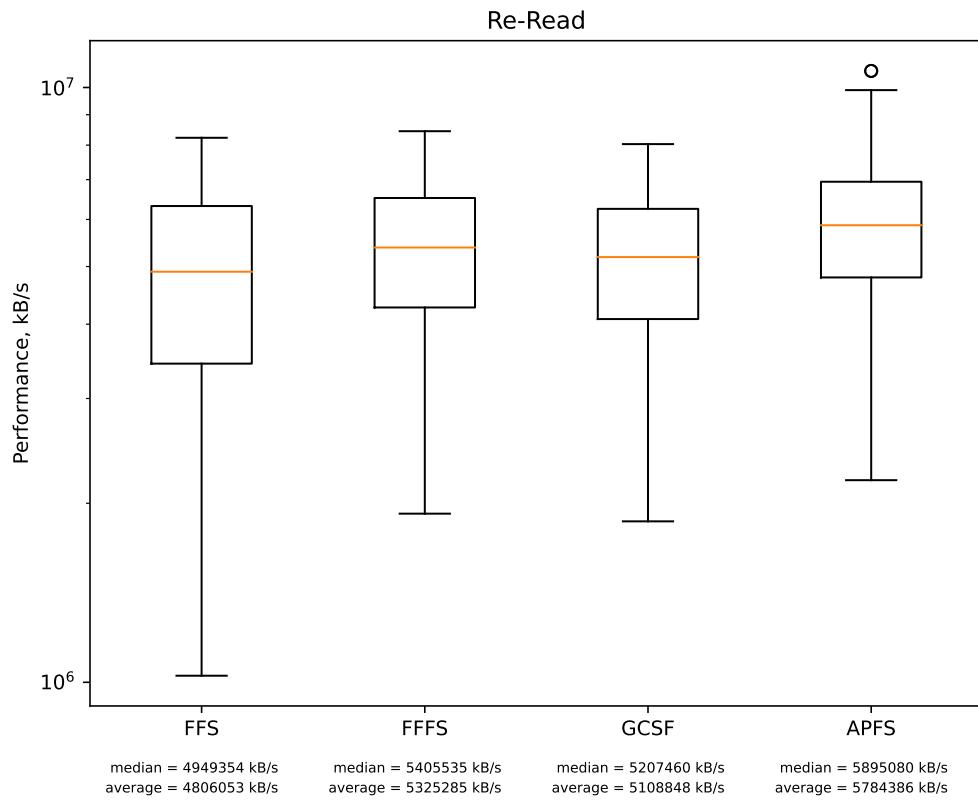


Figure 5.3: Box plot of the IOZone output for the Re-Read test on the different filesystems

Figure 5.2 presents a box plot for the Re-Write test for the filesystems. Similar to the Write test results presented in Figure 5.2, APFS has the best performance of the filesystems, followed by FFFS and finally the two cloud-based filesystems. APFS is the only filesystem that has a higher average and median performance for the Re-Write test compared to its Write test, with a 22% better median performance. The other filesystems have worse average and median performance for the Re-Write compared to their Write test. The median performance of the Re-Write test for FFS, FFFS, and GCSF are 85%, 82%, and 64% of the median performance of their Write test, respectively.

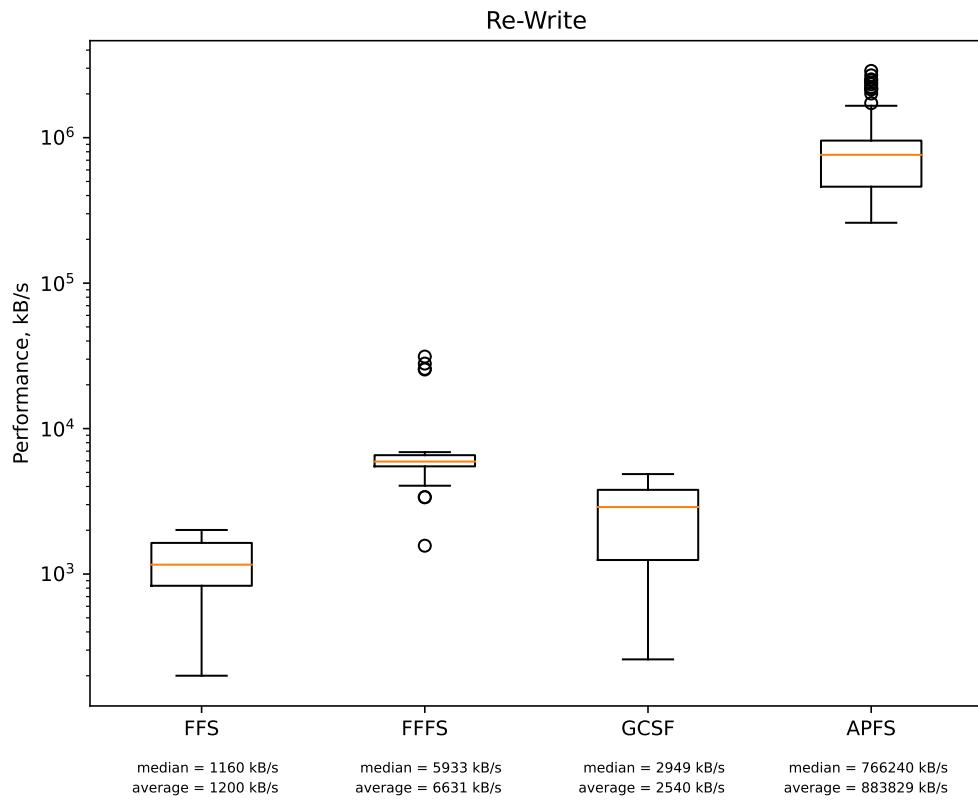


Figure 5.4: Box plot of the IOZone output for the Re-Write test on the different filesystems

Figure 5.2 presents a box plot for the Random read test for the different filesystems. The results are similar to the results for the Re-Read test presented in Figure 5.2, however, FFS has a bigger spread of values than APFS has in the Re-Read test. FFFS has the best average performance of the filesystems, and APFS has the best median performance. The median and average performance of FFS is lower than the other filesystems.

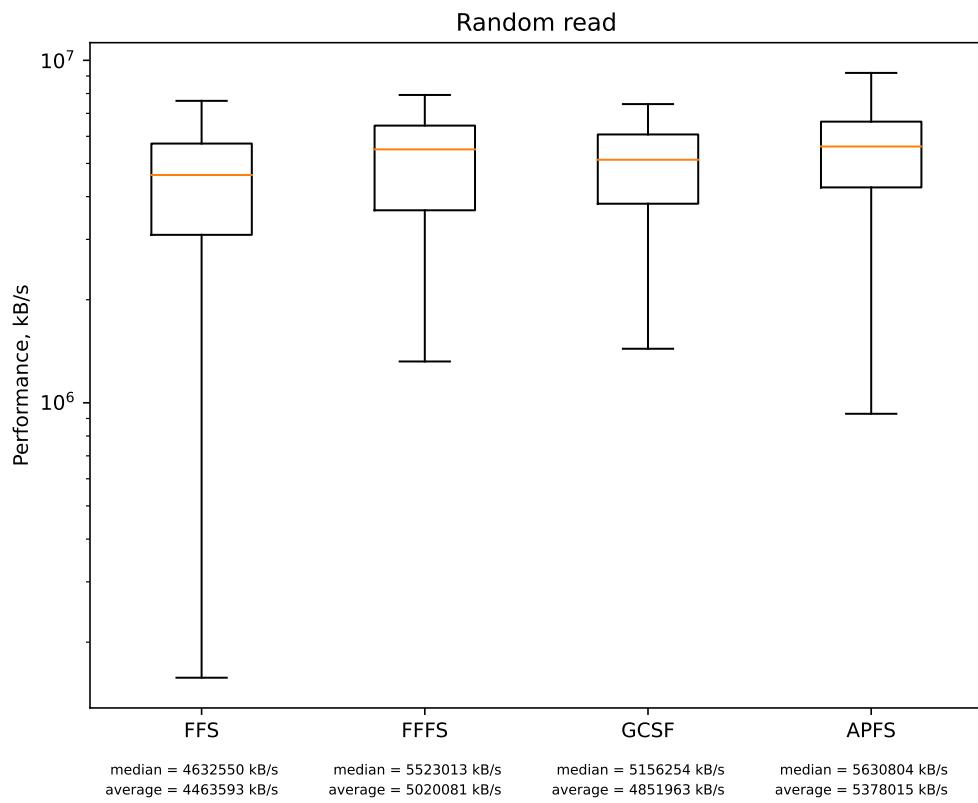


Figure 5.5: Box plot of the IOZone output for the Random read test on the different filesystems

Figure 5.2 presents a box plot for the Random read test for the different filesystems. APFS has the highest performance, followed by FFFS and the cloud-based filesystems. GCSF has better performance than FFS. The performances are similar to the Re-Write for all filesystems.

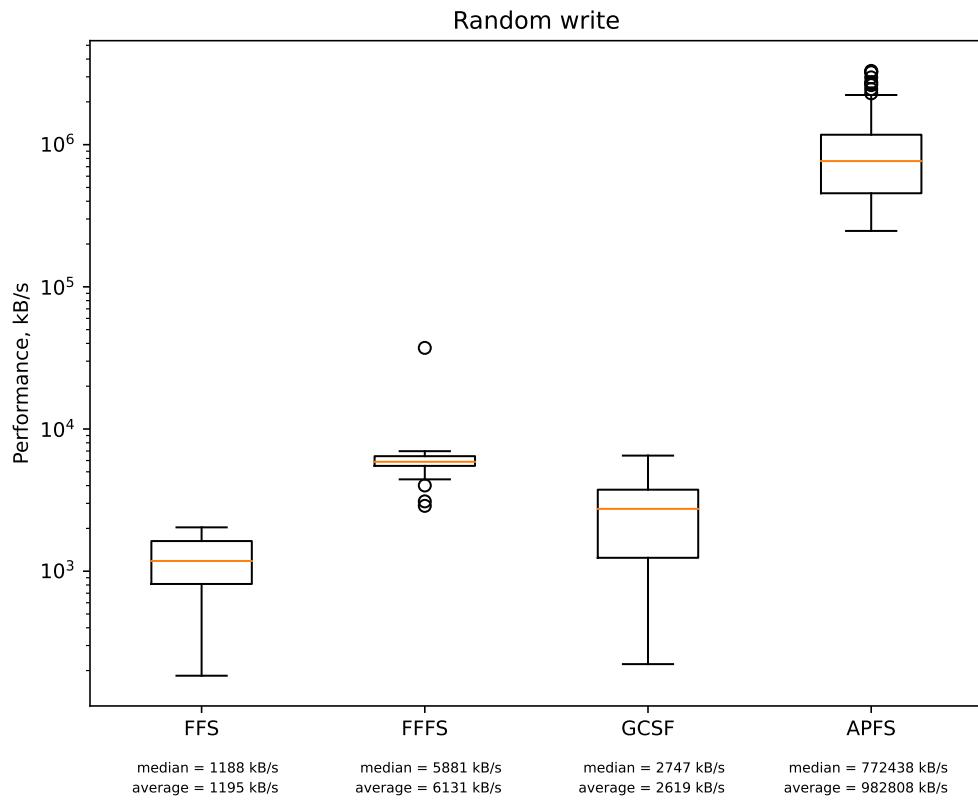


Figure 5.6: Box plot of the IOZone output for the Random write test on the different filesystems

FFS does not have the best performance in any of the box plots presented. GCSF has better performance than FFS for all tests run with the benchmarking. Following are diagrams presenting the performance of each benchmarking test per file size, for each filesystem. The raw data tables can be found in Appendix C. Figure 5.2 to Figure 5.2 present the performances of the Read, Write, Re-Read, Re-Write, Random Read, and Random Write tests for FFS. Figure 5.2 to Figure 5.2 present the performances of the Read, Write, Re-Read, Re-Write, Random Read, and Random Write tests for FFFS. Figure 5.2 to Figure 5.2 present the performances of the Read, Write, Re-Read, Re-Write, Random Read, and Random Write tests for GCSF. Figure 5.2 to Figure 5.2 present the performances of the Read, Write, Re-Read, Re-Write, Random Read, and Random Write tests for APFS.

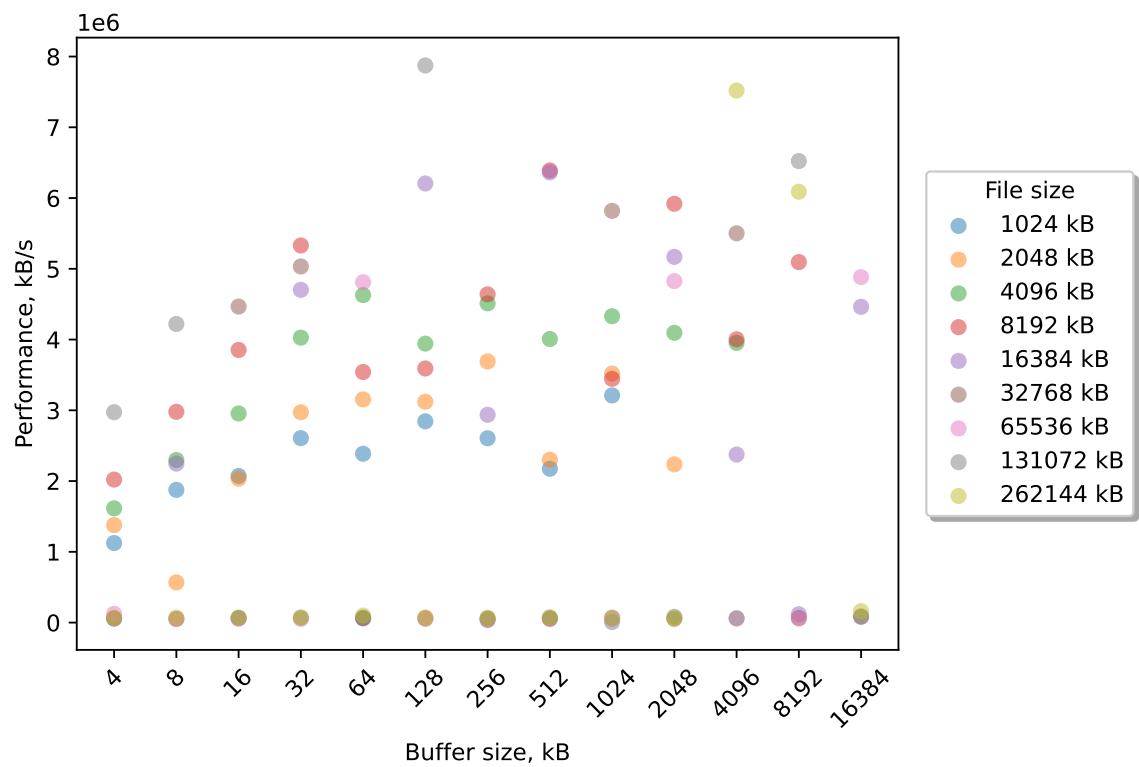


Figure 5.7: IOZone output for FFS Read

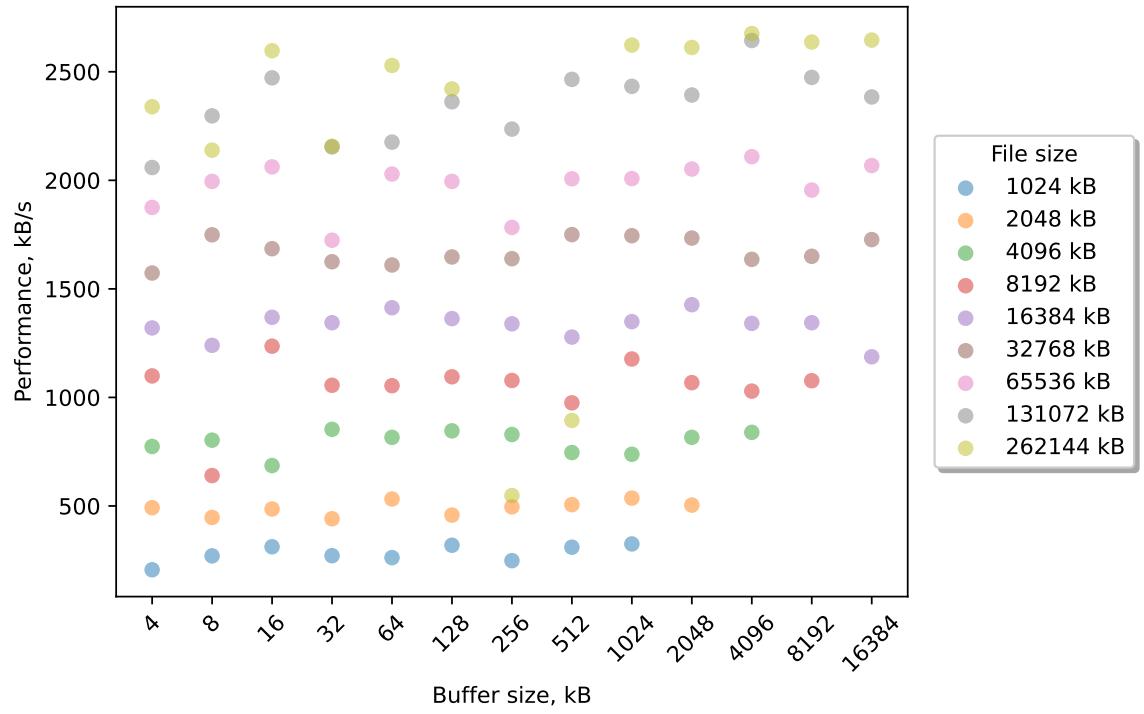


Figure 5.8: IOZone output for FFS Write

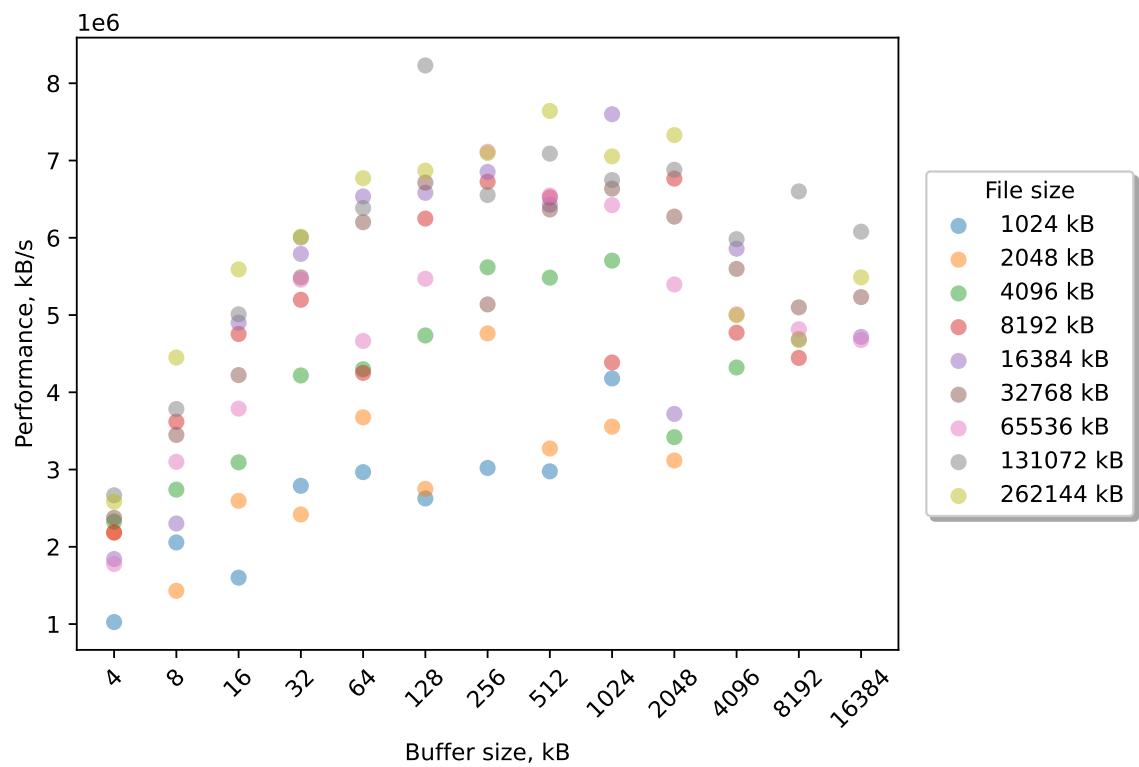


Figure 5.9: IOZone output for FFS Re-Read

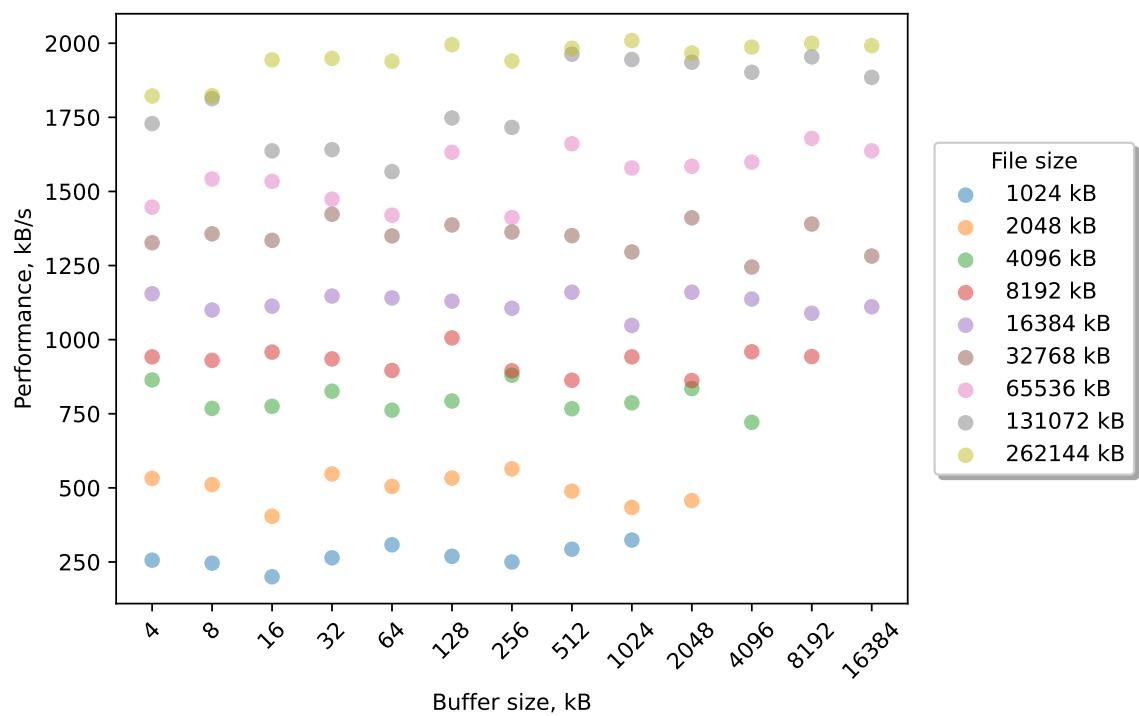


Figure 5.10: IOZone output for FFS Re-Write

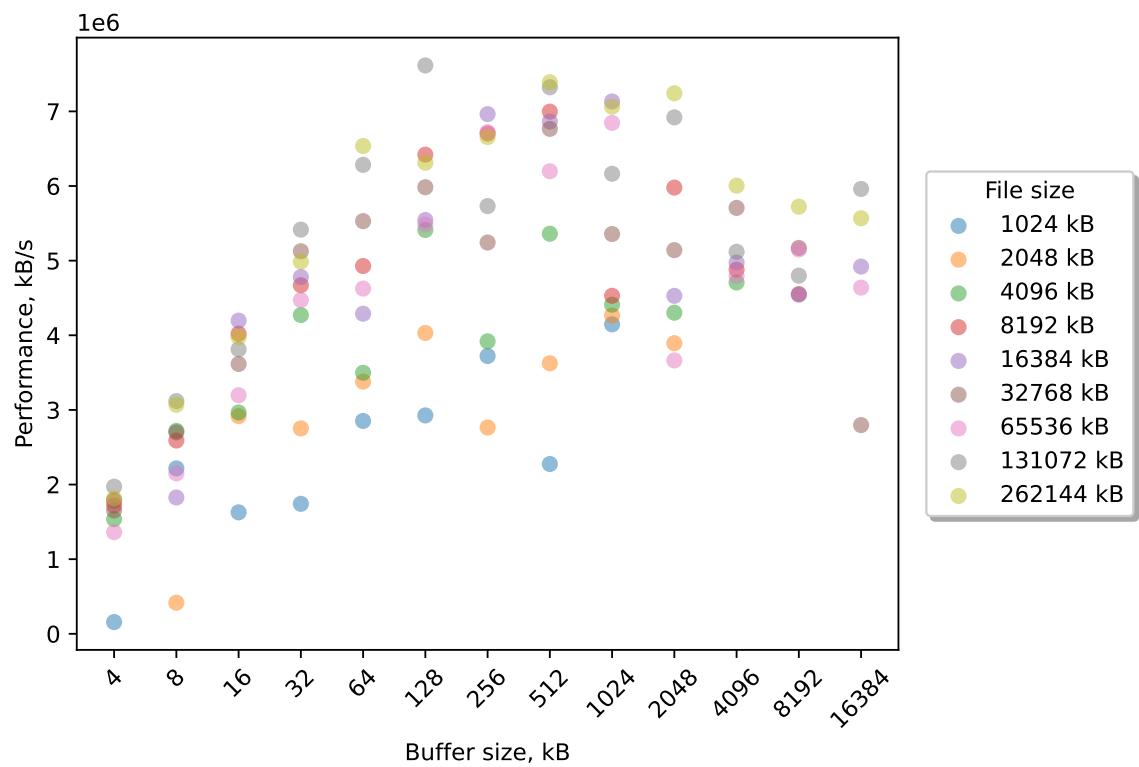


Figure 5.11: IOZone output for FFS Random read

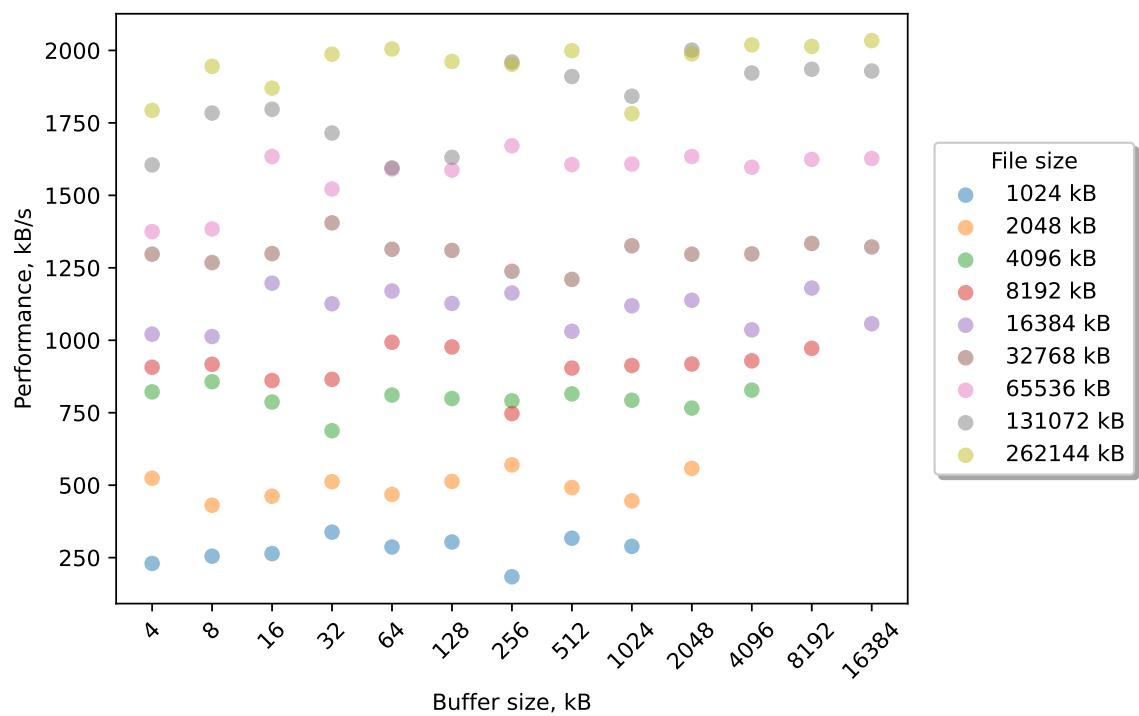


Figure 5.12: IOZone output for FFS Random write

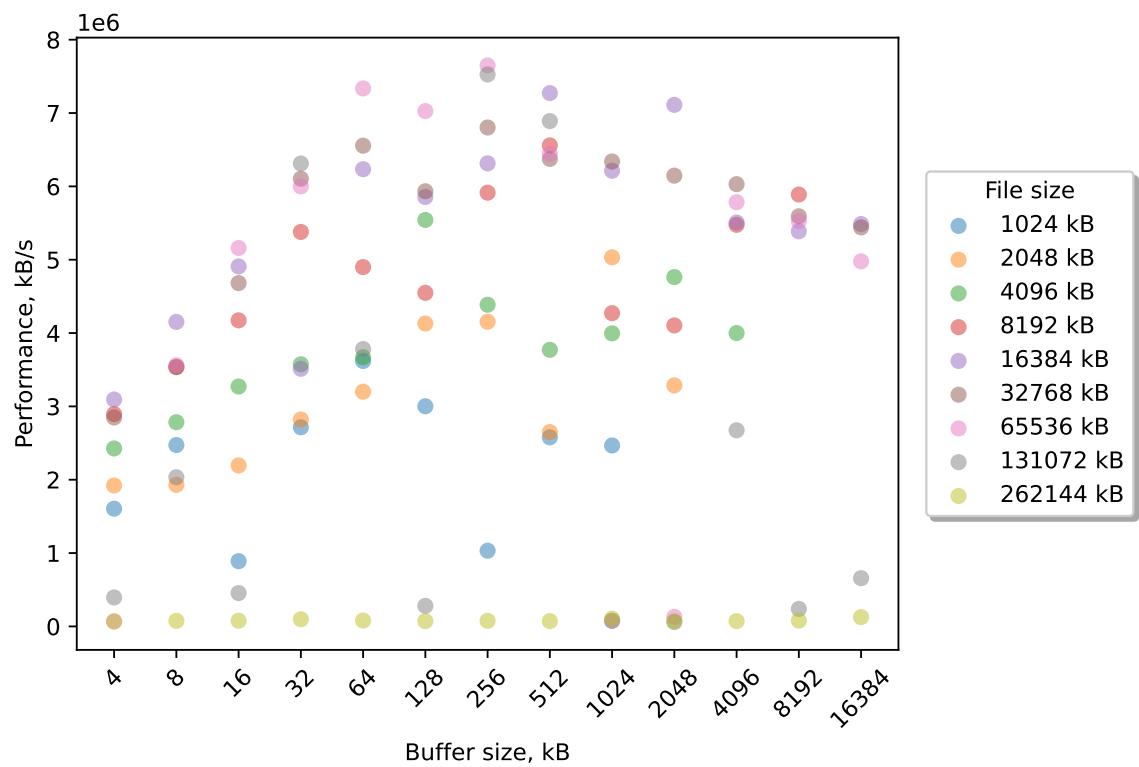


Figure 5.13: IOZone output for Fejk FFS Read

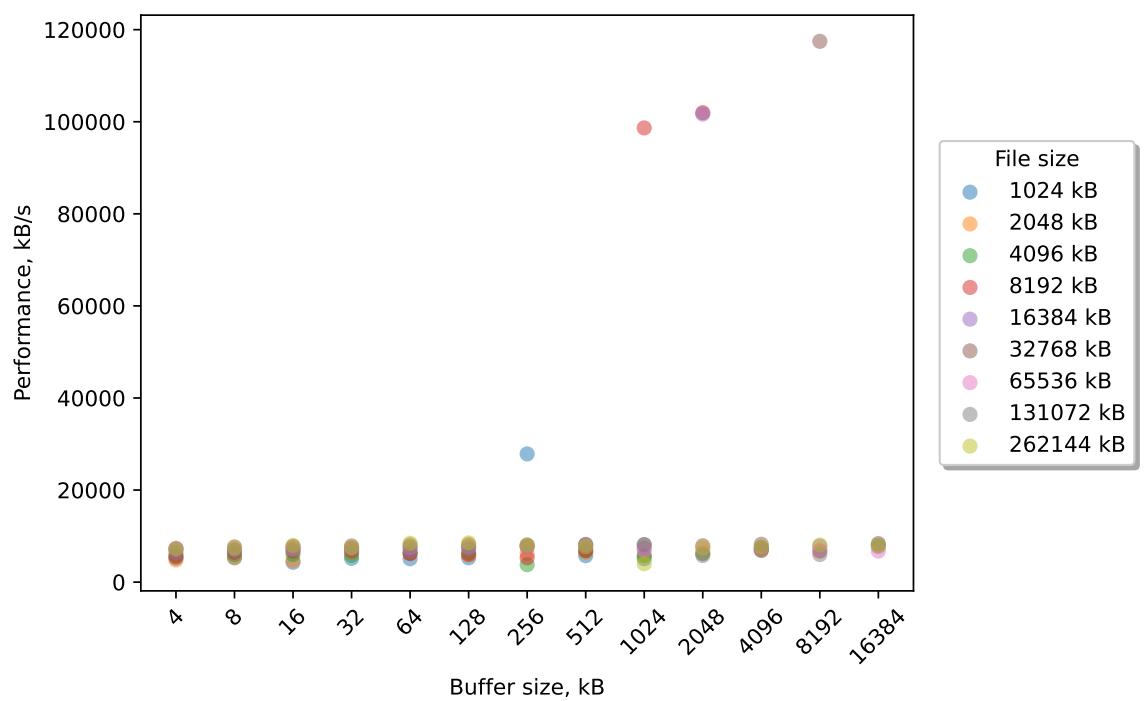


Figure 5.14: IOZone output for Fejk FFS Write

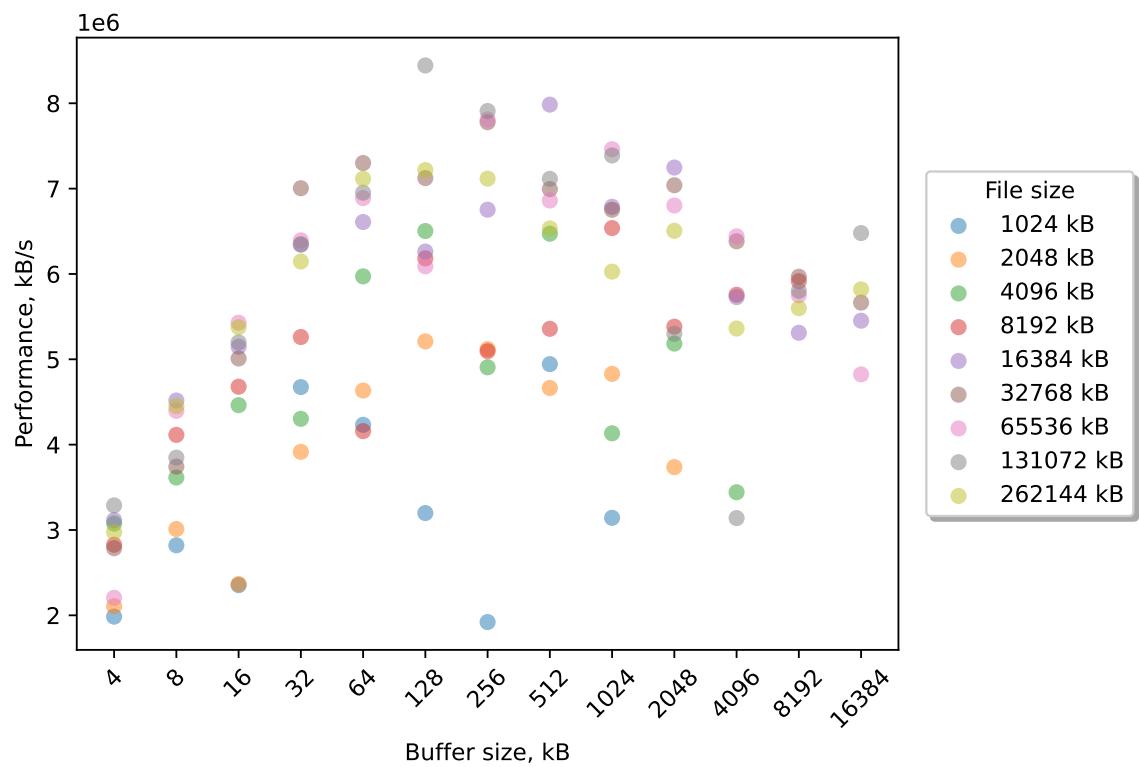


Figure 5.15: IOZone output for Fejk FFS Re-Read

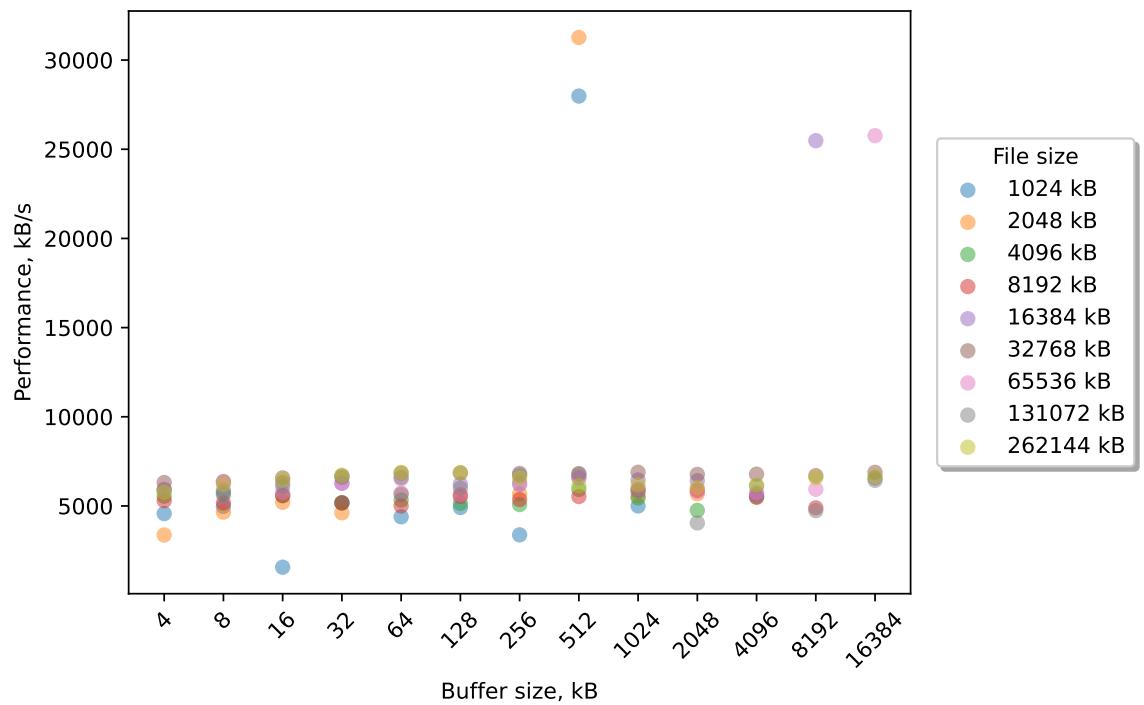


Figure 5.16: IOZone output for Fejk FFS Re-Write

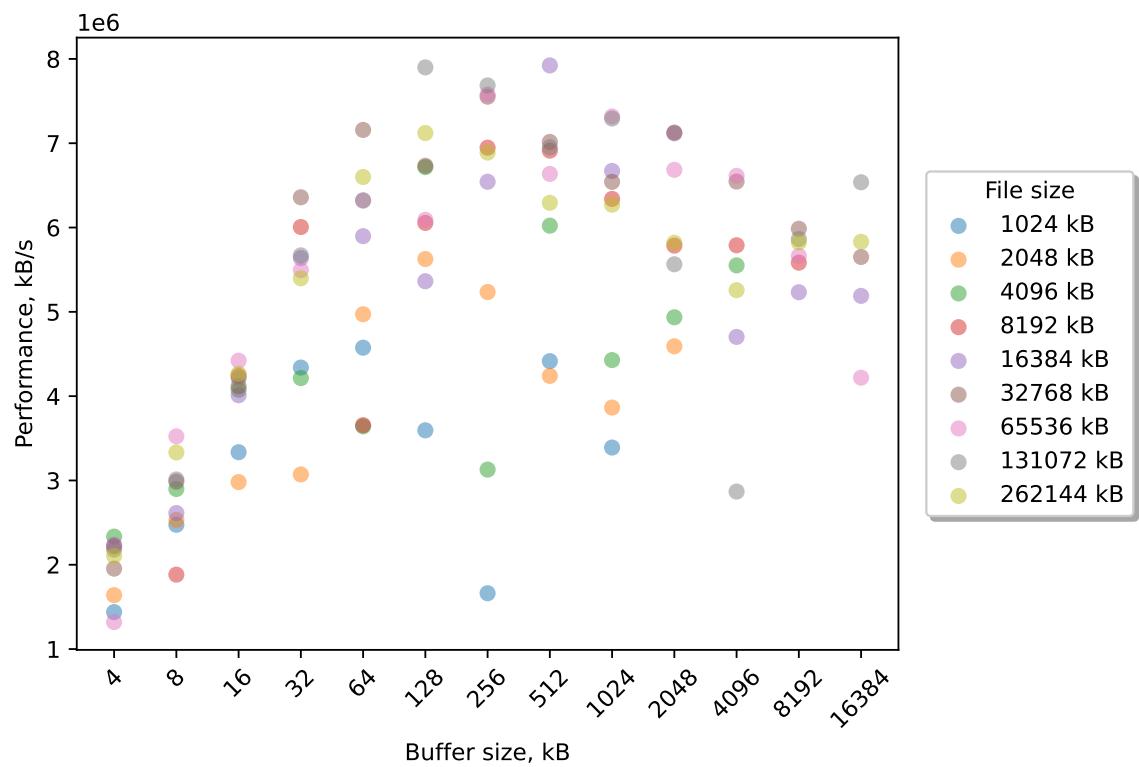


Figure 5.17: IOZone output for Fejk FFS Random read

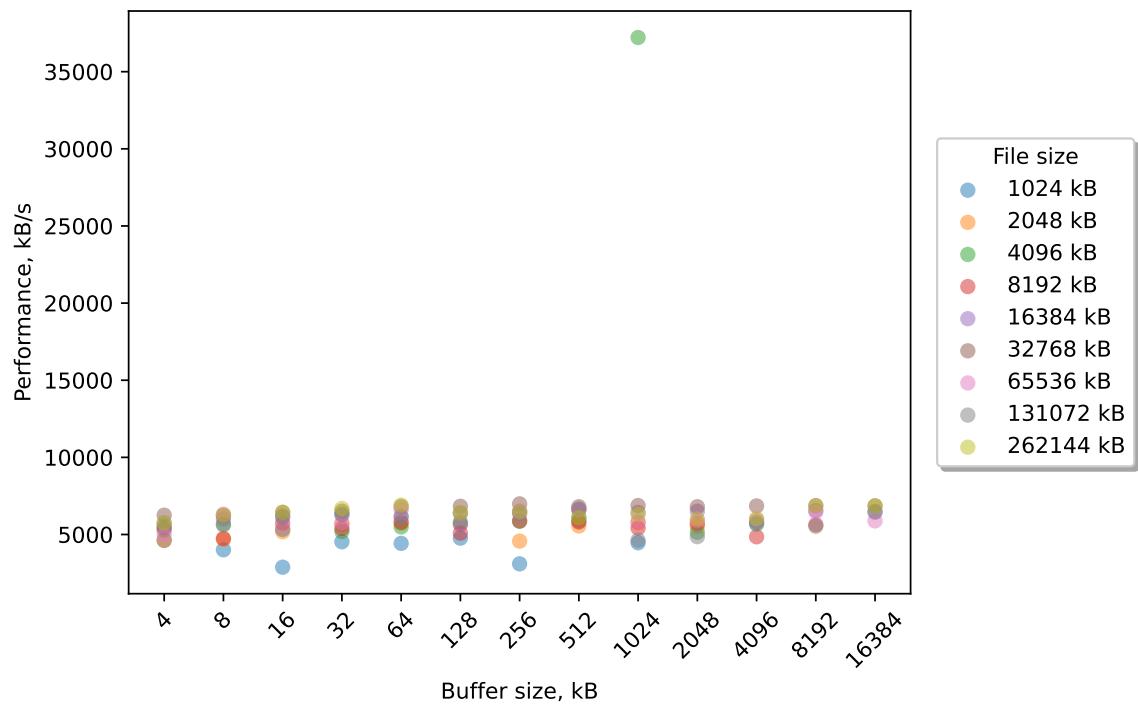


Figure 5.18: IOZone output for Fejk FFS Random write

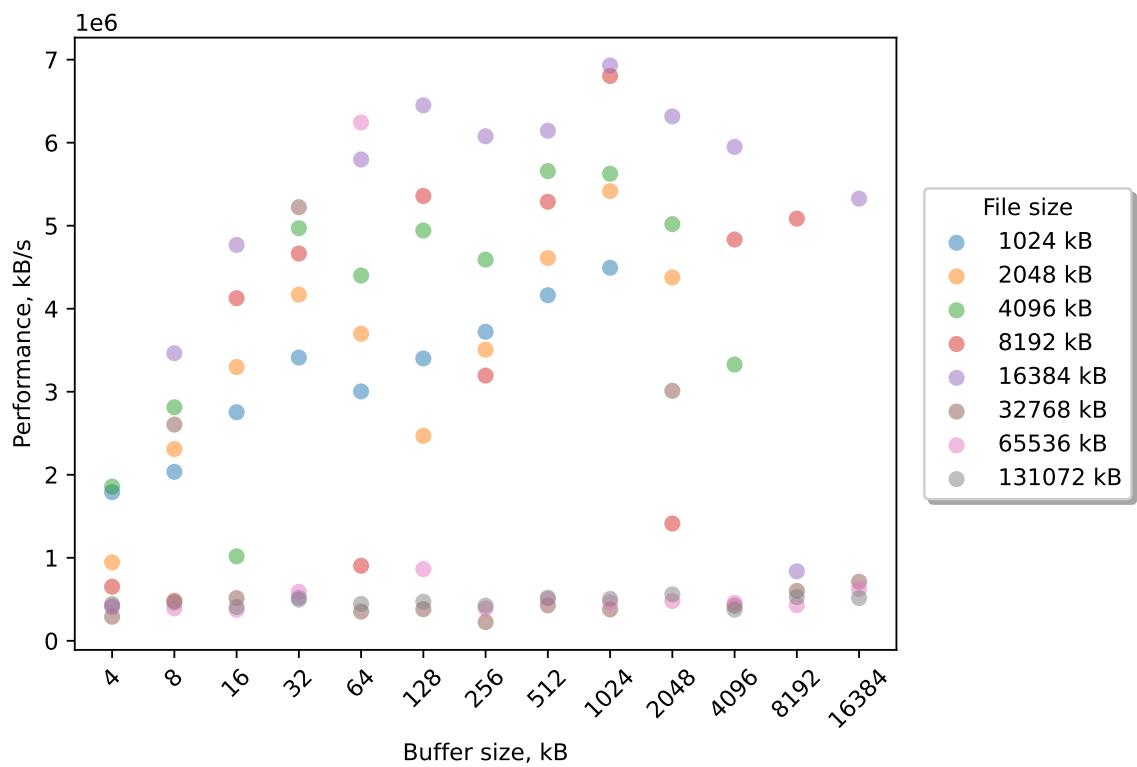


Figure 5.19: IOZone output for GCSF Read

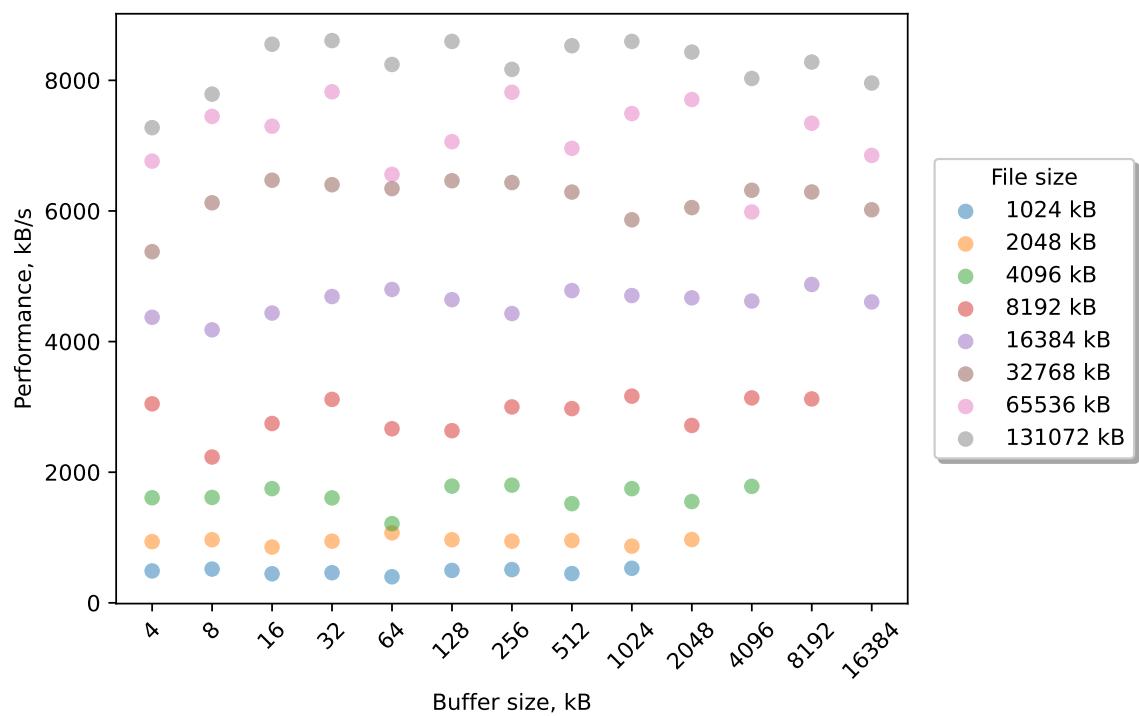


Figure 5.20: IOZone output for GCSF Write

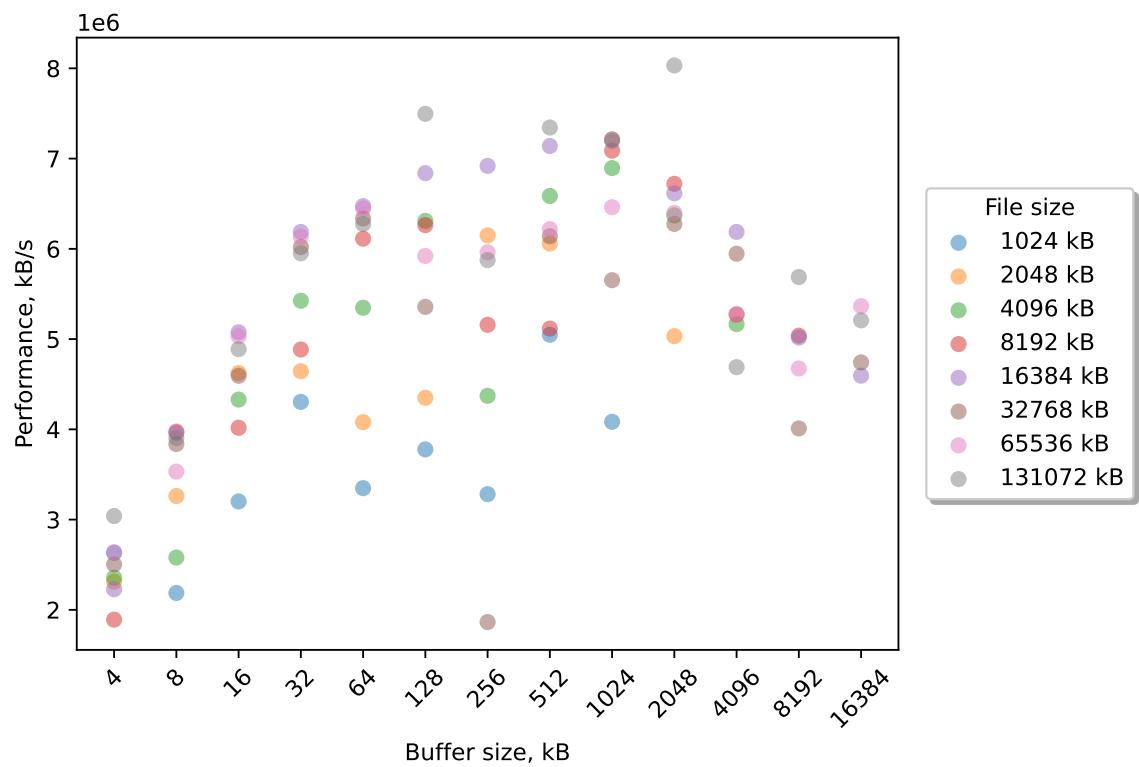


Figure 5.21: IOZone output for GCSF Re-Read

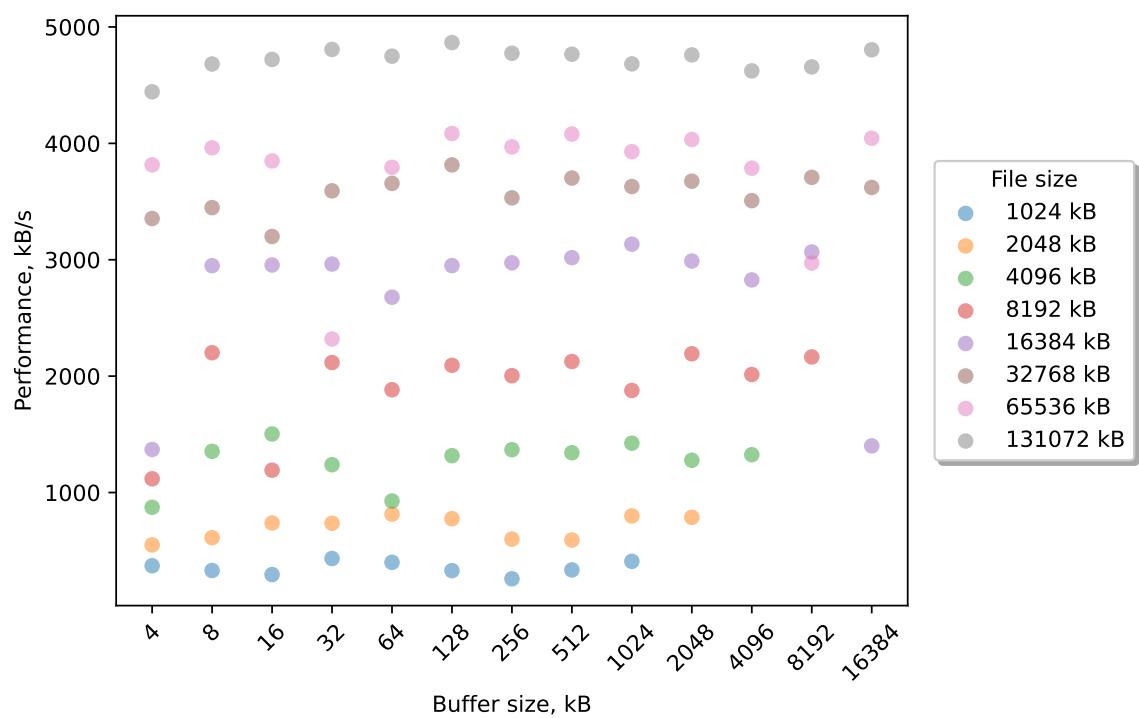


Figure 5.22: IOZone output for GCSF Re-Write

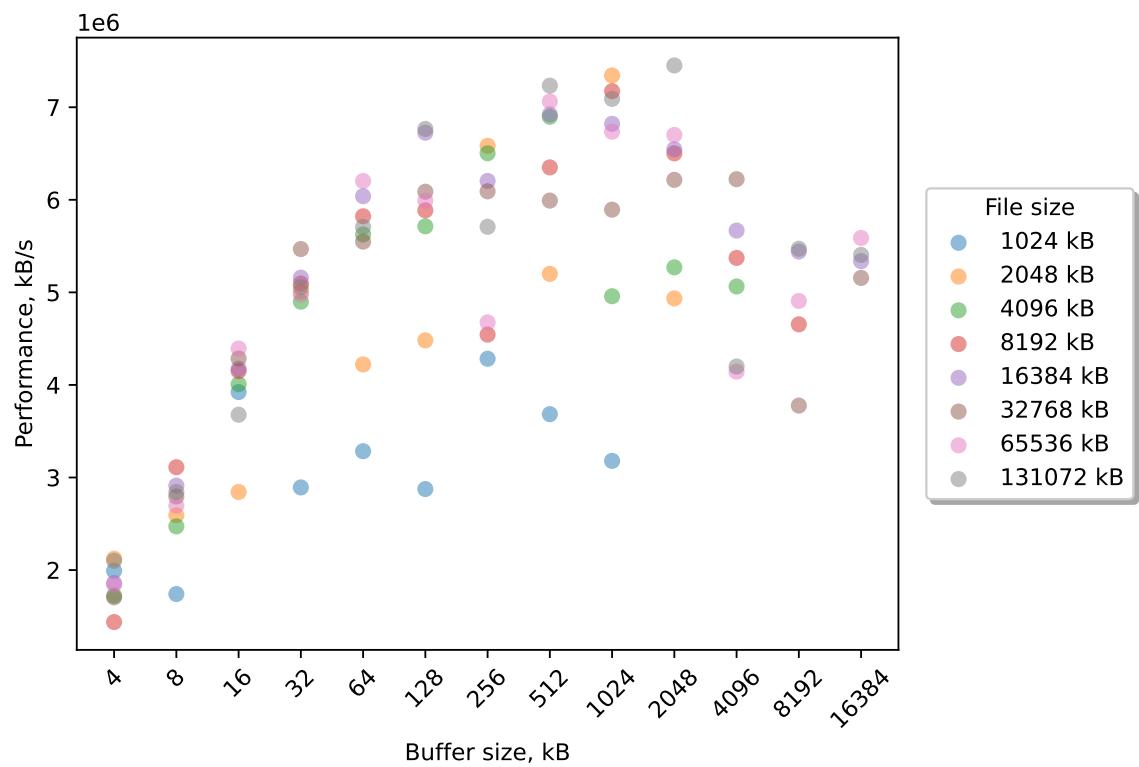


Figure 5.23: IOZone output for GCSF Random read

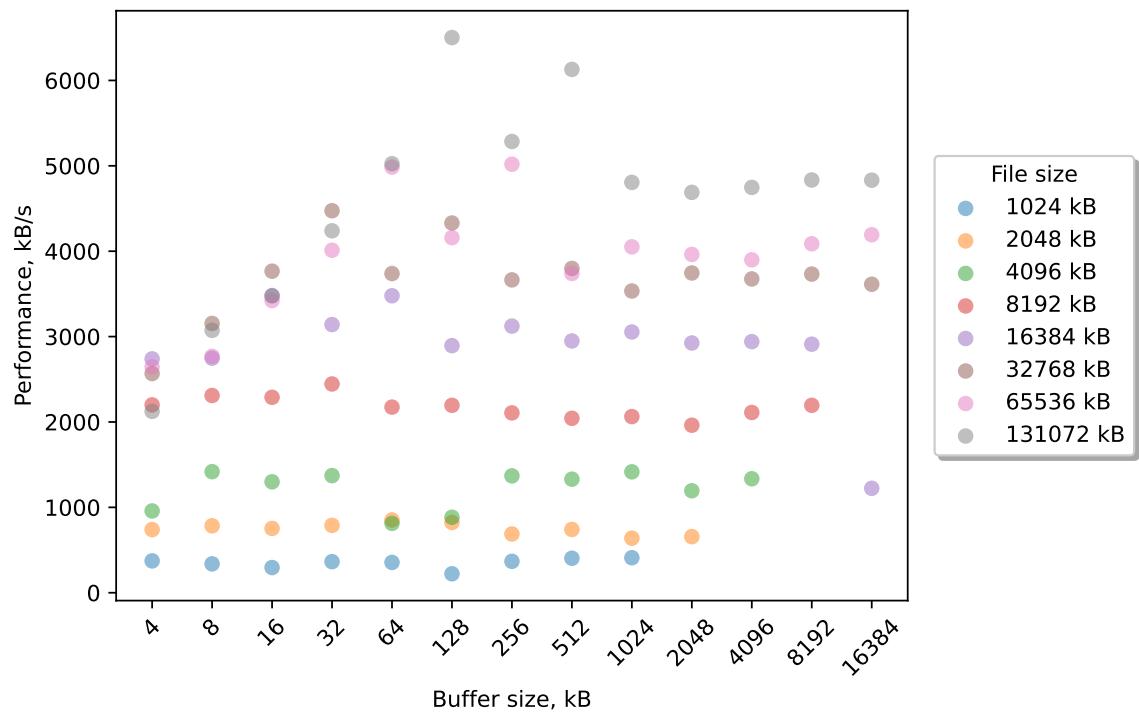


Figure 5.24: IOZone output for GCSF Random write

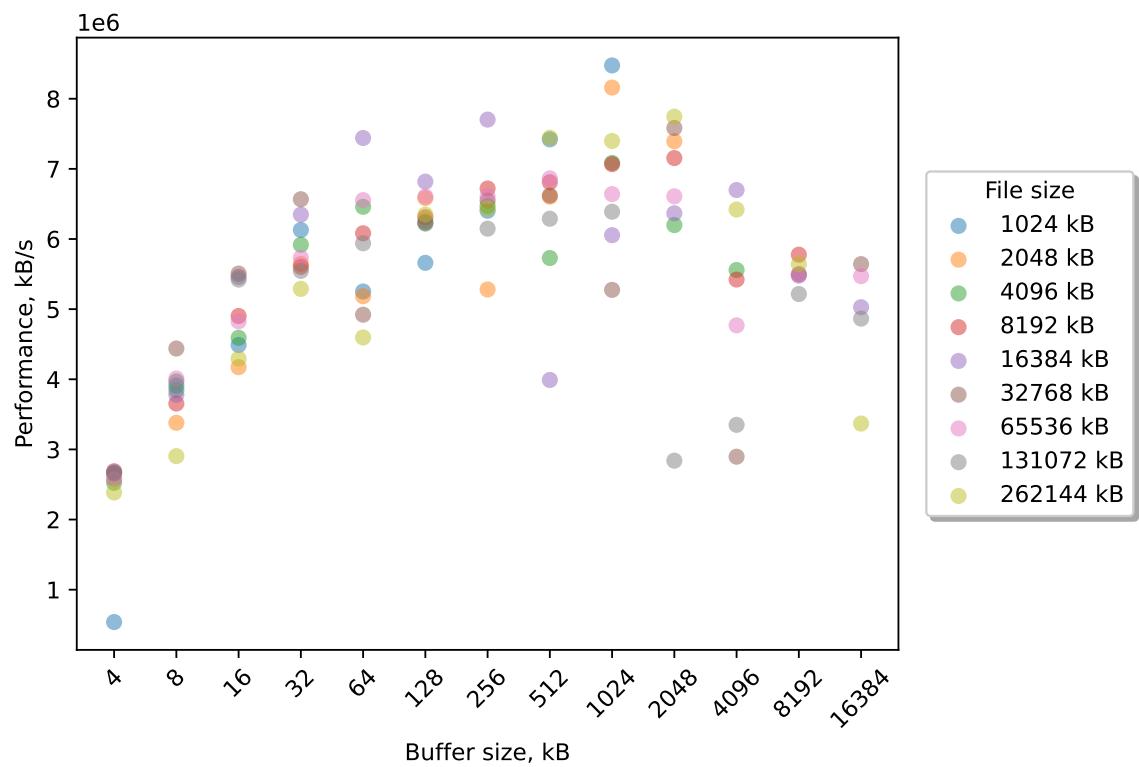


Figure 5.25: IOZone output for APFS Read

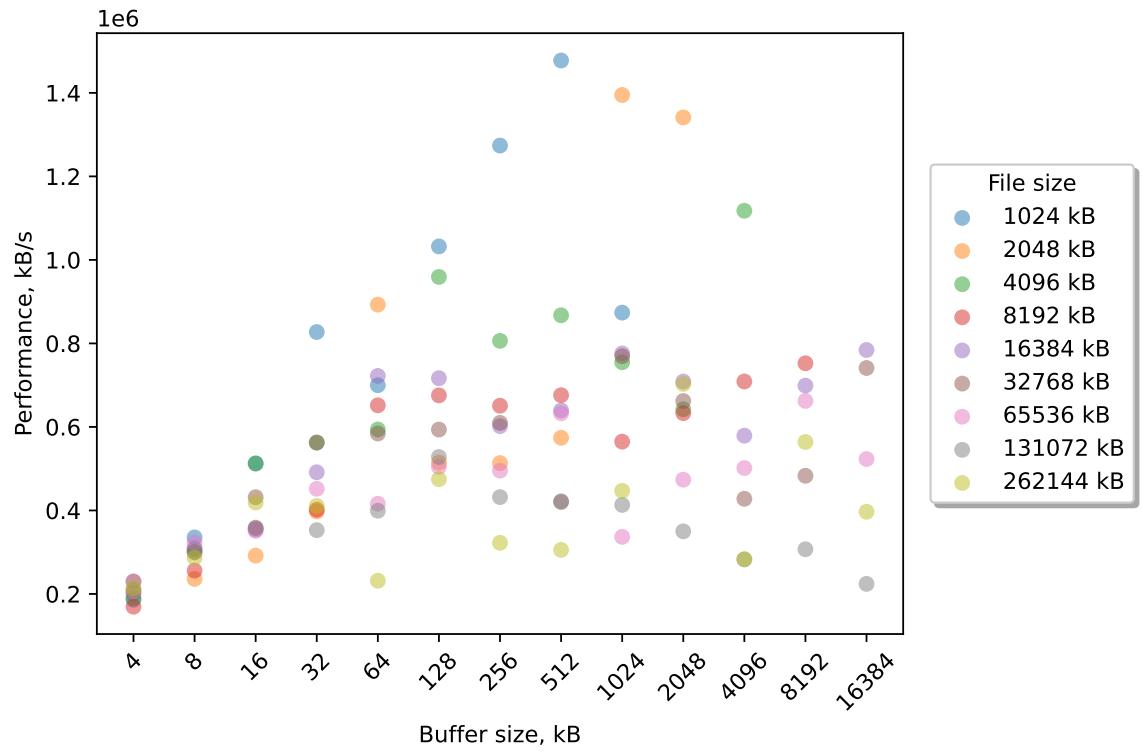


Figure 5.26: IOZone output for APFS Write

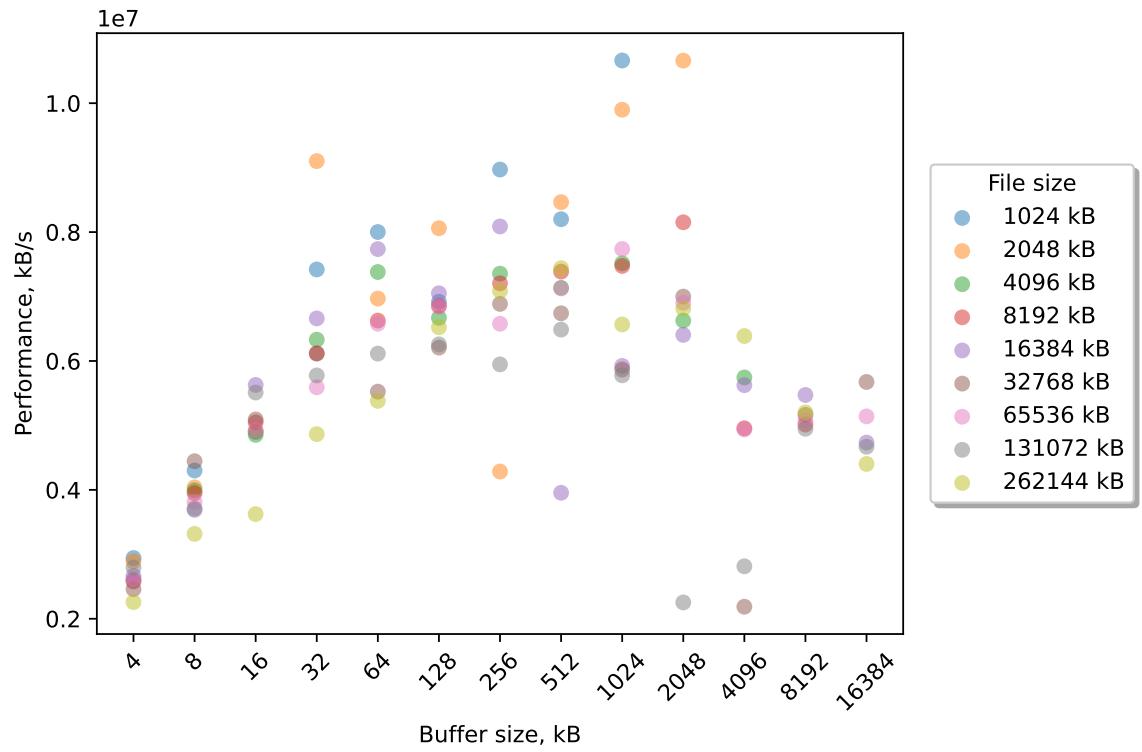


Figure 5.27: IOZone output for APFS Re-Read

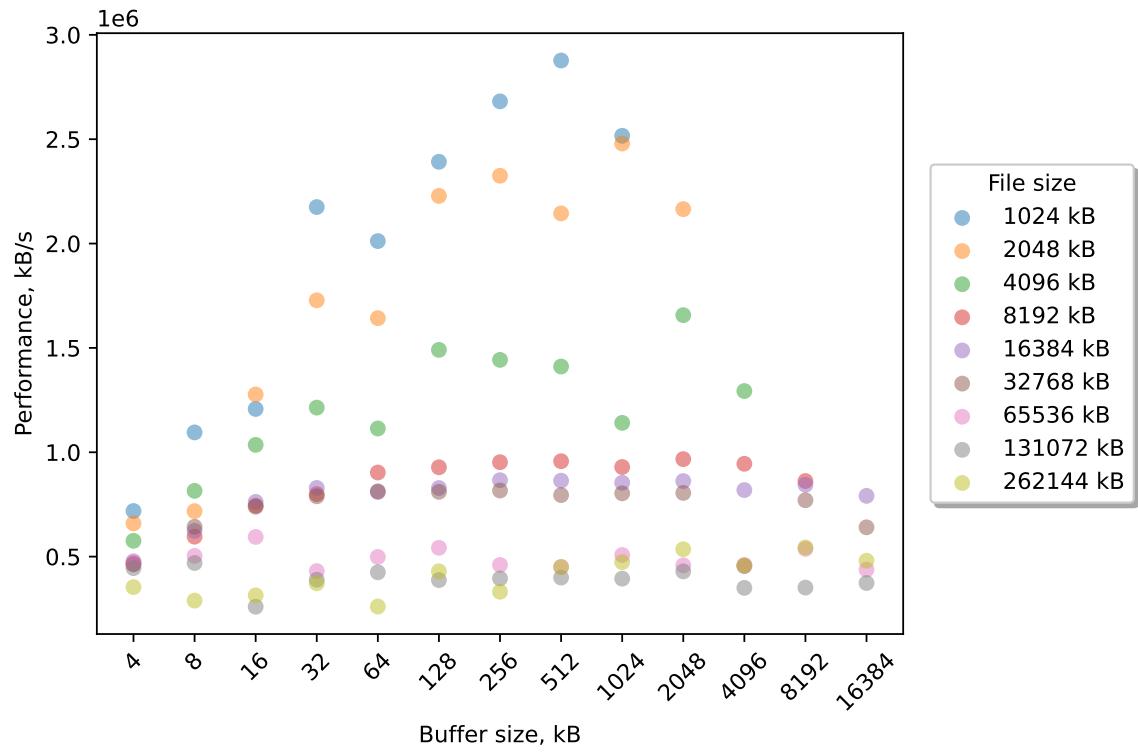


Figure 5.28: IOZone output for APFS Re-Write

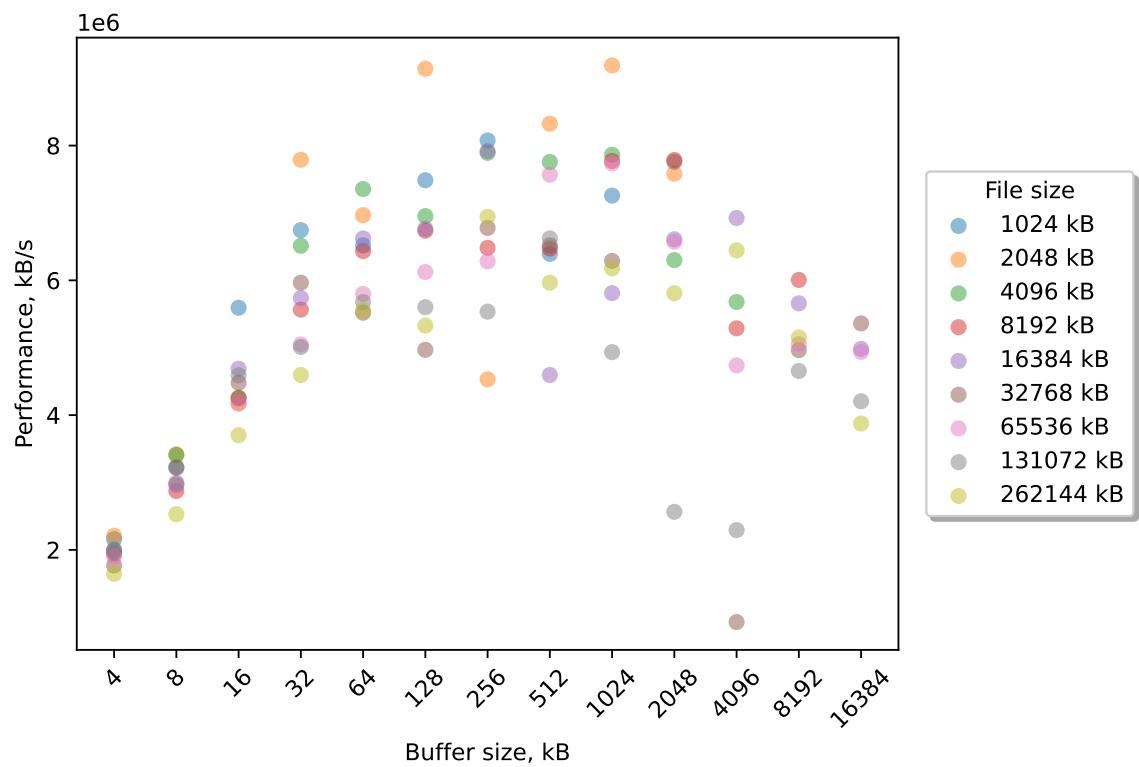


Figure 5.29: IOZone output for APFS Random read

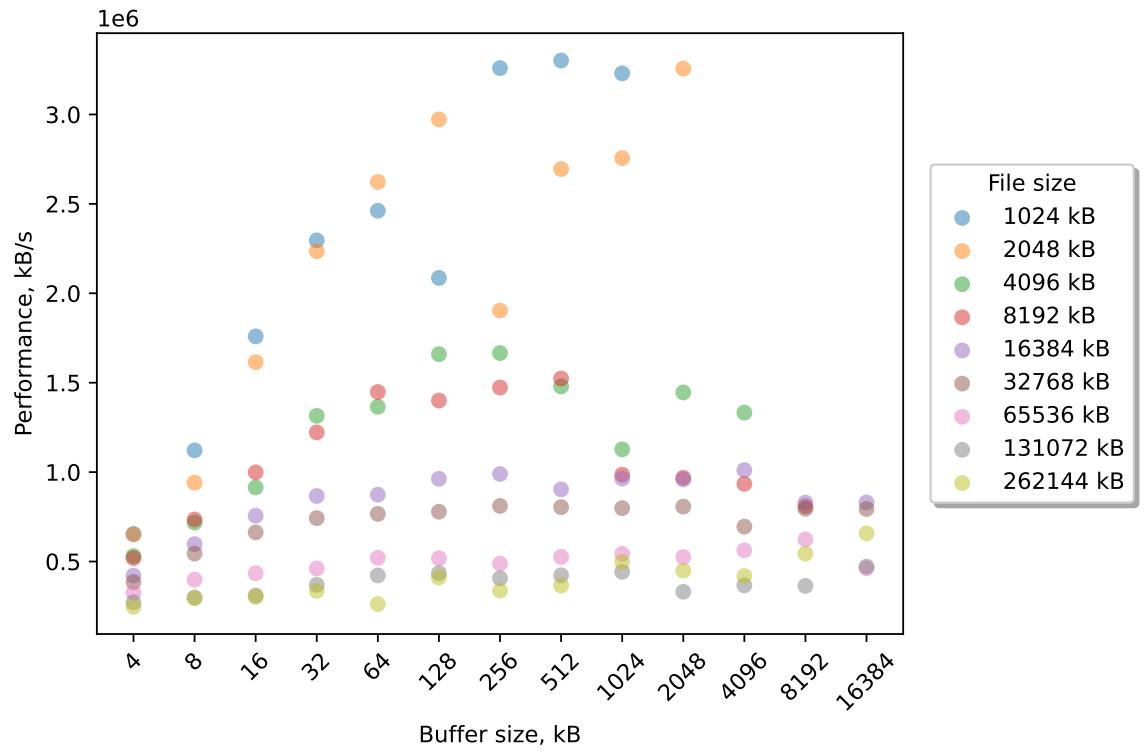


Figure 5.30: IOZone output for APFS Random write

Chapter 6

DISCUSSION

The benchmarking results presented in the previous chapter are analyzed and discussed in Section 6.1. Furthermore, FFS’s deniability and security are analyzed and discussed in Section 6.2. Potential societal and environmental impacts of FFS are presented in Section 6.3.

6.1 Filesystems

Figure 5.2, Figure 5.2, and Figure 5.2 show that FFS performs poorly for the Read tests with a small buffer size. Beginning at a 4 kB buffer size, the performance in general increases with the first few buffer sizes. This could be influenced by the overhead of the FFS read operation. Overhead of the read operation includes, among other things, the time to fetch the images from Flickr if they are not in the filesystem cache, and decrypting the images which is required even if the images are in the filesystem cache. Further, it is expected that the Re-Read tests perform better than the Read tests when the file size is small enough to fit in the filesystem cache. This is also a conclusion that can be drawn from the result. However, looking at Figure 5.2, and Figure 5.2, we can see that the Re-Read tests overall performs better for file sizes bigger than the 5 MB cache file size limit as well. Especially for file sizes 32 768 kB to 262 144 kB, the performance of the Read tests is in general very low compared to the Re-Read tests. As Figure 5.2 and Figure 5.2 shows, the average performance of the Re-Read tests are more than double the average performance of the Read tests for FFS. The reason why the Re-Read tests perform better than the Read test for files bigger than the filesystem cache size limit is most probably due to kernel caching of the files. The performance is higher than a usual internet connection bandwidth would be. An internet connection’s bandwidth is often limited to a maximum of 1 Gbit/s = 125 000 kB/s by the ISP, depending on the subscription. For the read

operations of the cloud-based filesystems that exceed 125 000 kB/s, the data has most probably been provided by some kind of cache. Note that this limit is much higher than the measured reference bandwidth presented in Section 5.2, but we use this limit as a reference of a maximum bandwidth of the connection rather than as the actual bandwidth of the connection. All the data points for the Re-Read tests for FFS and GCSF exceed 1 000 000 kB/s indicating that all these files were served by some cache. For FFS, the files over 5 MB were most probably served from the kernel cache as they cannot fit in the filesystem cache. As the performances differ significantly between the filesystems, it is possible that not all data was provided by the kernel cache, but that some data was provided by internal filesystem caches. Otherwise, the data could be more similar, assuming the kernel cache has the same performance for all filesystems tested. Many data points of the Read tests for FFS and GCSF also exceed 125 000 kB/s, indicating that some data returned when running this test were also served by some cache. This data could be saved in the cache after the Re-Write tests which precedes the Read tests. The data could also be cached after the first Read test of the file which could explain the increasing performance for the smaller buffer sizes in the beginning of the tests. The biggest file sizes have lower performance than the other file sizes for the Read tests of FFS and FFFS, although the performance is still higher than the maximum bandwidth reference point of 125 000 kB/s, indicating that the kernel cache has worse performance for bigger files.

Other than the data being provided by the kernel cache, it is also possible that IOZone does not close the file before it is read again, meaning that the file can be kept in memory for FFS and FFFS as they cache open files that have been read. IOZone does not specify when the file is closed, however it could be assumed that the files are closed between tests. If the file would not be closed after a write test, the write tests of FFS should have similar performance for the write tests as the write tests of FFFS as neither of the two filesystems save the data in their storage medium until the file has been closed. As the write tests of FFS and FFFS are not similar it is improbable that the file is not closed after the write tests. The Re-Read test is performed after the Read test, and as the Re-Read test is significantly faster than the Read test for both FFS and FFFS, even for files bigger than the cache limit of the filesystems, it is possible that the files are not closed between the two tests.

However, if this was the case, the Re-Read tests would probably be more similar for FFS and FFFS than the results show, as the data could be served just as fast by both filesystems. The theory that the kernel cache is providing a better performance of the Re-Read is more probable as the tests are less consistent between the two filesystems. If the kernel would not have the requested data in its cache, the filesystem would have to be called. This could be the explanation why the filesystem performances differ significantly between the two filesystems. Cache misses in the kernel cache requires FFS and FFFS to get the data from their cache if it is present there, or from their respective storage medium. This introduces performance differences between the filesystems. Cache misses in the filesystem cache is less probably as there are no more files being saved, meaning that the files will not be removed from the cache.

While the Re-Read and Random Read tests increases in performance for the first buffer sizes for FFS, the performance also decreases eventually. Looking at the data presented in Figure 5.2 and Figure 5.2, the buffer sizes 4096 kB to 16 384 kB have, in general, lower performance than the buffer sizes 256 kB to 2048 kB, for the same file size. This indicates that the optimal buffer size for the FFS read operations on previously read files is not the biggest possible buffer size, but rather around 512 kB, depending on the file size. The biggest file size has its best performance for a buffer size of 512 kB. Looking at the 131 072 kB file size, it peaks for both the Re-Read test and the Random read test at `buffer size = 128 kB`, and its performance for that buffer size for both tests are higher than any other performance of any file size or buffer size in both tests, for the filesystem. This is interesting because the 131 072 kB file size does not always outperform the other file sizes. Looking at the Re-Read test, the 262 144 kB has the best performance for seven of the 13 tests while the 131 072 kB file size has the best performance for five buffer sizes, namely the first one, the last three and for `buffer size = 128 kB`. The 16 384 kB file size has the best performance of the test once, for `buffer size = 1 024 kB`. Considering how fast the operations actually are, it is possible to understand why the values can fluctuate. For instance, the Re-Read test for FFS using `file size = 16 384 kB`, `buffer size = 1 024 kB` has a performance of 7 599 353 kB/s. Transferring 16 284 kB at 7 599 353 kB/s takes 2.14 ms. If it would take 10% more time, the performance would instead be under 7 000 000 kB/s, meaning that the 262 144 kB file size would have better performance

for the same buffer size. However, if it instead would take 10% less time to perform the `file size = 16 384 kB, buffer size = 1 024 kB` Re-Read test, it would reach a performance of 8 443 726 kB/s which would be the highest performance of the test on FFS of all file sizes and buffer sizes. Small time differences can significantly affect the performance of the tests. The time of the filesystem operations can be fluctuated by process scheduling and the performance of the kernel cache, among other things.

The performance of the write operations of FFS are highly influenced by the file size. As shown in Figure 5.2, Figure 5.2, and Figure 5.2, bigger file sizes implicate better performance for the write operations, generally. The best performing file size was most often the largest file size, 262 144 kB. Furthermore, the biggest file size of the tests perform better for the Write test than for the Re-Write and Random Write test. This is interesting as the Write test includes the overhead of creating the files before writing to them, which Re-Write and Random Write does not.

One interesting comparison is between the benchmark results of FFS and GCSF. Both filesystems are cloud-based FUSE filesystems dependent on an internet connection to their respective storage servers. Looking at the box plots in Section 5.2, we can see that GCSF outperforms FFS in both average performance and median performance for all tests. However, GCSF does not have any data for the biggest file size while FFS has data for it. Looking at Figure 5.2 and Figure 5.2, we can see that FFS performs better than GCSF for many of the bigger file sizes for the Re-Read test. It is possible that FFS would perform better than GCSF for the 262 144 kB file size test if GCSF could run the test. However, even if that would be the case, it is also possible that GCSF would still perform better overall. One reason that GCSF generally outperforms FFS could be because the FFS cache stores the encrypted version of the image, meaning that before the data is read, the image must first be decrypted and decoded. As Google Drive provides the raw data of the file stored, GCSF can store the raw data in its cache meaning that the data in the read operation can be returned faster. If Google Drive caches the raw file data as well, it does not have to decrypt the data when serving it to GCSF. GCSF also outperforms FFS in all the write tests. The reason could be that GCSF does not have to encrypt the data nor encode it as images. This could save significant computation time. The average

(reference point) bandwidth measured when the two filesystem benchmarks were run are similar, indicating that there was not a big difference in the internet connection to the measurement servers. However, as this does not measure the actual internet connection to the OWS, the actual bandwidth of the filesystem could be different from this value. However, even assuming that the bandwidth of the internet connections of GCSF and FFS are equal, GCSF can still benefit from fewer REST API calls. As Google Drive is a filesystem, the inode table of the filesystem, or how ever the filesystem is organized, can be stored on the service without exposing it to the user. For instance, assuming that Google Drive uses an inode table like FFS, the inode table would never have to be downloaded and uploaded by GCSF. By simply uploading a file and specifying its path and filename, the inode table does not have to be modified by the user but can be handled by Google Drive in the background, potentially after the request has completed requiring less time for the file upload request. Meanwhile, FFS has to upload the inode table after every file modification. Additionally, the old version of the file and inode table must be removed. This requires FFS to perform at least four requests for all modifications:

- Upload a new image with the new file content,
- Upload a new image with the new inode table content,
- Remove the old file, and,
- Remove the old inode table

Although, removing the old images is performed on another thread and does not affect the filesystem operation time. However, it can affect the congestion of the bandwidth to the OWS if it is performed at the same time as another request, such as a file upload. Meanwhile, uploading a modified file to Google Drive requires one API call using the file's ID [102] which will perform the same functionality as the four requests required for FFS. The ID of the file could be stored locally in memory by GCSF to be able to serve file ID's quickly, but this data structure does not have to be uploaded to Google Drive. Furthermore, when downloading a file, parts of the file can be downloaded rather than the full file [103]. This can reduce the time as the full file does not have to be downloaded every time a file is read. Even if we could download parts of a file from Flickr, it would not make sense for FFS as we need the full file content to decode the image pixel data as the encrypted cipher text. However, by downloading the full image when it is read, subsequent reads are faster which is beneficial for the benchmarking tests as it often needs to read the file multiple times at different offsets. Google Drive has 800 million daily users [104] versus Flickr's 60 million monthly users [105], which means Google Drive is a much bigger service. This could mean that Google Drive has better infrastructure and that they can process the uploaded data faster and serve the data for download faster than Flickr can.

Certain data points in the graphs presented in Section 5.2 are outliers from groups of data points. For instance, looking at the Random Write test for GCSF in Figure 5.2 for `file size = 65 536 kB, buffer size = 16 384 kB`, the test data point has significantly lower performance than the other data points for the other buffer sizes in the same test with the same file size. There are many possible reasons behind this drop in performance. One reason could be a slow internet connection to Google Drive or slower data processing by Google Drive, for instance, due to a higher load of other user requests to the service at the point in time when the specific data point was benchmarked. Due to the OWS being an external service that other users use

at the same time, it is always possible that the OWS of the cloud-based filesystems experience a high user demand at any time. Another reason for the data outlier can also be because the operating system scheduler scheduled the GCSF process unfavorable at that time. This is an especially possible reason for the outlier data points for the non-cloud-based filesystems FFFS and APFS as they do not rely on an internet connection or an OWS. For instance, Figure 5.2 shows two outliers for APFS for `file size = 131 072 kB`, namely `buffer size = 4 096 kB` and `buffer size = 8 192 kB`. They could also have lower performance due to disk scheduling and cache management. The files in the APFS cache could be invalidated and removed if other processes are reading other files from the disk at the same time, resulting in a cache miss of the benchmark file.

Other outlier data points have much higher performance than the other data points in a test. For instance, looking at the Write test for FFFS in Figure 5.2, there are data points for `file size = 8 192 kB`, `file size = 16 384 kB`, and `file size = 32 768 kB` that have much higher performance than the other data points. While most data points are approximately between 6500 kB/s to 8300 kB/s, two of these file sizes have one outlier, and one has two outliers, of approximately 100 000 kB/s. Outliers can also be seen in Figure 5.2 and Figure 5.2 for the Re-Write and Random Write tests on FFFS. FFFS is not a cloud-based filesystem and is therefore not affected by, for instance, a fluctuating bandwidth of an internet connection. Rather, this is possibly the result of favorable process scheduling and disk operation scheduling. As both file sizes exceed the cache limit of FFFS, the cache of the filesystem should not affect the value. However, it is also a possibility that IOZone did not close the file after the test or that the `close` operation was not performed correctly after test, which would mean that the data would not be written to the storage medium resulting in shorter execution time, leading to a higher performance for the write tests. The data of the open file would also be stored in the memory of FFFS. Therefore, if there was a missed `close` operation, a subsequent read test should also be an outlier data point with higher performance than the other data points. Considering the outlier for the Re-Write test for `file size = 16 384 kB`, `buffer size = 8 192 kB`, and looking at the subsequent Read test for `file size = 16 384 kB`, `buffer size = 8 192 kB`, the data point for the Read is not an outlier. This indicates that the outlier in the

Re-Write test probably is not due to a missed `close` call. Rather, it is possible that the higher performing Re-Write tests outliers are due to process scheduling.

Comparing FFFS benchmarking results against the APFS benchmarking results, we can compare the theoretical best performance of FFS against a general-purpose widely-used filesystem. Furthermore, we can compare FFFS against the underlying filesystem in which it is storing its data. In Figure 5.2 and Figure 5.2 we can see that the read operation perform similarly for FFFS and APFS, where APFS is in general faster than FFFS. However, for certain data points, such as `file size = 131 072 kB, buffer size = 256 kB`, FFFS has a higher performance than APFS with 7 525 973 kB/s for FFFS and 5 927 107 kB/s for APFS. As the file size is bigger than 5 MB it was not stored in the cache of FFFS. The reason why FFFS outperformed APFS at this data point is could be due to process scheduling or because the buffer size used by the test is less efficient for APFS than the one called on APFS by FFFS. The buffer size used by FFFS to read the file from APFS is not certain to be the same as FFFS was called with. The buffer size used by FFFS on APFS is set by the implementation of `basic_filebuf` [106]. This has been found through testing to be the same size as the image written by FFFS to APFS if it is less or equal than 65 536 B, otherwise multiple buffers are used where the biggest ones are 65 536 B. It is also possible that the data was provided by the kernel cache to FFFS while the same test for APFS did not get the data from the kernel cache. Another possibility is that FFFS read the data from APFS, but it was provided by a cache of APFS rather than being read from the APFS storage device, while the same test for APFS read the data from the storage device.

The cache of a filesystem can generally influence the performance of the read operations. However, there is no significant drop in performance for FFFS when reading a file that fits in the FFFS cache, and one that does not. In fact, the performance of the Read test for `file size = 8 192` is in general better than for `file size = 4 096` and `file size = 2 048` on FFFS, even though the 8192 kB file cannot fit in the FFFS cache while the other file sizes can, as long as the encrypted data and the PNG attributes do not make the file bigger than 5 MB. The reason why these files can be provided fast is most probably due to the kernel caching of the files. However,

the performance of the `file size = 262 144 kB` compared to many of the other file sizes is much lower, indicating that these files were not, at least entirely, cached by the kernel, possibly due to size constraint. As the 131 072 kB file size has similar performance to the 262 144 kB file size for some of the FFFS Read tests buffer sizes, but significantly higher performance for other buffer sizes, it is possible that the kernel cache size limit is around 131 072 kB. However, as it seems to fluctuate, the size limit might be dependent on factors such as the available memory of the system at the time. When the memory usage is high, for instance, by other processes running at the same time, it is possible that the data stored in the kernel cache for FFFS is removed, which decreases the performance for certain tests.

The only implementation difference between FFS and FFFS is that FFS stores the produced images on Flickr while FFFS stores the produced images on the local filesystem. Therefore, the time difference of an FFS operation compared to an FFFS operation should only depend on the internet connection to Flickr and how fast Flickr can process the requests. For instance, looking at the Write tests for the two filesystems, FFFS outperforms FFS significantly. Looking at one file size, for instance, `file size = 8 192` FFFS has an average performance of approximately 15 800 kB/s and FFS has an average performance of approximately 1050 kB/s for the Write test. This means that the test took on average 518 ms for FFFS and 7802 ms for FFS. The same test for the same file size for APFS had an average performance of 612 000 kB/s, meaning it took on average 13 ms for APFS to save the 8192 kB file. The time the test takes for FFFS is the same as the write operation overhead plus the time APFS takes to save the file. Subtracting the APFS write time from the test time of FFFS, we get the average overhead of the Write test for both FFS and FFFS as they have the same overhead. This overhead includes encrypting the data and encoding the result as an image. The average overhead time of the Write test for FFS and FFFS is therefore 505 ms, meaning that the request and the request's overhead by FFS took on average $7802 - 505 = 7297$ ms which is approximately 94% of the computation time for this test. Assuming the upload bandwidth to Flickr is the same as the measured reference bandwidth of 92.95 MB/s, uploading 8192 kB would take 705 ms. This means that the remaining 6592 ms were used for request overhead, such as preparing for the request, waiting for Flickr to process the data, and receiving the response from

Flickr, including the post ID. Preparing the request includes first saving the image to the local filesystem, and then reading it when uploading it. Assuming the file was saved with the same APFS performance as above, it would take 13 ms to save the file. Reading the file with the APFS average Read test performance for a 8192 kB file of 5 505 000 kB/s would take 1.5 ms. The remaining 6577.5 ms are used for creating the request, receiving the request response, and for Flickr to process the data. The most significant time consumption of these three tasks is most probably the data processing of Flickr. This indicates that with faster data processing by Flickr, FFS could potentially be faster. Furthermore, it indicates that the bandwidth of the internet connection to the OWS is not the most important factor of the performance of FFS. Even if uploading the file over the internet to the OWS would be instant, it would reduce the file operation time by less than 10%. To improve the filesystem operation performance, using a OWS that can process the data faster is of more importance. For instance, if the OWS would process the data in the background and instantly return, the write operation performance could be reduced. This could mean, however, that the image is not seen on the OWS instantly which could mean that it is not possible to download the file instantly after it has been uploaded. The calculations above assume that the bandwidth to Flickr was approximately the same as the bandwidth to the measurement servers. It is possible that the bandwidth to Flickr was much lower, which would mean that the bandwidth has more impact of the filesystem operation time. Future work includes using multiple OWSs to compare their performances, as well as measuring the individual filesystem's bandwidth for more precise calculations.

While the values of the read operation for FFFS and APFS are comparable to each other, this is not the case for all tests. For instance, the write operation of FFFS is much slower than the write operation of APFS. The write operation performance average of FFFS is approximately 1.5% of the average performance of the write operation on APFS. While it is understandable that the FFFS write performance is lower than the APFS write performance as all data written to FFFS must also be written to APFS, the difference in performance is significant. The reason for this could be the fact that FFFS has to encrypt the data stored, including creating all the cryptographic variables such as the salt and the IV. Using the calculations above, we estimate that the average overhead of an FFFS write operation for a 8192 kB file is

505 ms out of the total 518 ms for the filesystem operation, which is 97% of the time of the operation. Assuming that this number is similar for other file sizes, it is a very significant portion of the execution time. While APFS is also an encrypted filesystem, it is possible that the filesystem prepares the cryptographic variables before they are needed. For instance, the next cryptographic key and its salt could be derived while the filesystem is idle as it does not depend on the content of the stored data. It is also possible that APFS is using multiple threads to write the data which could speed up the operation. For instance, it is possible that FFFS requires multiple `write` calls to the underlying APFS filesystem. If each `write` call to APFS is computed on a different thread, the multiple `write` calls could possibly be completed faster rather than if they were completed sequentially.

FFFs and GCSF are comparable in some tests, which is interesting as GCSF is dependent on an internet connection and an OWS while FFFS is not. The median performance of the Re-Read test on GCSF is slightly worse than the medium performance of the Re-Read test on FFFS. Meanwhile, the median Read performance of GCSF is significantly less than the median Read performance of FFFS. This indicates that a lot of the data served by FFFS and GCSF was served by the kernel cache of the FUSE filesystems. Furthermore, it indicates that FFFS is faster than GCSF for files not in the kernel cache. However, as the Read tests performance is higher than a reasonable internet bandwidth, it is probable that the data from GCSF is still served from an internal cache rather than the data being fetched from Google Drive. As the Read tests performances are higher for FFFS than for GCSF, it indicates that FFFS has a faster internal cache than GCSF, or that the kernel cache was used for the FFFS Read tests while it was not used for GCSF.

The Write, Re-Write, and Random Write tests on FFFS outperform the same tests on GCSF. This is reasonable as the data written to GCSF must be uploaded to Google Drive, while the data written to FFFS is stored on the local disk. Uploading 16 MB of data with the average (reference point) upload speed of 91.83 Mbit/s would take approximately 1.4 s. Meanwhile, we can see in Figure 5.2 that APFS can write 16 MB of data as fast as $6\,921\,222 \text{ kB/s} = 6921.2 \text{ MB/s}$, meaning it would take approximately 2 ms to write the data. Meanwhile, the maximum Write performance of FFFS is

101 677 kB/s, meaning that FFFS can write 16 MB in approximately 157 ms. With this data, we can see that FFFS can write the 16 MB of data approximately 7800% slower than APFS can, and that GCSF can write the 16 MB of data approximately 800% slower than FFFS or approximately 70 000% slower than APFS.

It is easy to see, and it is not unexpected, that APFS outperforms FFS in performance. As a professional local filesystem, APFS will always have better performance than FFS. Further, like FFFS, the performance of FFS depends on the performance of APFS as the file which is uploaded to Flickr first needs to be saved on disk. This dependency could be removed, for instance, by providing the temporary file to the FlickrCURL library via a FUSE filesystem. Further, the median performance of the Re-Read test on FFS is approximately 72% of the performance of the Re-Read test on APFS. This is probably high for many of the tests because of the kernel cache of FFS, but as it differs significantly from APFS, FFS calls are probably also performed. With higher bandwidth and with another OWS with faster data processing, it is possible that FFS could increase its read performance. In contrast, the median performance of the Re-Read test on FFS is approximately 76% of the median performance of the same test on GCSF.

Generally, the figures of the benchmark data presented in Section 5.2 have visibly similar patterns for the Write tests and similar patterns the Read tests, per filesystem. For instance, the patterns of the FFS Read, Re-Read, and Random Read tests follow a similar pattern with a similar curve of the data points, while the Write, Re-Write, and Random Write tests follow another distinct pattern. The Read, Re-Read, and Random Read figures of GCSF follow another distinct pattern, as well as the three Write test data follow a fourth distinct pattern. The three write test patterns of FFS are dissimilar to the patterns of the FFFS write tests even though both filesystems are implemented very similarly, other than the storage medium. However, some patterns are similar even though they are from different filesystem, for instance, the Read tests of FFS and FFFS. In Figure 5.2 and Figure 5.2, the Read test shows that certain file size data points are found on the lower spectrum of the plot, while the other file sizes follow a somewhat similar curve for both filesystems. However, the pattern of the Re-Read test data of FFS and FFFS differ significantly. It might be

possible to use these distinct patterns to create a fingerprint of a filesystem. This could be used, for instance, to identify a filesystem based on its performance when the filesystem is unknown. This could be useful when the filesystem is masked by an overlaying filesystem such as Cryptfs. However, by benchmarking the overlying filesystem, the pattern of the underlying filesystem might be lost. Analyzing if it is possible to identify filesystems based on benchmark fingerprints and identifying underlying filesystems using this technique is part of future work.

The bandwidth reference measurements are performed every five minutes while FFS and GCSF are benchmarked. Each bandwidth measurement test takes about 20 s each. During this time, the measurement tool is uploading and downloading data to the measurement servers. This can cause congestion of the internet connections of the filesystems which could reduce their performance. Bredbandskollen estimates that each measurement requires approximately as half as many bytes as the measurement shows in bits per second [99]. The average bandwidth measurements while the two filesystems were running were both approximately 90 Mbit/s for both the upload and download speeds. This means that the measurements consumed about 45 MB per measurement. This is bigger than most file sizes tested when benchmarking. Furthermore, background processes running at the same time as the filesystem benchmarks and using internet connections can further congest the internet connection of the filesystems. If we could measure each filesystem's individual internet connection's bandwidth, calculations regard the impact of the bandwidth could be more precise. This is part of future work.

6.2 Security and Deniability

The data stored in FFS images is encrypted with state-of-the-art encryption standards. Using AES-GCM, FFS not only provides confidentiality of the data, but it also provides the authenticity of the data. The cryptographic algorithms are implemented using good cryptographic standards, such as cryptographic secure number generators [107]. However, the security of FFS is dependent on, among other things, the password the user chooses. A bad password, for instance, short or commonly

used, is easily breakable for an adversary. An adversary who has access to an FFS encrypted image could brute-force the bad password used to derive the encryption key much faster than they could brute-force the decryption key. FFS does not put any constraints on the password used - as long as it is at least one byte it is acceptable for FFS. This puts the responsibility on the user for a secure password.

FFS puts a lot of trust in the open-source library Crypto++ [85]. Crypto++ provides cryptographic functions that FFS uses for, among other things, deriving the encryption key, encrypting the data, and verifying the authentication tag. While there are no reported CVE security vulnerabilities as of the time of this writing [87], there may be vulnerabilities that have not yet been discovered or that have been found but not published in the CVE database. There is also a possibility that FFS has vulnerabilities, such as side channels, which could be exploited. FFS was developed by a single author without a review from anyone.

Anyone with access to Flickr.com can view and download the original images stored by FFS, both registered users on Flickr, and anonymous visitors, as the account is set to allow this. An example of how the profile might look is shown in Figure 6.1. The images found on the account present little information about the filesystem. For users unaware of FFS who view the Flickr profile, they see different sizes of images with seemingly randomly generated pixel colors. However, for adversaries who know about the details of FFS, more information can be retrieved. For instance, they could assume that the most recently uploaded image to Flickr is the inode table. However, as we assume the adversary does not have access to the decryption key, they cannot decode the plain-text data of the image and thus cannot verify that this is indeed the inode table. The exact number of files and directories in FFS cannot be known precisely without access to the content of the inode table. Even if the Flickr account has, for instance, 15 images stored, and we know that one represents the inode table and one represents the root directory, it is not possible to conclude if other images stores file data or directory data. The remaining 13 images in the example could represent:

- one big single file split over 13 images, or
- one big single directory split over 13 images, or
- 13 different files, or
- 13 different directories, or
- one directory and 12 different files, or
- 13 copies of the same file, et cetera.

It is possible to see the size of an image, and a big image can suggest that a file or directory consists of multiple images on Flickr.

It is also not possible to know if an image stored on Flickr has been uploaded by FFS or by the user manually to further inflate and diffuse the amount of data stored on the service. For instance, by encrypting random data using FFS's encoder and uploading the images to Flickr, but without saving the posts in the inode table or in a directory of FFS, the images will look indistinguishable from the other images on Flickr. Only with access to the decrypted inode table can one know if the image is relevant to FFS or not. However, it is possible that Flickr could have logs about the uploaded images, and can be able to distinguish images uploaded from the API from the user interface. Future research could extend FFS to post encrypted random data at random time intervals to automatically diffuse the knowledge about the images on the OWS. This would mean that even Flickr would be unable to distinguish the uploaded data as it would all be uploaded from the same service. FFS would be required to upload the diffusing data using the same pattern as is used when a file or directory is updated or created so that the upload pattern for the diffusing data is undistinguishable from the regular data for users without the decryption keys. For instance, a write operation on a file will remove the old file and the old inode table, and upload one new image as the new file data and one new image as the new inode table. Similarly, for a new file created in the filesystem, the new file content is uploaded as an image, one image is uploaded as the parent directory's new data, one image is uploaded as the new inode table, and the old directory image and inode table image are removed from Flickr. To simulate file write and file create filesystem operations, two or three images must be uploaded and two images must be deleted. One problem with this could be that the last image uploaded should always be the inode table. While the data of the

inode table can easily change by changing the encryption key, the size of the inode table could remain the same which could be suspicious for adversaries with access to snapshots of the Flickr account’s images. This could be solved by always adding a random amount of filler bytes when encoding the image. The filler bytes are not read by the decoder anyway. However, adding filler bytes can increase the resulting file size of the images, decreasing the overall storage capacity of FFS. Furthermore, storing diffusing images on Flickr that are not stored in the FFS filesystem decreases the storage capacity of FFS.

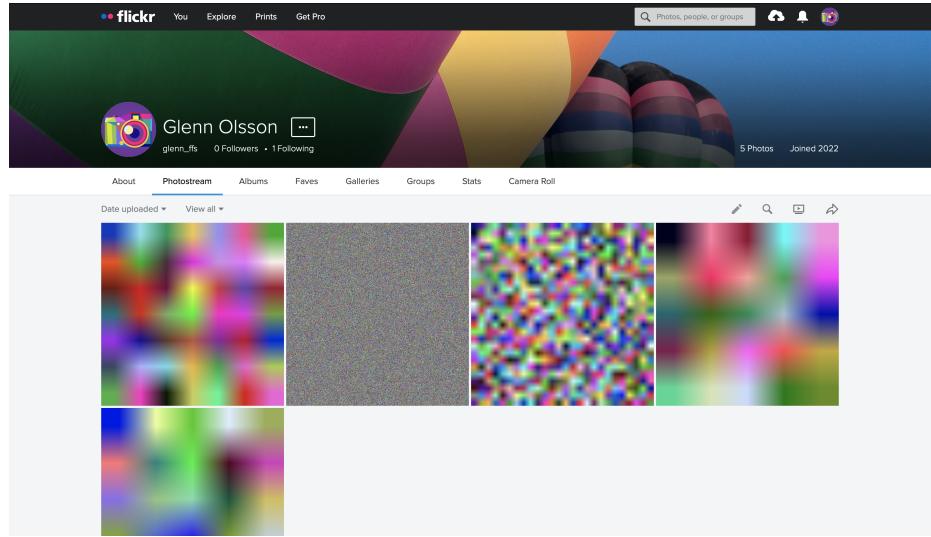


Figure 6.1: Screenshot of the Flickr profile used for FFS. At the moment of the screenshot, the filesystem is storing a previous version of this thesis in a directory inside the root directory. The images seen are the inode table, the thesis data, the root directory data, the subdirectory (containing the thesis) data, and a temporary file containing extra attributes of the thesis document created by macOS while FFS was mounted (this file is sometimes referred to as a *turd* [108]).

The size of data stored in an image is not completely hidden. While the exact number of bytes of unencrypted data that the image stored is not possible to know without the decryption key, it is possible to get an estimate. If you know the binary structure of the image (as presented in Appendix B), you can find out how many bytes the encrypted cipher is, the value of the IV data, the value of the salt used for the encryption key derivation, and the value of the authentication tag. By knowing the length of the cipher, the length of the unencrypted data can be placed in a range.

The length of the cipher L_c in bytes is divisible by 16 (as AES is a 16-byte block cipher), and the length of the plain text must be less than L_c due to the requirement of at least one bit of padding [93]. The smallest possible size for the length of the plain text is $L_c - 16$. Therefore, the length of the plain text L_p is:

$$L_c - 16 \leq L_p < L_c$$

By examining all the images stored on Flickr and the possible values of L_p , it is possible to know the upper limit and lower limit of all the FFS data stored on Flickr at a certain time, assuming that all images on Flickr are stored in FFS. However, it is **not** possible to know if all this data is stored on FFS through entries in the inode table. It is also **not** possible to know if the plain text represents a file or directory without the decrypted data of the inode table. One image can be assumed to be the inode table of which a size-estimate is also possible.

If a user supplies a different password when mounting FFS than used previously, the images stored on Flickr cannot be decrypted. When FFS tries to read the image it believes represents the inode table (the most recently uploaded image) and it fails, it will simply create a new inode table representing an empty filesystem, and upload the image representing this inode table, essentially replacing the potentially previous inode table (if it existed). As it is not possible to know if the images already uploaded to Flickr represent an inode table without the correct decryption key, it is impossible to determine if the image that could represent the inode table is indeed an inode table encrypted with another password, or if it is some arbitrary data. In a potential rubber-hose situation¹, the user of the filesystem could easily claim that they uploaded FFS images with arbitrary data, using randomly generated keys that they do not remember and that the filesystem is empty. There is no way to prove the existence of any meaningful data on Flickr without the decryption key. As the FFS encoder also uses random salting for the encryption key, it is not even possible to prove that the images are encrypted with the same password as the encryption keys will differ for all images, even when the same password is used.

¹ When an adversary might torture the user, with for instance a rubber hose. See Section 3.1

However, as mentioned earlier, we assume that an adversary has access to the structure of FFS images as well. To counter this, the user who want to hide their data could, after creating a filesystem containing meaningful information, mount FFS again with another password. FFS would then create a new inode table and upload this table, creating a dummy FFS. In a rubber-hose situation, the user could give up the password to the dummy FFS instance, which is empty. The adversary can verify that this password indeed decrypts the most recently uploaded image and that the unencrypted image data represents an empty inode table. If the user proceeds to claim that they do not know the passwords of the other images, the adversary cannot prove that they contain meaningful data or that they have been uploaded by the user. These images could, for instance, have been uploaded by another user of FFS. Further, with no password constraints by FFS, a user could also create a dummy FFS with a password that is easily breakable, to make the adversary believe they found the correct password if they perform a brute-force attack. As long as the user remembers which post represents the inode table, the images uploaded after this inode table could simply be removed from Flickr before mounting FFS with the correct password when the user want to access their actual FFS instance. Alternatively, the user could save the image representing the inode table in another storage medium and upload it again when they want to access their actual FFS instance.

One aspect where FFS is better than GCSF is its security against the potential adversary of the storage owners. GCSF stores the data in its original format on Google Drive, essentially providing an overlay filesystem for Google Drive. While this can be desired in certain situations, such as using GCSF on one machine and the Google Drive website on another, it gives Google Drive access to your data. As mentioned, Google Drive encrypts your data from outside agents, but as they control the encryption and decryption keys themselves, the data stored can be accessed by the company. The data could also be given to authorities who are requesting it with a subpoena. However, to use Google Drive while maintaining your own encryption methods, an overlay filesystem could be mounted on top of GCSF using a stackable filesystem, such as Cryptfs [74]. Future work could include researching the performance of such an overlay filesystem on GCSF and compare it to FFS.

FFS on the other hand gives the user control of all its data. While Flickr can give out the images uploaded by FFS, this data can be accessed by anyone with access to Flickr.com anyway. The only way to access unencrypted data is by using the password that the user controls. This provides FFS with one aspect of better security than GCSF, but this might also be a factor why FFS is slower than GCSF. By requiring the data to be encrypted when it is written and uploaded, and decrypted when it is downloaded and read, FFS will need to compute new cryptographic variables every time a file or directory is written which requires a lot of computations. Further, every time an image is read it must be decrypted, even if it is in the cache of FFS. Decrypting an image requires a lot of computations as well, as other than decrypting the data, the decryption key must first be derived from the password. Meanwhile, it is possible that Google Drive is caching the unencrypted files, or performing the cryptographic computations on high-performance computers requiring less computation time. So while gaining a security aspect of the filesystem, FFS sacrifices the performance of the filesystem operations.

Every Internet Service Provider (ISP) in Sweden is required to keep data generated or managed during internet access for ten months [109]. European Court of Justice (ECJ) has declared that retained data should only be accessed when fighting serious crimes or if national security is at stake [110]. In the United States, there are no data retention laws requiring ISPs to store identifiable information, however, no major American ISP has enacted zero data retention policies [111]. Furthermore, American ISPs can be forced to give out what information they have about a customer by US law, including the websites the customer has been visiting [112]. Using FFS or GCSF, your ISP can identify your internet traffic and know that you are accessing Flickr or Google Drive. Furthermore, by combining the data with the IP logs of Flickr or Google Drive, it could also be possible to identify you as the uploader of data to FFS or GCSF. However, technologies such as Tor or a Virtual Private Network (VPN) could hide your identity from your ISP. According to Swedish law, VPN providers are not required to retain logs of its users [113]. However, they are not prohibited from storing such data. Furthermore, the ISP of the VPN provider must still log the network traffic originating from the VPN service. Even though they cannot identify specific users without logs from the VPN provider, they can determine what websites

are accessed from the VPN service, even though they might not know that the service is a VPN provider. If the VPN provides logs about you to adversaries, you could still be identified. Tor provides the user with multiple routing layers to hide the origin of the internet traffic [114]. The internet connection is encrypted and the source IP address is changed for each hop, and the final node has no information about the original source address of the request. Furthermore, the nodes used by the client are changed periodically. However, Tor is slow due to the layered connections and would therefore decrease the already low performance of FFS further.

FFS writes temporary files to the local filesystem when uploading images to Flickr due to limitations in the Flickr library used. Even though the images are stored for a short time in the filesystem and removed shortly after being created, there are possibilities to recover removed data from APFS [90, 91, 92]. Furthermore, if FFS would crash for some reason while uploading a file, the temporary file could remain readable in the APFS filesystem. This could be solved by storing the temporary file in a temporary filesystem. For instance, a secure in-memory FUSE filesystem could be mounted on the computer and be used as the temporary file storage. This is part of future work for FFS.

Flickr state in their community guidelines [115] that they do not allow non-photographic elements in their service. FFS uploads images with seemingly random noise, not photographs. It is therefore probable that Flickr would remove the images uploaded by FFS if they were discovered or reported by the community. Another adversary of FFS is thus detection from Flickr. During testing of the filesystem, while big files have been uploaded, there have not been more than 50 images stored on Flickr by FFS at a time which is far from their 1 000 image limit. No FFS images has been removed from Flickr as of writing and it is possible that the Flickr account has not raised suspicion from Flickr due to the low number of images. If images were removed from Flickr, it could have very negative effects on the usability of the filesystem. For instance, if the image representing the inode table was removed, the post ID of each filesystem would be lost unless FFS was running at the same time as the inode table is cached in memory. While the images could still be decrypted by FFS, the filename and path of each file and directory would be lost. If an image representing a directory

was removed (but the inode table was not removed), the files and directories in the directory would not have a filename associated with them. They would also not be findable in the filesystem as FFS does not support links, so there is only one filepath per file or directory in the filesystem. If an image representing a file was removed, the file data would be lost. If an image representing one part of a file was removed, only the data stored in that image would be lost. The remaining images could still be decoded and decrypted on their own, but the lost data cannot be recovered. It is important that the images are not removed from the OWS for the data stored in FFS to be safe. However, this guarantee is hard to achieve as the Flickr terms of service state that Flickr retains the right to remove user content from the service at any time [33]. If Flickr would have knowledge about FFS it is possible that they would implement detection techniques of the FFS images, and remove them. Combating detection by the OWS is part of future work.

6.3 Impact

This section presents the impact FFS could have. Section 6.3.1 presents societal impacts that FFS could introduce. Section 6.3.2 presents the environmental impacts of FFS.

6.3.1 Societal impacts

Secure and hidden data is not only for the better good. As the data stored on FFS cannot be decrypted by bad guys or good guys, illegal data could be stored on the system without anyone knowing about it. It is known that end-to-end encryption does not only have a positive impact on society, for instance, terrorist organizations are known to be using end-to-end encryption to spread their messages across the internet [116]. FFS could potentially provide secure storage for illegal groups such as terrorist organizations and child pornography rings. It is not possible to limit who uses FFS, by other means than not publishing the source code of the filesystem. However, this does not prevent criminal organizations from using other end-to-end encrypted

filesystems or develop their own. Some terrorist organizations consist of well-educated engineers who could develop similar technologies for their organization [117].

An ethical consideration of FFS is that it is breaking the terms of services of Flickr by exploiting its free storage. Flickr and many other OWSs provide users with a lot of free storage. By exploiting this storage, the costs for the OWSs could increase requiring them to charge users for the storage or decrease the free storage quota. This would hurt honest users of the service who are following the guidelines. Content creators, such as photographers on Flickr, could have to pay money to use the previously free service which could deter the usage of the platform. If the OWS would implement detection techniques to combat the FFS images, these could falsely mark legit images for removal which again could affect honest users of the service. Fewer users of the OWS could eventually require the company to reduce their staff due to loss of revenue.

FFS provides free storage for all users. This benefits people who might not have money to spend on commercial cloud-based storage or physical hard disks. However, as FFS requires the user to run macOS which natively only runs on Apple's computers which are often considered expensive, this might not benefit the poor. Furthermore, the cost of a hard disk or commercial cloud-based storage is often not expensive.

6.3.2 Environmental impact

FFS uses Flickr's data centers to store its data. Globally, data centers have a large environmental impact. It has been estimated that they use over 2% of the world's electricity [118] and emit roughly the same amount of carbon dioxide as the global airline industry emits burning aircraft fuel [119]. However, the emissions of the data centers depend on their location. For instance, some data centers in Sweden are powered with 100% carbon-free energy [120, 121]. The data centers Flickr are using and where they are located have not been found.

As mentioned previously, encrypting and encoding the stored data as images requires more storage than the actual data stored. This means that more storage is required to store all the data in FFS, as opposed to storing the same data in a local filesystem.

It also means that the network request will carry more data than necessary, requiring more energy. This fact is also true when comparing FFS to a cloud-based filesystem, such as Google Drive. While both Google Drive and FFS store their data in data centers, the data that Google Drive stores can be less than the same file stored in FFS due to only storing the encrypted file data rather than an encoded image. While the extra PNG data is expected to be less than 10% of the total image size, big files will require a lot of storage for just the PNG attributes. Furthermore, as Google Drive is a filesystem, operations and data structures could be optimized for a filesystem while FFS is a layered filesystem on top of Flickr. As mentioned in Section 6.1, Google Drive could potentially implement a more efficient filesystem with its REST API than Flickr does with its API. FFS is also developed by one developer during a limited time while Google Drive is maintained by multiple teams and was released over ten years ago. Google Drive also has requirements of efficient power- and storage usage as it is a massive company where small improvements can save a lot of money. FFS on the other hand has no such requirements and is developed with usability as its main focus.

Other than storing data in the cloud, data is often stored on physical devices such as memory sticks or hard disks. FFS provides on-demand storage when the user needs it, and can be forgotten when not in use. It does not require the user to purchase hardware whenever they need more storage, possibly just temporarily. Such hardware could produce litter if the user disposes of it after use. While the storage devices can be cheap, they can promote single-use of the devices which in turn could increase littering. However, with the low-performance of FFS compared to a local filesystem, FFS can often not be used as a substitute to a physical storage device. While a filesystem on a portable storage device was not included in the analysis of the thesis, FFS will probably perform worse than most portable storage devices. Many modern storage devices are based solid-state disks which in general are very fast. Even hard-drive based storage devices are probably faster than a cloud-based filesystem in many cases.

Chapter 7

CONCLUSIONS AND FUTURE WORK

This chapter presents the conclusions from the thesis from what has been discussed under Chapter 6. Finally, future work on the topic is discussed.

7.1 Conclusions

FFS is a cryptographic and deniable cloud-based filesystem with free storage through exploiting online web services. Compared to other filesystems, FFS is slow and is not suitable as a multi-purpose filesystem, for instance as a hard drive for a computer. It performed poorly even compared to another cloud-based filesystem, GCSF. However, one key difference between these two filesystems is that FFS manages the cryptography of the filesystem, while GCSF delegates this task to Google Drive. This provides security benefits for FFS, but might also contribute to the slower computation time. The results also show that even when removing the dependency of an internet connection, FFS performs poorly, especially for the read operations compared to GCSF and APFS. The write operations of FFFS perform better than GCSF and FFS. The read operations of FFS and FFFS are more similar than the write operations, however, FFFS outperforms FFS for every read operation test leading to the conclusion that the internet connection and the OWS influence the file operations significantly. With better read performance than write performance, FFS is best suited as a many-read-few-write filesystem.

While the filesystem is slow, it provides security aspects such as end-to-end encryption and deniability. As long as the filesystem is not mounted to the computer, it is not possible to prove how much data is stored on FFS, or even prove that data is stored on FFS. However, it is possible to get a upper-limit amount of data stored. End-to-end cryptography provides the user with confidential data. Further, by using

authenticated encryption, FFS provides the user with proof of the authenticity of the data it stores.

7.2 Future work

As mentioned previously, FFS does not implement all features that the POSIX standard defines. Future development for FFS could be to implement more of these functions, such as links and file permissions. This could make FFS resemble a regular filesystem further. Another improvement could be to move from userspace using FUSE, to kernel space. This could speed up filesystem operations. Another feature that could be interesting to evaluate is the possibility to share files with other users, similar to Google Drive.

Even though the files are encrypted so that the data is confidential, further research could include hiding the user's online activity through the use of for instance Tor. Currently, the anonymity of the user is not considered but for FFS to be further plausibly deniable, this should be addressed as the user could otherwise be identified by its IP address and other online fingerprints that could be provided by the online web services and ISP.

To improve the dependability and increase the storage capacity of FFS, support for more online web services could be implemented. For instance, GitHub provides free user accounts with many gigabytes of data. Even free-tier distributed filesystems, such as Google Drive, could be utilized. If multiple user accounts are used in coordination over multiple services, FFS could achieve even more storage. Future work includes comparing such a filesystem with the current state of FFS.

To increase the storage capacity further, FFS could take advantage of storing videos on the OWS as well. Flickr allows videos up to 1 GB on its service. Future work could include researching how much steganographic data can be stored in videos and how efficient a filesystem using encoded videos could be.

If the OWS would pursue identifying FFS images stored on their service to remove them, it would be a problem for FFS. Even removing a single image could remove the full functionality of the filesystem. Future work includes finding evasion techniques to hide the hidden data even further. For instance, hiding less data in the images is a possibility which could mean that the images could look like actual images, such as photographs. This is similar to the idea of CovertFS [6] where a maximum of 4 kB per image would be used. However, this would significantly decrease the storage capacity of FFS. Part of future work is to explore if more data could be stored in the images, or if multiple OWSs could be used to overcome the decreased storage capacity.

The benchmark tests showed visible patterns, seemingly distinct between filesystems. Future work includes analyzing these patterns to create fingerprints that could be used to identify filesystems based on their benchmark data.

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APPENDICES

Appendix A

DIRECTORY, INODETABLE, AND INODEENTRY CLASS AND ATTRIBUTES REPRESENTATION

This chapter present pseudo-code of the different data structures used by FFS. Listing A.1 presents the attributes each C++ class stores in-memory, that is also encoded into the binary representation of the object when it is serialized before being uploaded to the OWS.

Listing A.1: The attributes classes representing directories and the inode table in FFS

```
# typedef inode_id = uint32_t

# Represents a directory in |gls{FFS}|. Keeps track of the
# filename and inode of each file
class Directory
    # Map of (filename, inode id) representing the
    # content of the directory
    map<string, inode_id> entries

# Represents an entry in the inode table, representing a file
# or directory
class InodeEntry
    # The size of the file (not used for directories)
    uint32_t length
```

```

# True if the entry describes a directory, false if
it describes a file
uint8_t is_dir

# When the file first was created
uint64_t time_created
# When the file was last accessed
uint64_t time_accessed
# When the file was last modified
uint64_t time_modified

# A list representing the posts of the file or
directory.
string [] post_ids

# Represents the inode table of the filesystem. The table
consists of multiple inode entries

class InodeTable
    # Map of (inode id, inode entry) for each file and
    directory in the filesystem
    map<inode_t, InodeEntry> entries

```

Appendix B

BINARY REPRESENTATION OF FFS IMAGES AND CLASSES

This appendix visualizes the binary structures produced when serializing the `InodeTable`, the `InodeEntry`, and the `Directory` objects, and the binary structure of the encoded FFS images. The models are in terms of bytes, index 0 indicating the first byte, index 1 indicating the second byte, etc.

B.1 Serialized C++ objects

The `InodeTable`, `InodeEntry`, and the `Directory` class all have one `serialize` and one `deserialize` method each. The `serialize` method converts the object's data into binary form, and the `deserialize` method converts the serialized data into an object. The deserializer expects the same format of its input data as the serializer produces. The figures in this section visualize the serialized output of the different classes. Figure B.1 visualizes the serialized format of the `InodeTable`. Figure B.1 visualizes the serialized format of the `InodeEntry`. Figure B.1 visualizes the serialized format of the `Directory`.

B.2 FFS Images

An FFS image consists of multiple binary structures, including the FFS header and the encrypted data. This section visualizes these binary structures. Figure B.2 visualizes binary format of the FFS header. Figure B.2 visualizes the PCD of FFS images stored on the OWS.

InodeTable	
0	3
# Inode Entries	
4	7
Inode 1	Inode Entry 1
Inode 2	Inode Entry 2
⋮	
Inode N	Inode Entry N

Figure B.1: # Inode Entries is an unsigned integer representing the amount of inode entries the inode table contains. Following are # Inode Entries entries of an unsigned integer representing the inode of the inode entry, and the serialization of the corresponding InodeEntry object

InodeEntry	
0	3
length	is_d
4	5
12	13
16	
$t_{accessed}$	$t_{created}$
17	20
21	
28	29
32	
$t_{accessed}$	$t_{modified}$
	# Posts
Post 1	
Post 2	
⋮	
Post N	

Figure B.2: Byte representation of a serialized InodeEntry, representing a file or directory stored in FFS. length is an unsigned integer representing the amount of data stored on FFS by the file or directory, for instance the size of the file. is_d is a boolean with the value true ($\neq 0$) if the inode entry represents a directory, and false ($= 0$) if the inode entry represents a file. $t_{created}$, $t_{accessed}$, and $t_{modified}$ are unsigned integers represents timestamps of when the file or directory was created, last accessed and last modified, respectively. # Posts is an unsigned integer representing the amount of posts the file or directory is stored in on the OWS. Following are # Posts NULL-terminated strings representing each post ID in the OWS. The size of this field depends on the OWS used, for instance does Flickr often generate 11-byte post IDs. However, as the strings are NULL-terminated, the deserializer can read the bytes until the NULL-character is found

Directory	
0	3
# Entries	
4	7
Inode 1	Filename 1
Inode 2	Filename 2
⋮	
Inode 3	Filename 3

Figure B.3: Byte representation of a serialized Directory. # Entries is an unsigned integer representing the amount of entries in the directory. Following are # Entries inode-filename pairs. The Inode is an integer representing the inode of the file or directory, corresponding to the file's or directory's entry in the inode table. The filename is a NULL-terminated strings representing the filename of the file or directory in FFS. The size of this field can vary from filename to filename, but the maximum size of the field is 129B (128 characters + NULL character). As the strings are NULL-terminated, the deserializer can read the bytes until the NULL-character is found

FFS Header							
0	1	2	3	4	11	12	15
'F'	'F'	'S'	V		Timestamp		Data length

Figure B.4: 'F' and 'S' are the literal letters F and S in ASCII code. V is an integer representing the version of the FFS image produced. Timestamp is an unsigned integer representing the number of milliseconds since Unix epoch when the image was encoded. Data length is an unsigned integer representing the number of bytes stored after the header. Following the header is Data length bytes, containing the actual data stored in the image.

Pixel Color Data in FFS images

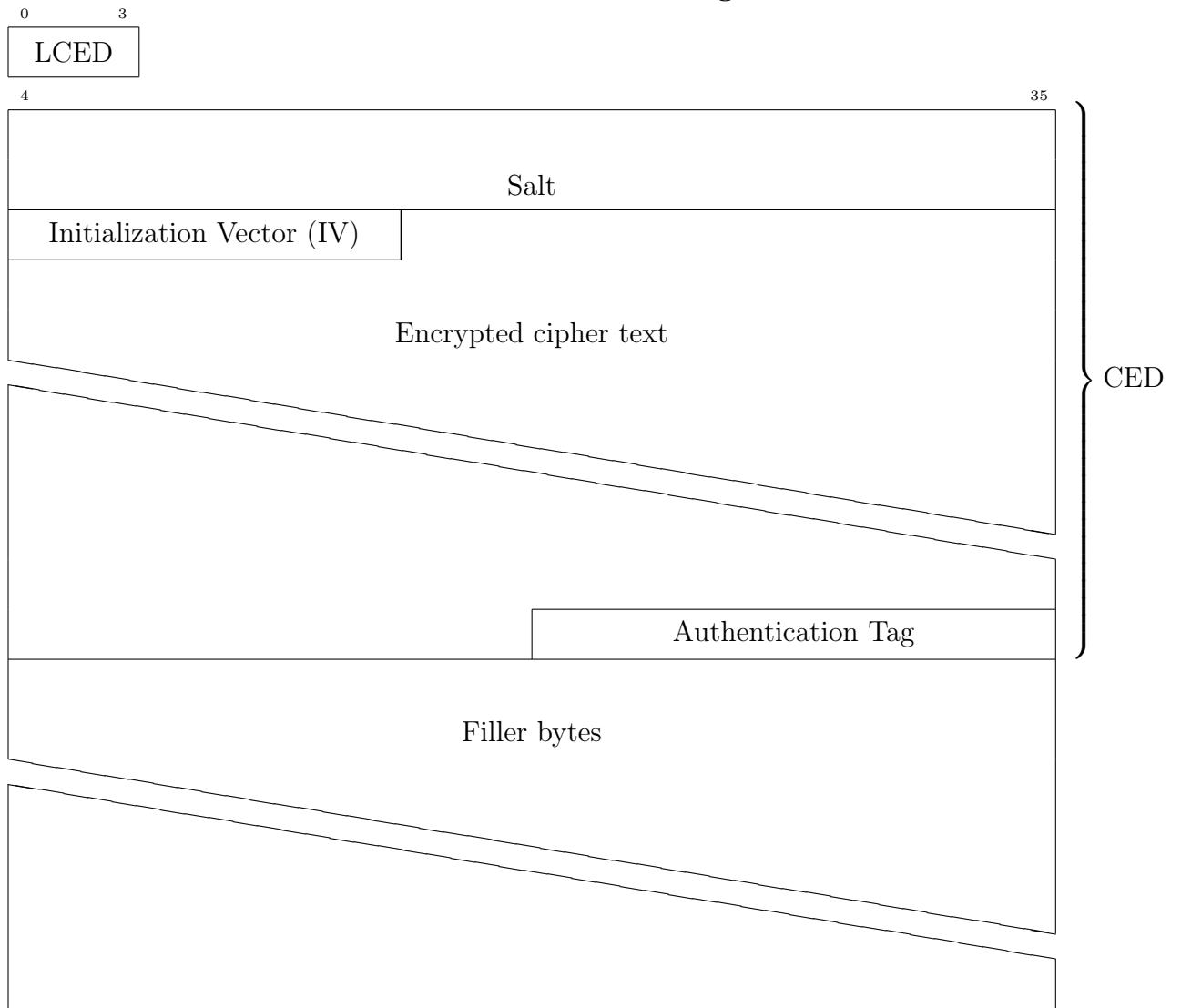


Figure B.5: Byte representation of the data stored as PCD in FFS images. LCED is an unsigned integer representing the Length of the CED. The Salt is a 64-byte randomized vector used to derive the encryption and decryption key. The IV is a 12-byte randomized vector used as the initial state of the encryption and decryption methods. Following is the Encrypted cipher text of variable size, depending on the size of the unencrypted data. The FFS header and the data to be stored, for instance the data of a file, is what is encrypted to become the Encrypted cipher text. The Authentication Tag is a 16-byte vector produced by the authenticated encryption method, and verified by the decryption method, to ensure data integrity has been upheld. Following is a number of filler bytes, depending on the size of the preceding data, to ensure the image has enough number of pixels for its calculated dimensions.

Appendix C

IOZONE BENCHMARKING DATA

This appendix contains tables of the IOZone benchmarking outputs produced. Each section contains the raw table output for the benchmarking results of the specific filesystem. Each table represents one IOZone test for a filesystem. Each table presents the throughput in kilobytes per second for a test, for the different file sizes and buffer sizes, both presented in kB.

C.1 FFS

Table C.1: IOZone result for the Read test on FFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	1124099	1875690	2072054	2606476	2386350	2844715	2604895	2173780	3210456				
2048	1378181	567636	2033695	2972495	3154809	3121562	3690142	2301200	3519302	2235910	4095510	3953206	
4096	1614527	2298370	2955012	4027344	4628439	3942321	4511750	4007615	4329816	4003788	5095007		
8192	2021184	2978787	3852936	5329730	3541581	3591558	4638941	6390362	3444652	5919188	4003788	5095007	
16384	60625	2246482	63191	4702688	61471	6206148	2936754	6362439	69217	5168507	2375140	117941	4462939
32768	55818	52177	4466247	5033507	60178	54036	35729	54242	5819047	53512	5501562	64800	86733
65536	124344	50556	54524	52190	4810367	67341	53582	50273	52437	4826246	56654	56309	4882655
131072	2973359	4220618	68079	70359	69429	7874149	60407	70434	7260	81991	62072	6522596	79478
262144	68103	70685	68449	69849	99154	70227	68031	71294	68417	59723	7519272	6089594	161814

Table C.2: IOZone result for the Write test on FFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	206	270	312	271	262	319	248	310	325				
2048	492	447	486	441	532	458	496	506	536	504			
4096	774	803	686	853	816	846	829	746	738	816	839		
8192	1099	640	1236	1056	1054	1095	1078	975	1177	1068	1029	1077	
16384	1320	1240	1369	1344	1413	1363	1339	1278	1349	1427	1341	1344	1187
32768	1573	1749	1685	1625	1610	1647	1639	1750	1745	1734	1636	1650	1727
65536	1875	1995	2062	1724	2029	1995	1783	2007	2008	2052	2109	1955	2068
131072	2059	2297	2472	2154	2176	2362	2236	2465	2433	2393	2644	2474	2384
262144	2339	2139	2597	2157	2529	2421	548	894	2623	2612	2676	2637	2646

Table C.3: IOZone result for the Re-Read test on FFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	1025833	2056183	1600327	2789291	2966535	2625597	3020783	2976816	4178773				
2048	2183619	1430271	2595298	2418469	3675930	2748949	4762117	3272598	3555722	3117032			
4096	2326065	2740095	3093350	4218190	4298399	4735608	5618365	5483860	5704175	3419011	4321103		
8192	2185761	3618412	4754484	5197511	4250966	6248582	6725591	6522590	4385525	6765318	4771651	4445097	
16384	1841910	2301789	4900900	5791387	6534875	6582447	6852209	6427904	7599353	3720236	5858035	4687931	4717539
32768	2375173	3448145	4222679	5487065	6201613	6714556	5137750	6366213	6636098	6273801	5597460	5099433	5232021
65536	1777628	3099807	3788868	5457737	4664497	5469466	7114221	6547080	6423160	5395284	5009273	4816014	4676161
131072	2666778	3783414	5009036	6003942	6385321	8230640	6553543	7089250	6747555	6880134	5982251	6600438	6078894
262144	2583743	4449684	5590363	6013557	6771275	6868693	7097066	7641769	7053902	7329012	4997807	4674122	5487959

Table C.4: IOZone result for the Re-Write test on FFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	256	246	200	264	308	269	250	293	324				
2048	532	511	404	547	505	533	564	489	434	457			
4096	864	768	775	826	762	793	880	767	787	835	721		
8192	942	930	958	935	896	1006	895	863	942	862	959	943	
16384	1155	1100	1113	1147	1141	1130	1106	1160	1048	1160	1137	1089	1111
32768	1327	1357	1335	1423	1350	1387	1363	1351	1296	1411	1245	1390	1282
65536	1447	1542	1534	1474	1420	1632	1412	1661	1579	1585	1599	1679	1637
131072	1729	1813	1637	1641	1567	1748	1716	1963	1945	1936	1902	1954	1885
262144	1822	1823	1944	1949	1939	1995	1940	1983	2009	1967	1987	2000	1992

Table C.5: IOZone result for the Random read test on FFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	157493	2216407	1627617	1741810	2852271	2926114	3722435	2275110	4146499				
2048	1782585	416667	2916978	2752473	3379461	4031308	2763987	3624742	4265523	3894239			
4096	1536962	2719708	2965725	4270618	3497668	5411313	3918939	5360658	4409837	4302706	4707064		
8192	1719637	2589902	4021596	4670469	4928384	6420214	6703285	6996761	4528880	5978928	4879393	4551075	
16384	1790371	1826537	4196659	4780882	4288854	5544663	6963302	6863844	7133159	4528524	4973975	4546200	4920199
32768	1652689	2699602	3615596	5126252	5529450	5983722	5242798	6766123	5356822	5140824	5706695	5170803	2796839
65536	1361645	2149636	3197042	4471609	4626031	5484198	6721584	6197810	6846648	3663045	4794509	5149377	4639069
131072	1971894	3118619	3812353	5415790	6283727	7615527	5731410	7322871	6164024	6919971	5118969	4799231	5960782
262144	1813113	3068092	3975558	4985728	6536121	6311675	6655244	7390988	7063782	7242548	6004755	5722694	5567942

Table C.6: IOZone result for the Random write test on FFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	230	255	264	338	287	304	184	317	289				
2048	524	431	462	512	468	513	570	492	446	558			
4096	822	857	787	688	811	799	791	815	793	766	828		
8192	907	917	861	865	993	977	747	904	913	918	929	972	
16384	1021	1013	1197	1126	1170	1127	1163	1031	1119	1138	1036	1180	1057
32768	1297	1268	1299	1405	1314	1310	1238	1210	1326	1297	1298	1334	1322
65536	1375	1384	1634	1522	1591	1587	1671	1606	1608	1634	1597	1624	1627
131072	1605	1784	1797	1715	1595	1631	1960	1910	1842	2001	1922	1935	1929
262144	1793	1945	1870	1987	2005	1962	1952	1999	1782	1988	2019	2014	2034

C.2 GCSF

Table C.7: IOZone result for the Read test on GCSF in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	1790460	2035716	2753527	3411938	3003881	3401130	3722435	4162573	4493556				
2048	945007	2308622	3297725	4170264	3698085	2467800	3506373	4611288	5416763	4376355			
4096	1858527	2813233	1017897	4969868	4399673	4941279	4591331	5657217	5625724	5019235	3327622		
8192	651866	480214	4126896	4664763	903994	5357988	3195123	5288712	6804170	1412655	4833405	5085204	
16384	409261	3463891	4768276	518677	5797739	6450228	6077171	6143453	6930296	6316241	5948808	837411	5326345
32768	289995	2604351	514007	5222875	351689	380969	225834	428160	377558	3011251	422812	601160	710955
65536	420968	390311	374191	590919	6243421	863782	388813	506734	463735	478777	456922	429282	624033
131072	443068	462364	407350	496836	444001	471616	424145	518826	505112	559713	375452	526586	515828

Table C.8: IOZone result for the Write test on GCSF in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	489	517	445	461	399	496	509	448	529				
2048	937	966	854	944	1072	966	944	954	868	969			
4096	1609	1614	1749	1607	1213	1787	1802	1519	1748	1551	1784		
8192	3047	2233	2746	3115	2666	2636	3000	2974	3165	2716	3138	3122	
16384	4372	4180	4437	4690	4798	4642	4429	4781	4705	4670	4621	4875	4607
32768	5377	6125	6471	6402	6343	6463	6435	6289	5865	6052	6317	6291	6018
65536	6763	7448	7298	7825	6561	7061	7818	6959	7491	7706	5985	7343	6851
131072	7276	7789	8553	8609	8243	8596	8168	8530	8596	8433	8029	8280	7959

Table C.9: IOZone result for the Re-Read test on GCSF in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	2632033	2187063	3200886	4304412	3348104	3778101	3281592	5048117	4083422				
2048	2311728	3261415	4623699	4643695	4079167	4349761	6149699	6058611	7213548	5032754			
4096	2356697	2579635	4329816	5424983	5347310	6309619	4371684	6585338	6894546	6370451	5165626		
8192	1891555	3974610	4017834	4884942	6112956	6262248	5158495	5116249	7087688	6720329	5270864	5038228	
16384	2228199	3960364	5075741	6187150	6473317	6838571	6919132	7139088	7211005	6614761	6187707	5016457	4594528
32768	2503678	3836954	4593731	6020418	6336861	5357031	1864671	6139832	5652480	6276093	5945927	4010262	4741431
65536	2639381	3531600	5031555	6133503	6445904	5921182	5961505	6217859	6461207	6398788	5278722	4674094	5364747
131072	3039494	3904216	4889073	5950781	6275836	7495395	5875292	7344197	7196622	8031869	4689156	5687415	5207460

Table C.10: IOZone result for the Re-Write test on GCSF in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	371	330	295	433	400	329	259	335	409				
2048	550	612	738	736	814	775	600	592	799	787			
4096	873	1354	1503	1239	927	1317	1368	1342	1424	1277	1325		
8192	1118	2201	1192	2117	1883	2093	2004	2126	1877	2192	2014	2165	
16384	1370	2949	2955	2963	2678	2950	2974	3018	3134	2989	2827	3067	1401
32768	3354	3448	3200	3592	3656	3815	3532	3702	3629	3675	3508	3708	3621
65536	3815	3962	3849	2319	3794	4085	3970	4080	3929	4033	3787	2972	4044
131072	4443	4682	4721	4807	4749	4866	4774	4766	4683	4760	4623	4657	4804

Table C.11: IOZone result for the Random read test on GCSF in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	1992279	1741104	3923040	2892612	3284101	2875184	4282950	3684119	3179559				
2048	2122645	2592166	2843590	5006356	4221501	4481379	6583305	5200329	7343043	4934459			
4096	1723189	2471992	4007615	4899008	5625724	5713661	6503078	6897314	4958393	5270212	5063617		
8192	1438199	3111222	4149824	5095007	5821902	5885728	4543853	6350207	7173514	6501608	5372229	4654652	
16384	1859705	2912112	4175240	5158807	6039252	6725463	6203907	6921919	6820923	6546080	5667676	5441055	5336686
32768	1705159	2794224	4285618	5467855	5548200	6087347	6091664	5991547	5893405	6215636	6222672	3776853	5156254
65536	1843064	2695626	4393982	4975003	6203125	5990477	4676082	7062855	6735419	6700285	4143421	4907587	5587993
131072	2100647	2842719	3678063	5056629	5706720	6765741	5708261	7233171	7090347	7451506	4198987	5471360	5404768

Table C.12: IOZone result for the Random write test on GCSF in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	373	338	295	364	355	222	368	404	410				
2048	739	784	753	789	852	823	688	741	639	657			
4096	958	1418	1299	1372	812	884	1369	1330	1416	1194	1335		
8192	2200	2310	2289	2445	2174	2195	2106	2043	2063	1962	2111	2195	
16384	2739	2747	3476	3141	3478	2894	3123	2949	3054	2925	2941	2911	1223
32768	2567	3154	3766	4474	3738	4330	3664	3798	3534	3745	3675	3732	3613
65536	2646	2769	3422	4011	4985	4159	5019	3739	4051	3962	3899	4087	4193
131072	2124	3073	3481	4239	5025	6502	5285	6129	4806	4689	4747	4834	4832

C.3 Fejk FFS

Table C.13: IOZone result for the Read test on FFFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	1605111	2472911	889631	2715230	3618930	3001782	1032244	2578312	2467229				
2048	1921339	1930406	2194777	2821176	3200654	4130162	4154130	2649737	5032754	3286370			
4096	2426601	2784507	3271230	3574071	3670280	5542240	4386193	3771811	3995498	4763181	4000150		
8192	2895693	3535750	4173008	5378957	4899570	4548665	5914094	6558696	4271046	4104220	5475825	5888754	
16384	3094244	4152032	4908602	3512941	6234299	5855539	6313919	7272051	6212881	7111751	5507336	5387732	5486670
32768	2848900	3537882	4681672	6104381	6554760	5933093	6802626	6375072	6339199	6146697	6030191	5591994	5440583
65536	70116	3562495	5159913	5999237	7335592	7026566	7648924	6445904	77043	129764	5783761	5526649	4978066
131072	394463	2034461	454646	6311863	3782086	280028	7525973	6890568	75477	59220	2674224	238745	657556
262144	65486	75529	77854	97658	79916	72736	76276	71780	106689	72269	72176	79924	126614

Table C.14: IOZone result for the Write test on FFFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	5193	5287	4303	5160	5076	5282	27847	5736	5086				
2048	4807	5335	4665	6305	6258	5920	6228	6453	5811	6301			
4096	5767	5943	5979	5807	6265	6320	3784	6770	5759	6188	6844		
8192	5504	6464	6702	6783	6175	6015	5288	6874	98659	101980	7043	6738	
16384	6430	6955	7463	7442	6794	7637	7667	7628	7337	101677	7553	7824	7735
32768	7232	7656	7808	7859	8075	8142	8075	8062	8161	7896	8229	117474	8377
65536	7370	7246	7273	7350	7530	7664	7658	8170	6959	7196	7192	7019	6735
131072	7160	6974	6961	7229	7593	7217	7901	8196	8116	5763	7398	5990	8025
262144	7167	7419	7937	7545	8435	8520	8030	7742	3996	7468	7601	8066	7891
524288	7578	7967	8161	82	8189	8494	8454	8327	8466	8501	8370	8308	5935

Table C.15: IOZone result for the Re-Read test on FFFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	1984913	2820430	2353657	4674510	4232305	3198502	1920993	4943530	3142339				
2048	2107025	3011047	2367151	3915540	4633675	5209791	5119743	4663865	4829046	3736694			
4096	3075079	3614679	4462528	4302706	5971855	6503078	4906002	6471234	4132949	5184332	3442303		
8192	2826843	4114541	4678737	5261179	4158362	6182248	5094251	5357152	6537482	5382328	5756551	5915112	
16384	3115426	4517212	5147601	6343059	6609036	6262707	6753222	7984318	6787239	7246745	5728625	5310703	5452279
32768	2786858	3742299	5009656	7004755	7299786	7123475	7777741	6994062	6752162	7039557	6382473	5967613	5664360
65536	2205856	4396090	5428742	6393876	6889031	6089074	7811071	6860318	7461842	6801920	6440769	5750246	4823451
131072	3287977	3847707	5198793	6348527	6951999	8443258	7909267	7114111	7388515	5298401	3139222	5802490	6479087
262144	2974653	4452026	5376537	6145825	7115944	7217446	7116911	6533364	6027138	6506108	5360469	5598732	5819467

Table C.16: IOZone result for the Re-Write test on FFFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	4574	4975	1566	5157	4391	4913	3380	27982	5001				
2048	3371	4654	5206	4614	5631	5635	5680	31266	5577	5685			
4096	5548	5728	5588	5188	5330	5148	5077	5928	5449	4753	5515		
8192	5296	5167	5574	5177	5002	5540	5362	5527	5913	5893	5485	4895	
16384	5933	5866	6309	6263	5714	6230	6215	6563	6454	6412	5640	25482	6565
32768	6314	6369	6575	6687	6841	6852	6824	6819	6889	6768	6782	6699	6885
65536	5933	6327	5753	6290	6514	5615	6329	6632	5962	5815	5749	5935	25761
131072	5885	5619	6099	6598	6601	5990	6717	6763	5816	4048	6124	4737	6436
262144	5769	6203	6474	6722	6879	6865	6565	6140	6177	6033	6164	6586	6653

Table C.17: IOZone result for the Random read test on FFFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	1438461	2474336	3335105	4339202	4574926	3594699	1662264	4415030	3390391				
2048	1639674	2531808	2980747	3071337	4971585	5626082	5235193	4240255	3864455	4591569			
4096	2333965	2898672	4076076	4214051	3641495	6716643	3128843	6022095	4428023	4935601	5551194		
8192	2217071	1882745	4242044	6006101	3655755	6054786	6947247	6912307	6339662	5785631	5789530	5583494	
16384	2235520	2613523	4010753	5637917	5897753	5362924	6542963	7922644	6671272	7117644	4702688	5233056	5189585
32768	1953956	2985674	4118168	6358850	7157605	6732647	7552086	7015482	6541963	7126430	6545707	5985025	5650853
65536	1320279	3522910	4420978	5494832	6317898	6091233	7578280	6635907	7317626	6684480	6613236	5663404	4218907
131072	2179297	3011967	4211016	5669935	6324062	7899720	7685258	6951208	7292757	5564284	2867974	5863448	6536945
262144	2105727	3331986	4265958	5398262	6599796	7121152	6889437	6293359	6270783	5819868	5256751	5823875	5831010

Table C.18: IOZone result for the Random write test on FFFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	4619	4008	2880	4530	4425	4764	3097	5879	4465				
2048	4620	4691	5179	5665	5728	5660	4573	5554	5775	5519			
4096	5284	5681	5333	5194	5488	5822	5854	6127	37216	5145	5738		
8192	5442	4747	5737	5386	5800	5088	5881	5811	5414	5708	4852	5635	
16384	5553	6011	6191	6267	6188	5654	6348	6585	6428	6509	5831	6558	6496
32768	6253	6238	6434	6511	6810	6829	6984	6800	6877	6801	6853	6875	6857
65536	4967	6318	5379	5753	6616	6361	6528	6611	5854	5900	5980	6472	5881
131072	5754	5611	6114	6317	6102	6407	6469	6662	4629	4861	5661	5536	6443
262144	5741	6259	6439	6689	6907	6427	6463	6100	6309	5998	6035	6849	6857

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Table C.19: IOZone result for the Read test on APFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	538364	3908759	4488860	6128613	5251818	5660167	6402699	7420395	8474583				
2048	2582813	3379461	4172290	5644567	5184636	6583305	5280246	6603549	8159088	7393606	5558378		
4096	2523925	3846119	4591331	5918366	6459069	6225028	6471234	5728903	7085049	6198078			
8192	2689438	3653812	4902367	5603526	6081578	6310553	6720329	6809564	7067279	7154097	5422249	5776876	
16384	2675387	3779365	5457909	6347747	7440550	6818216	7702417	3990259	6054683	6367155	6698584	5477922	5027467
32768	2654604	4438267	5507073	6566975	4920870	6247564	6546954	6621073	5274791	7583338	2896268	5498920	5641806
65536	2574587	4011012	4825568	5732617	6554261	6607037	6608467	6864601	6640556	6608467	4768972	5492416	5470445
131072	2665860	3968043	5421344	5545873	5938696	6221082	6147894	6289118	6388735	2839445	3350171	5215562	4865147
262144	2385943	2904121	4293712	5289093	4596201	6348519	6435108	7442619	7397503	7744086	6419575	5641535	3369068

Table C.20: IOZone result for the Write test on APFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	186358	335392	512232	827258	699870	1032244	1273788	1477555	873705				
2048	229598	236085	291779	397593	892849	514465	513420	574009	1394966	1341170			
4096	190955	306150	512697	562558	593887	959243	806157	867415	754866	642314	1117622		
8192	169441	255864	357293	401784	651754	675577	650779	675976	564729	633023	708889	752384	
16384	229954	310425	353652	491394	722178	716747	601890	639573	775984	708683	579081	698945	784336
32768	201952	299576	431731	562454	584277	593696	609775	421778	769363	662034	427841	483047	741123
65536	205960	323049	351173	451792	416014	504320	495422	632520	336679	473751	501468	662240	523098
131072	210777	300665	358868	352807	399321	527975	431966	419926	413309	349982	282681	307020	224134
262144	213134	286667	418873	410737	231669	474854	322547	305477	446954	702936	283134	563923	396791

Table C.21: IOZone result for the Re-Read test on APFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	2942149	4300102	4898425	7420395	8000971	6918376	8970167	8199542	10662628				
2048	2892423	4038890	4911886	9101380	6967792	8059569	4284671	8464610	9898453	10660056			
4096	2603876	3991785	4853336	6330545	7380284	6669706	7355007	7135072	7515892	6625976	5744227		
8192	2578436	3948121	5047109	6118398	6627005	6855760	7205103	7386322	7474698	8152152	4955393	5013234	
16384	2666252	3689278	5628220	6660280	7736235	7050461	8087683	3954666	5923170	6405137	5624535	5472251	4733787
32768	2459325	4444294	5092820	6114429	5524116	6207215	6885441	6739910	5866989	6999048	2186853	5164391	5674182
65536	2609539	3811988	4921646	5591403	6577945	6843750	6577315	7125655	7737415	6903565	4937914	5074468	5140421
131072	2795139	3709708	5510463	5775607	6114321	6257620	5947047	6486732	5777367	2253302	2813722	4947994	4669283
262144	2259139	3316468	3623921	4864863	5380721	6522434	7086865	7440101	6565902	6814965	6387391	5202306	4402011

Table C.22: IOZone result for the Re-Write test on APFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	718605	1095150	1207534	2174880	2011877	2391665	2681328	2877110	2516377				
2048	659151	717873	1276781	1728076	1642495	2228370	2324867	2144371	2479196	2164908			
4096	575755	815146	1035380	1213970	1113926	1490556	1442740	1410868	1140927	1656880	1293391		
8192	465744	595615	743978	799606	902996	928069	952326	957100	929425	967176	944862	862231	
16384	477530	623578	762230	829106	809485	828646	866283	863811	854137	861904	818997	844138	791153
32768	462407	643152	739050	789018	812878	810386	816665	794817	803352	805249	454334	770251	640425
65536	471824	503414	594355	430945	498426	542350	460111	450153	507700	458117	460379	537131	437673
131072	444825	469368	259988	389394	424943	387612	395487	399679	394444	429177	350255	351668	373706
262144	353860	289345	314443	372257	260874	429759	331707	450561	473636	535371	457672	544259	480567

Table C.23: IOZone result for the Random read test on APFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	2159571	3229770	5593820	6744549	6519323	7485055	8076196	6393168	7257394				
2048	2209455	3418463	4170264	7789164	6967792	9140117	4531020	8325147	9189005	7582884			
4096	2004931	3407483	4262142	6512939	7355007	6953144	7892238	7756829	7863339	6300364	5679660		
8192	1944875	2874376	4248864	5565406	6434642	6736139	6481984	6470997	7772279	7786370	5287898	6006101	
16384	1991764	2995773	4687931	5736755	6622411	6764523	7918992	4595758	5809993	6609036	6924710	5659275	4982992
32768	1767526	3215713	4479493	5964247	5520123	4968725	6777467	6518388	6288441	7759298	928793	4964956	5361210
65536	1900469	2952349	4178758	5048558	5798157	6123665	6282233	7567639	7736326	6572597	4738064	5052920	4938268
131072	1973295	2972025	4590640	5011365	5677078	5602332	5535598	6621505	4934581	2565107	2293317	4654537	4205861
262144	1645466	2529888	3703645	4595951	5555647	5328877	6941457	5965271	6178287	5808891	6445013	5152113	3875397

Table C.24: IOZone result for the Random write test on APFS in kilobytes per second

File size (kB)	Buffer size (kB)												
	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384
1024	653942	1121751	1758930	2295784	2461573	2086145	3259181	3301774	3229770				
2048	651403	941176	1615011	2235328	2622235	2972495	1903457	2694623	2756005	3256469			
4096	530639	717717	914318	1314470	1365344	1659601	1665715	1479262	1127080	1445410	1332929		
8192	519368	735363	998544	1222122	1447895	1400334	1472909	1523253	985796	968649	934531	808924	
16384	421455	596907	756066	866599	873862	962622	989541	903290	964053	959142	1011178	829827	830368
32768	385047	544336	662903	742733	766501	778374	810807	804240	798655	807050	695475	795015	794009
65536	325765	398351	434435	461241	520668	518300	488421	525891	542606	525094	562661	623386	461969
131072	271885	299055	309948	369675	422510	435145	406463	422968	442190	330912	366528	363675	471680
262144	247316	294339	301800	336086	262214	410092	337473	365472	497358	449168	418914	544169	657338