Distributed Enctypted File System

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ABSTRACT

In this paper, I propose a Distributed Encrypted File System (DEFS) which allows clients to store large scale data on a cluster of untrusted servers. Files in DEFS are stored in a distributed and encrypted manner. It provides exclusive account for each client, as well as full recoveries for possible damaged files.

KEYWORDS

Distributed File System; Distributed Data Storage; Encrypted FIle System.

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1 INTRODUCTION AND RELATED WORK

Distributed Encrypted File System (DEFS) is designed to take advantages of both encryption technic and distributed storage. Through DEFS, clients are able to store large scale data on untrusted servers. DEFS provides encryption services to prevent servers from stealing any clients' information. Also, it offers full recoveries if any of the clients' file is damaged by malicious servers. The distributed storage gives DEFS the capacity of hosting large scale of data. LockServer grants read-write locks for clients, which keeps a high consistency for DEFS.

1.1 Encrypted File System

Many non-networked file systems aims at keeping clients' data secure and checking integrity. An early example designed for Unix is Cryptographic File System (CFS)[2]. A modern classic encrypted file system is SUNDR[5], which is a general-purpose, multi-user network file system. The whole design in DEFS is largely inspired by this work.

1.2 Distributed File System

Typical traditional distributed file systems are NFS[6] and AFS[4]. Main difference between them is that AFS obtains better performance by caching the files, and it sacrifices the synchronization. NFS is later optimized to be Serverless Network File Systems[1]. Hadoop Distributed File System[7] and Google File System[3] concentrates on the support for large distributed data-intensive applications.

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2 SYSTEM OVERVIEW

This section introduces the overview design of Distributed Encrypted File System (DEFS). As illustrated in Fig. 1, DEFS is composed of two parts, namely Distributed File System (Sec. 4) and Encrypted Layer (Sec. 3).

Encrypted Layer guarantees that all the data (including file content ,filename and client's directory structure) in DEFS is encrypted. All file contents are signed by clients, which insures that any modification will be detected. Before executing requests, firstly it examines authority for every command carefully. Detected illegal attempts will be logged. The layer keeps clients' accounts secure from illegal operations from possible malicious users.

Distributed File System consists of LockServer, one trusted NameNode and a cluster of many untrusted DataNodes. LockServer provides read-write locks to maintain consistency. The NameNode/DataNode design is largely inspired by Hadoop [7] and Google File System[3]. In general, DEFS stores all metadata on one trusted server (NameNode), and stores application data blocks on others untrusted servers (DataNodes). NameNode records mappings with regards to file blocks and DataNodes, and hosts location related information. DataNodes stores the assigned block replicas.

3 ENCRYPTED LAYER DESIGN

As shown in Fig. 2, the Encrypted Layer provides all encryption-related services. It is transparent for both clients and servers, and it insures all the information stored on servers are encrypted. The login manner offers separate accounts for each client, which prevents clients from possible malicious users as well. Illegal attempts made by clients will be recorded in a special log file by the Encrypted Layer. The following subsections introduces detailed designs in this layer.

3.1 Account Initialization

The Encrypted Layer generates one pair of RSA key (n_1, e_1, d_1) and one AES key K for each newly registered client. The private key (n_1, d_1) is written at the client's designated input location, and the client is fully responsible for keeping it safe. The public key (n_1, e_1) is stored in the system. The the system uses it (n_1, e_1) to encrypt the AES key K to be K_{en}, and stores it in the system as well. To be specific, the system maintains a mapping between clients' names and their corresponding keys' locations. RSA public key (n_1, e_1) is later used for client authentication and encrypting file full paths (filename included). AES key K is taken to encrypt file contents.

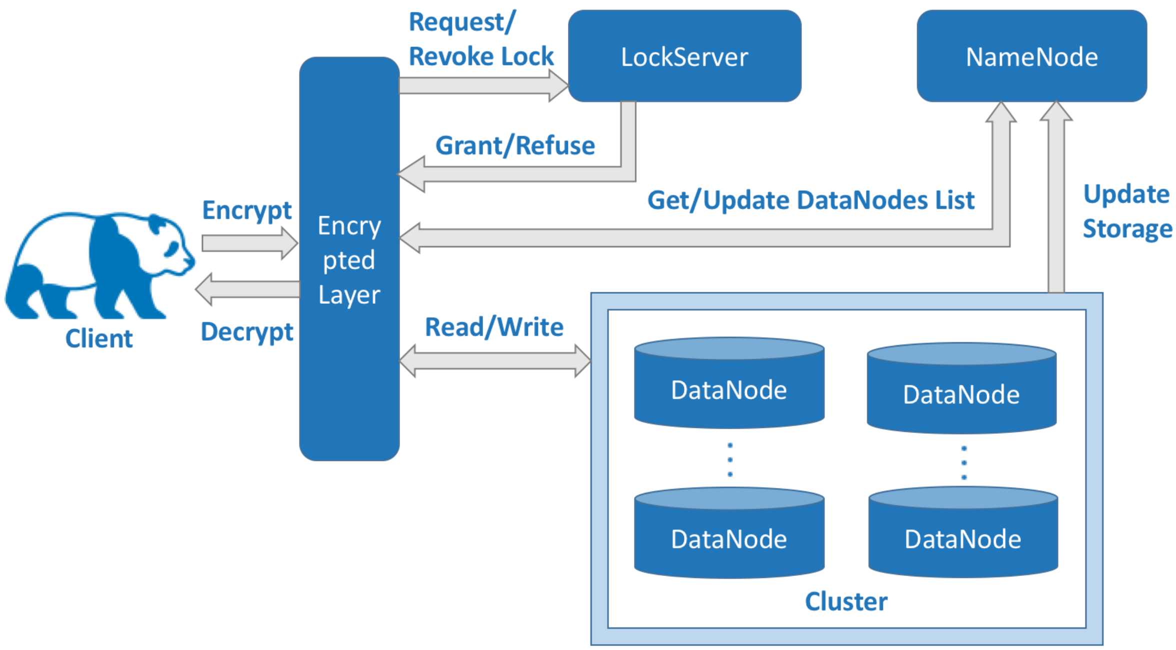

Figure 1: An overview of Distributed Encrypted File System (DEFS). The system contains an Encrypted Layer (left part) and a Distributed File System (right part). The Encrypted Layer provides encryption-related services. Generally, each request in Distributed File System requires getting the corresponding lock from LockServer first, and is responsible to revoke it when finished. After granted a lock, the client asks NameNode for IP addresses where the file blocks are stored (a list of DataNode IDs). Then the client writes or reads data blocks from DataNodes directly. To ensure that NameNode offers reasonable allocations of DataNodes, each DataNode sends Update Storage message to NameNode after any modification immediately.

When a client wants to login to DEFS, he must provide both the user name and the exact location of his RSA private key (n_1, d_1) correctly. If it matches with (n_1, e_1), then user authentication is granted.

3.2 File Uploading/Writing

When a client requests to Upload/Write a file, the Encrypted Layer makes sure all the information is encrypted according to the following procedures.

- File full path with filename included(to insure uniqueness of each file) is encrypted with (n_1, e_1) as its encrypted filename on the server.
- The system uses client's provided private key (n_1, d_1) to decrypt (K_{en}) to get AES key K. File content is encrypted with K as encrypted data stored on servers.
- Client's private key (n_1, d_1) is used to sign the hash value of the whole encrypted content. Then the signature is added at the beginning of the encrypted file. By now, the encryption process is finished.
- A backup of the encrypted content is stored under its encrypted filename in the system for possible need of future recovery.
- Send Upload/Write request to the Distributed File System.

3.3 File Downloading/Reading

When a client requests to Download/Read a file, the Encrypted Layer decrypted the received file from Distributed File System in following steps.

- First, Encrypted Layer uses (n_1, e_1) to encrypt the file's full path (filename included) to get the encrypted filename.
- Then it checks the signature. The system decrypted the signature stored at the beginning of the encrypted data with public key (n_1, e_1). And if the result equals to the hash value of the whole content, authentication of this file is granted. Otherwise, the system considers the data

illegally modified, and after sending notification to the client, the backup version will be uploaded automatically to the Distributed File System.
- After checking integrity, Encrypted Layer uses private key (n_1, d_1) to decrypt (K_{en}) and get AES key K. Then it uses K to decrypt file content.
- The decrypted file is downloaded and is ready to be read.

3.4 Other Commands

The system provide other commands including *Move, Copy, Remove, etc.* Those commands could be converted to Upload/Write (Sec. 3.2) and Download/Read (Sec. 3.3). For example, command *Move* includes

- Download and remove the original file.
- Move and rename the backup version.
- Upload the file.

3.5 Layer Content

As introduced formerly in Sec. 3, there is some client-related data stored in directories in the Encrypted Layer. DEFS insures that even the Encrypted Layer is invaded entirely by hackers somehow, nothing will be leaked.

All data stored in Encrypted Layer includes:

- Mapping of (client name, location of corresponding RSA public key).
- Mapping of (client name, encrypted AES key).
- A log file recording all illegal attempts.
- Clients' RSA public keys.
- Clients' backup file with encrypted filename and encrypted file content.

As shown above, the Encrypted Layer is totally secure. The purpose of requiring RSA private key directly to login and persevering only the encrypted version of backup file is exactly to insure that there is no sensitive information in the Encrypted Layer.

4 DISTRIBUTED FILE SYSTEM DESIGN

Fig. 3 demonstrates the design of Distributed File System. It mainly consists of three parts, namely LockServer, NameNode, and a cluster of DataNodes. DEFS provides a distributed storage schema for large scale data.

4.1 LockServer

Generally, I consider the synchronization problem in DEFS as a typical readers-writers problem[8]. The LockServer provides services following readers-preference solution. That is to say once the first reader is in the entry section, LockServer will lock the resource. Doing this will prevent any writers from accessing it. Subsequent readers can just utilize the locked (from writers) resource. The very last reader (indicated by the reader-counting variable) must unlock the resource, thus making it available to writers.

When requesting for read or write locks, the client sends a control message $(encryptedfilename, locktype)$ to LockServer, and in return he gets the granted lock or a waiting instruction (1/0). After the operation, the client revokes the lock via another control message to the server $(encryptedfilename, locktype)$.

4.2 NameNode

The single NameNode in Distributed File System maintains all the metadata and is in charge of allocating data blocks to specific DataNodes. DEFS considers NameNode to be entirely trustworthy.

As illustrated in Fig. 3, there are two mappings. The mappings are kept both in RAM and in json files to improve durability. The data will not be lost if the server program crushes.

A DEFS client wanting to download/read a file first contacts with the NameNode for the locations of data blocks (DataNode IDs) comprising the data and then reads block contents from the DataNode closest to the client. When a client requests to upload/write a file, a message asking for file allocation or relocation is sent to NameNode. Then the NameNode nominate three DataNodes for each block and return their IDs as a list back to the client.

To guarantee the selected DataNodes have the capacity to store the assigned block replicas, NameNode updates the storage mapping (DataNode ID, Storage Left) immediately upon receipt of control messages from DataNodes. During the nomination, NameNode randomly selects three DataNodes for each block among which have enough storage.

4.3 DataNodes

Distributed File System contains a cluster of DataNodes to store data blocks. In DEFS, all DataNodes are considered not trustworthy, and the data sent to them are only clients' instructions and encrypted data blocks. Data pipeline goes between clients and DataNodes directly.

During the startup process of each DataNode, it performs a handshake with NameNode to inform the connection and its current storage capacity. And after processing storage-changing requests such as block deletion or allocation, DataNodes send control messages $(DataNodeID, Storage)$ to NameNode to update the space left.

4.4 Fault Tolerance

DEFS provides a robust data storage on untrusted servers. As long as the NameNode is trustworthy, the DataNodes can be untrusted. Block replicas hosted by DataNodes may be modified or deleted at anytime. DEFS has two methods in dealing with such situation.

Random Selection of DataNodes. As mentioned in Sec. 4.2, the NameNode nominate DataNodes randomly for each block. Assume there are totally n DataNodes, and m of them are malicious. Here we suppose that malicious DataNodes damage every data block sent to it. We also assume that the client's file contains k blocks, and the number of replicas in DEFS is r. Then the possibility of unrecoverable damage to one data block is $\frac{C_m^r}{C_n^r}$. The possibility of unrecoverable damage to the whole file is:

$$1 - (1 - \frac{C_m^r}{C_n^r})^k \tag{1}$$

As designed in DEFS, $r = 3$. And if $\frac{m}{n} = \frac{1}{3}$, which means one third of the DataNodes are malicious, the possibility of recovering the full file still remains to be:

$$(1 - \frac{C_m^r}{C_n^r})^k > (1 - (\frac{m}{n}))^k > (\frac{26}{27})^k \tag{2}$$

As calculated, DEFS keeps a high tolerance of fault.

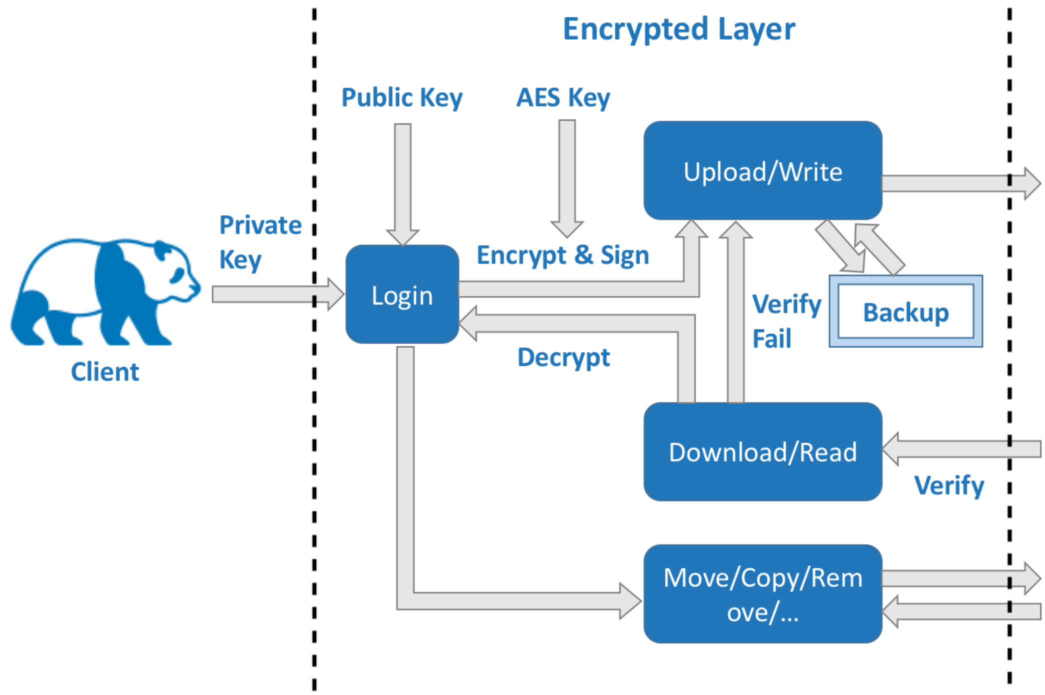

Figure 2: An overview of the Encrypted Layer. The client needs to provide the location of RSA private key to login to the system. The public key and the encrypted AES key is kept by the system. A simple work flow is shown here.

Encrypted File Backup. As introduced in Sec. 3.2, the Encrypted Layer maintains a backup for every encrypted file, which is absolutely practical when the file size is small. In the decryption procedure, if the retrieved file is found to be modified, the backup version will be used to correct the data on DataNodes automatically. This backup method provides a 100% percent recovery of any file.

5 IMPLEMENTATION

All the discussed design above about DEFS is fully implemented. I choose programming language Python, and library *Crypto* is used for encryption. Source code is available at https://github.com/kittenish/Distributed-Encrypted-File-System. Screen shots for command line interfaces are presented in Appendix Sec. A. This section will introduce detailed settings and side information in implementing DEFS.

5.1 Settings

The number of DataNodes is set to be 5, and the initial storage is 100MB. The number of replicas is 3. All communication is made through socket. For simplicity, clients consider the first DataNode (of the three IDs provided) to be the nearest one in transporting data. Besides user name and the private key, each client needs to provide an available socket port in logging-in process. The encrypted file backup method is adopted for fault tolerance. And all metedata are stored as *json* format in local file system. ALso, DEFS tries to catch exceptions as much as possible to avoid system crush.

5.2 Side Information

Ideally, socket connection between clients and DataNodes are supposed to be established when the transportation of data steam begins. But for simplicity, in my implementation, all socket connections between clients and other servers are built upon *login* command. The *login* request will fail if the client's socket port is unavailable or any of the initial connections fail.

Both the Encrypted Layer and the Distributed File System is transparent to clients. Commands of reading and writing is the same as traditional file systems. The command line interface is designed to be user-friendly, and clear help information is available for every function.

6 FUTURE WORK

Lots of extensions could be made to DEFS to achieve better performance. In this section, both design improvements and implementation modification will be discussed.

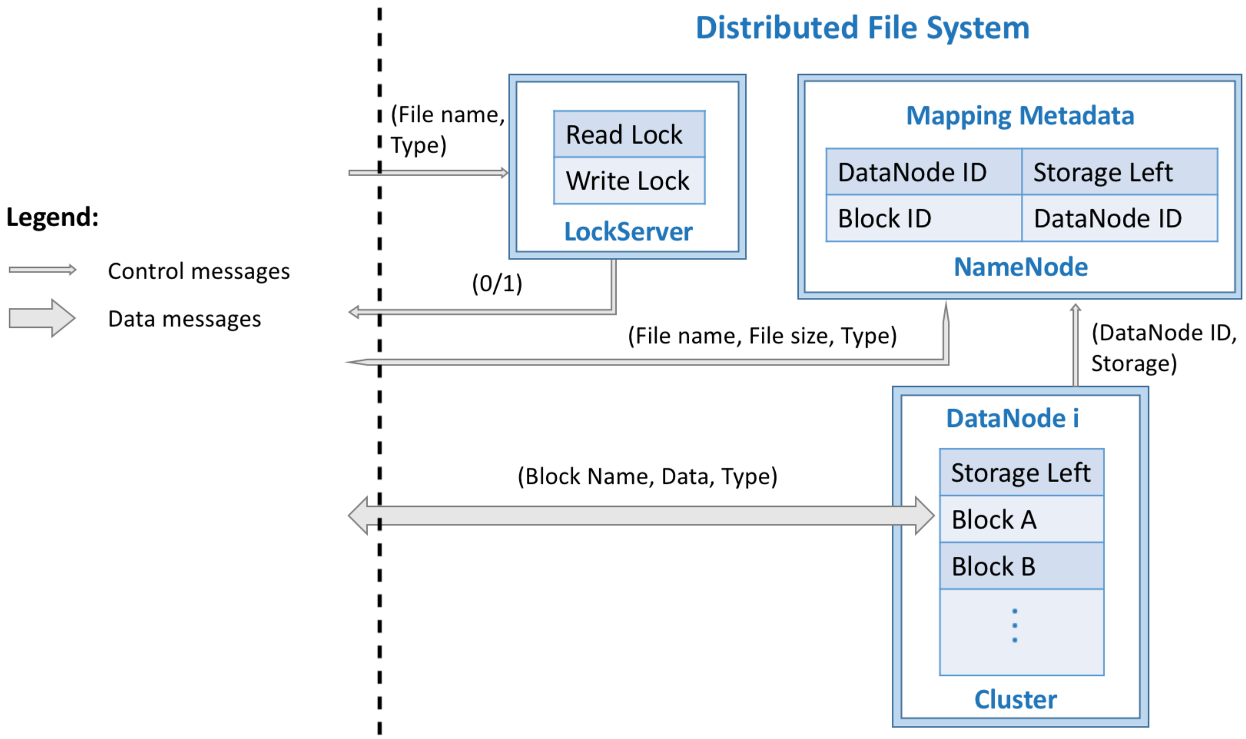

Figure 3: An overview of Distributed File System (DFS). The LockServer grants read-write locks. The NameNode stores the mapping metadata shown in the table. Data pipelines goes directly between clients and DataNodes.

From design aspect:

- Clients' separate accounts prevent files from being shared, the sharing function should be added.
- When file damage is detected, the client should report to NameNode. And more functions could be added to NameNode to locate malicious servers and disconnect with them when necessary.
- More NameNodes and more clusters of DataNodes can be added to improve storage capacity.
- The LockServer currently utilizes a readers-preference solution, which may cause severe starvation for writers. Other lock granting and revoking algorithms can be adopted.

From implementation aspect:

- Reduce the hard coded definitions in the system, and make DEFS more configurable.
- More rules in Encrypted Layer for examining commands' authority to avoid malicious users.
- When file damage happens, Encrypted Layer should try to recover the data from blocks inside DEFS first to get the latest version, before uploading the backup version.

7 CONCLUSION

In conclusion, DEFS is a file system designed to store large scale data on untrusted servers. Clients' data is hosted in a distributed and encrypted manner. And all clients' information is protected from both servers and possible malicious users.

A APPENDIX

Here are some screen shots of the fully implemented DEFS.

A.1 Client

Fig. 4 and Fig. 5.

A.2 LockServer

Fig. 7

A.3 NameNode

Fig. 6

A.4 DataNode

In sum there are 5 DataNodes, from Fig. 8 to Fig. 12.

```
python    python    python    python    python    python    python    ..le-System/src
Last login: Thu Dec 21 20:56:21 on ttys006
➜  src git:(master) ✗ python client.py
Distributed Encrypted File System Start...
Type 'help' for user guide...
DEFS/> NONE/> help

          help                                        print user-guide
          quit()                                      quit the efs

          cd                                          change directory (absolute/relative path are suppotred)
          pwd                                         show current absolute path
          ls [mode]                                   list all files
          mkdir                                       make a new directory (both absolute/relative path are suppotred)
          rm [mode]                                   remove file (add "-r" to remove directory, both absolute/relative path are suppotred, recursion not suppotred)
          mv [src] [dest]                             move the file from src to dest (only file move is suppotred, both absolute/relative path are suppotred)
          cp [src] [dest]                             copy file from src to dest (only file copy is suppotred, both absolute/relative path are suppotred)

          register [user_name] [PRK_loc]              regist with user name and specific location to store your private key
          login [user_name] [PRK_loc] [socket_port]   login with user name , private key location and an available socket port
          upload [src] [dest]                         upload the src file to the dest directory (both absolute/relative path are suppotred)
          download [src] [dest]                       download the src file to the dest directory (both absolute/relative path are suppotred)

DEFS/> NONE/> ls
Login first.
DEFS/> NONE/> login test /Users/mac/Desktop/test.pem 7986
Login succeeded.
DEFS/> test/> ls
['.DS_Store', 'dict1', 'dict2']
DEFS/> test/> cd ./dict1
Change directory ./dict1 successfully.
DEFS/> dict1/> cd ..
Change directory .. successfully.
DEFS/> test/> pwd
/test
DEFS/> test/> upload /Users/mac/Desktop/test.png dict1
Begin to encrypt: /Users/mac/Desktop/Distributed-Encrypted-File-Syst...
Begin to encrypt: ?PNG

IHDR?6/?`#iCCPICC Profi...
Send chunk 1 to DataNode 7003...
Send chunk 1 to DataNode 7001...
Send chunk 1 to DataNode 7004...
Send chunk 3 to DataNode 7005...
Send chunk 3 to DataNode 7003...
Send chunk 3 to DataNode 7002...
Send chunk 2 to DataNode 7002...
Send chunk 2 to DataNode 7003...
Send chunk 2 to DataNode 7004...
Send chunk 5 to DataNode 7001...
Send chunk 5 to DataNode 7004...
Send chunk 5 to DataNode 7002...
Send chunk 4 to DataNode 7005...
Send chunk 4 to DataNode 7003...
Send chunk 4 to DataNode 7001...
Send chunk 7 to DataNode 7002...
Send chunk 7 to DataNode 7003...
Send chunk 7 to DataNode 7001...
Send chunk 6 to DataNode 7001...
Send chunk 6 to DataNode 7004...
Send chunk 6 to DataNode 7005...
Upload file /Users/mac/Desktop/test.png successfully.
DEFS/> test/> mv dict1/1.png dict2/test_2.png
```

```
python    python    python    python    python    python    python    ..le-System/src
Begin to encrypt: /Users/mac/Desktop/Distributed-Encrypted-File-Syst...
Get chunk 1 from DataNode 7005...
Get chunk 2 from DataNode 7001...
Get chunk 3 from DataNode 7005...
Get chunk 4 from DataNode 7004...
Get chunk 5 from DataNode 7001...
Get chunk 6 from DataNode 7001...
Get chunk 7 from DataNode 7005...
Get chunk 8 from DataNode 7005...
Get chunk 9 from DataNode 7002...
Get chunk 10 from DataNode 7002...
Get chunk 11 from DataNode 7002...
Get chunk 12 from DataNode 7001...
Get chunk 13 from DataNode 7001...
Begin to encrypt: /Users/mac/Desktop/Distributed-Encrypted-File-Syst...
Remove chunk 11 from DataNode 7002...
Remove chunk 11 from DataNode 7005...
Remove chunk 11 from DataNode 7003...
Remove chunk 10 from DataNode 7002...
Remove chunk 10 from DataNode 7001...
Remove chunk 10 from DataNode 7003...
Remove chunk 13 from DataNode 7001...
Remove chunk 13 from DataNode 7004...
Remove chunk 13 from DataNode 7003...
Remove chunk 12 from DataNode 7001...
Remove chunk 12 from DataNode 7003...
Remove chunk 12 from DataNode 7004...
Remove chunk 1 from DataNode 7005...
Remove chunk 1 from DataNode 7001...
Remove chunk 1 from DataNode 7003...
Remove chunk 3 from DataNode 7005...
Remove chunk 3 from DataNode 7004...
Remove chunk 3 from DataNode 7002...
Remove chunk 2 from DataNode 7001...
Remove chunk 2 from DataNode 7005...
Remove chunk 2 from DataNode 7004...
Remove chunk 5 from DataNode 7001...
Remove chunk 5 from DataNode 7003...
Remove chunk 5 from DataNode 7004...
Remove chunk 4 from DataNode 7004...
Remove chunk 4 from DataNode 7005...
Remove chunk 4 from DataNode 7001...
Remove chunk 7 from DataNode 7005...
Remove chunk 7 from DataNode 7004...
Remove chunk 7 from DataNode 7001...
Remove chunk 6 from DataNode 7001...
Remove chunk 6 from DataNode 7005...
Remove chunk 6 from DataNode 7002...
Remove chunk 9 from DataNode 7002...
Remove chunk 9 from DataNode 7004...
Remove chunk 9 from DataNode 7005...
Remove chunk 8 from DataNode 7005...
Remove chunk 8 from DataNode 7002...
Remove chunk 8 from DataNode 7001...
Remove file name from NameNode...
Begin to encrypt: /Users/mac/Desktop/Distributed-Encrypted-File-Syst...
Begin to encrypt: ?PNG

IHDR??
0#iCCPICC Profi...
Send chunk 11 to DataNode 7005...
Send chunk 11 to DataNode 7001...
```

Figure 4


python
python
python
python
python
python
python
..le-System/src
Send chunk 10 to DataNode 7004...
Send chunk 10 to DataNode 7002...
Send chunk 10 to DataNode 7003...
Send chunk 13 to DataNode 7003...
Send chunk 13 to DataNode 7005...
Send chunk 13 to DataNode 7004...
Send chunk 12 to DataNode 7004...
Send chunk 12 to DataNode 7001...
Send chunk 12 to DataNode 7002...
Send chunk 1 to DataNode 7001...
Send chunk 1 to DataNode 7003...
Send chunk 1 to DataNode 7004...
Send chunk 3 to DataNode 7002...
Send chunk 3 to DataNode 7004...
Send chunk 3 to DataNode 7003...
Send chunk 2 to DataNode 7001...
Send chunk 2 to DataNode 7004...
Send chunk 2 to DataNode 7003...
Send chunk 5 to DataNode 7001...
Send chunk 5 to DataNode 7005...
Send chunk 5 to DataNode 7003...
Send chunk 4 to DataNode 7005...
Send chunk 4 to DataNode 7002...
Send chunk 4 to DataNode 7001...
Send chunk 7 to DataNode 7005...
Send chunk 7 to DataNode 7004...
Send chunk 7 to DataNode 7001...
Send chunk 6 to DataNode 7001...
Send chunk 6 to DataNode 7002...
Send chunk 6 to DataNode 7004...
Send chunk 9 to DataNode 7004...
Send chunk 9 to DataNode 7005...
Send chunk 9 to DataNode 7003...
Send chunk 8 to DataNode 7004...
Send chunk 8 to DataNode 7005...
Send chunk 8 to DataNode 7001...
Copy file dict2/test_2.png successfully to dict1/test_3.png .
DEFS/> test/> cd ./dict1
Change directory ./dict1 successfully.
DEFS/> dict1/> ls
['.DS_Store', 'test.png', 'test_3.png']
DEFS/> dict1/> pwd
/test/dict1
DEFS/> dict1/> cd ..
Change directory .. successfully.
DEFS/> test/> rm dict1/test_3.png
Begin to encrypt: /Users/mac/Desktop/Distributed-Encrypted-File-Syst...
Remove chunk 11 from DataNode 7003...
Remove chunk 11 from DataNode 7005...
Remove chunk 11 from DataNode 7004...
Remove chunk 10 from DataNode 7004...
Remove chunk 10 from DataNode 7002...
Remove chunk 10 from DataNode 7003...
Remove chunk 13 from DataNode 7003...
Remove chunk 13 from DataNode 7005...
Remove chunk 13 from DataNode 7004...
Remove chunk 12 from DataNode 7004...
Remove chunk 12 from DataNode 7001...
Remove chunk 12 from DataNode 7002...
Remove chunk 1 from DataNode 7001...
Remove chunk 1 from DataNode 7003...
Remove chunk 1 from DataNode 7004...
Remove chunk 3 from DataNode 7002...
Remove chunk 3 from DataNode 7004...
Remove chunk 3 from DataNode 7003...
Remove chunk 2 from DataNode 7001...
Remove chunk 2 from DataNode 7004...
Remove chunk 2 from DataNode 7003...
Remove chunk 5 from DataNode 7001...
Remove chunk 5 from DataNode 7005...
Remove chunk 5 from DataNode 7003...
Remove chunk 4 from DataNode 7005...
Remove chunk 4 from DataNode 7002...
Remove chunk 4 from DataNode 7001...
Remove chunk 7 from DataNode 7005...
Remove chunk 7 from DataNode 7004...
Remove chunk 7 from DataNode 7001...
Remove chunk 6 from DataNode 7001...
Remove chunk 6 from DataNode 7002...
Remove chunk 6 from DataNode 7004...
Remove chunk 9 from DataNode 7004...
Remove chunk 9 from DataNode 7005...
Remove chunk 9 from DataNode 7003...
Remove chunk 8 from DataNode 7004...
Remove chunk 8 from DataNode 7005...
Remove chunk 8 from DataNode 7001...
Remove file name from NameNode...
Remove file dict1/test_3.png successfully.
DEFS/> test/> cd ./dict1
Change directory ./dict1 successfully.
DEFS/> dict1/> ls
['.DS_Store', 'test.png']
DEFS/> dict1/> cd ..
Change directory .. successfully.
DEFS/> test/> download dict1/test.png /Users/mac/Desktop
Begin to encrypt: /Users/mac/Desktop/Distributed-Encrypted-File-Syst...
Get chunk 1 from DataNode 7003...
Get chunk 2 from DataNode 7002...
Get chunk 3 from DataNode 7005...
Get chunk 4 from DataNode 7005...
Get chunk 5 from DataNode 7001...
Get chunk 6 from DataNode 7001...
Get chunk 7 from DataNode 7002...
Download file dict1/test.png successfully, already at path /Users/mac/Desktop.
DEFS/> test/> quit()
Quit DEFS...
➜ src git:(master) ✗

Figure 5

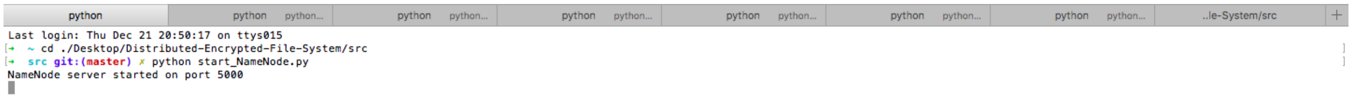

Figure 6

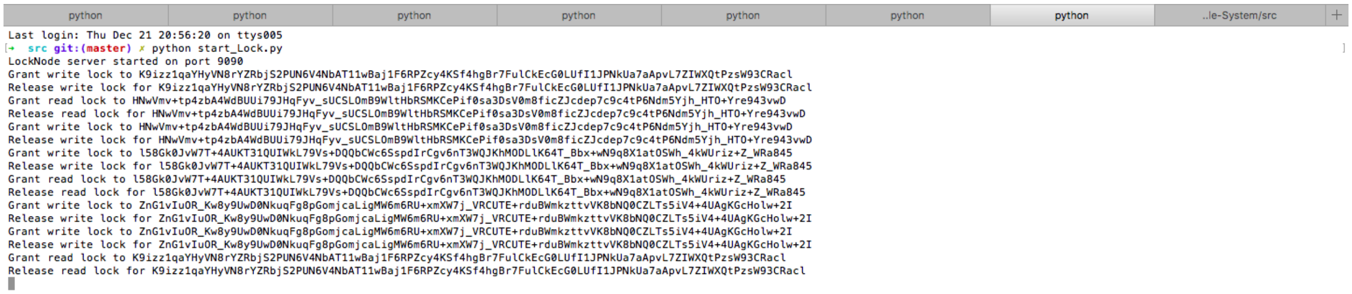

Figure 7

```
python | python | python python… | python python… | python python… | python python… | python python… | …le-System/src
Last login: Thu Dec 21 20:55:38 on ttys000
→  src git:(master) ✗ python start_DataNode_1.py
DataNode server started on port 7001
Update size to 100000000.0 kb...
Finish writing K9izz1qaYHyVN8rYZRbjS2PUN6V4NbAT11wBaj1F6RPZcy4KSf4hgBr7FulCkEcG0LUfI1JPNkUa7aApvL7ZIWXQtPzsW93CRacl_1
Update size to 99983616.0 kb...
Finish writing K9izz1qaYHyVN8rYZRbjS2PUN6V4NbAT11wBaj1F6RPZcy4KSf4hgBr7FulCkEcG0LUfI1JPNkUa7aApvL7ZIWXQtPzsW93CRacl_5
Update size to 99967232.0 kb...
Finish writing K9izz1qaYHyVN8rYZRbjS2PUN6V4NbAT11wBaj1F6RPZcy4KSf4hgBr7FulCkEcG0LUfI1JPNkUa7aApvL7ZIWXQtPzsW93CRacl_4
Update size to 99950848.0 kb...
Finish writing K9izz1qaYHyVN8rYZRbjS2PUN6V4NbAT11wBaj1F6RPZcy4KSf4hgBr7FulCkEcG0LUfI1JPNkUa7aApvL7ZIWXQtPzsW93CRacl_7
Update size to 99939372.0 kb...
Finish writing K9izz1qaYHyVN8rYZRbjS2PUN6V4NbAT11wBaj1F6RPZcy4KSf4hgBr7FulCkEcG0LUfI1JPNkUa7aApvL7ZIWXQtPzsW93CRacl_6
Update size to 99922988.0 kb...
Send file HNwVmv+tp4zbA4WdBUUi79JHqFyv_sUCSLOmB9WltHbRSMKCePif0sa3DsV0m8ficZJcdep7c9c4tP6Ndm5Yjh_HTO+Yre943vwD_2
Send file HNwVmv+tp4zbA4WdBUUi79JHqFyv_sUCSLOmB9WltHbRSMKCePif0sa3DsV0m8ficZJcdep7c9c4tP6Ndm5Yjh_HTO+Yre943vwD_5
Send file HNwVmv+tp4zbA4WdBUUi79JHqFyv_sUCSLOmB9WltHbRSMKCePif0sa3DsV0m8ficZJcdep7c9c4tP6Ndm5Yjh_HTO+Yre943vwD_6
Send file HNwVmv+tp4zbA4WdBUUi79JHqFyv_sUCSLOmB9WltHbRSMKCePif0sa3DsV0m8ficZJcdep7c9c4tP6Ndm5Yjh_HTO+Yre943vwD_12
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Figure 8

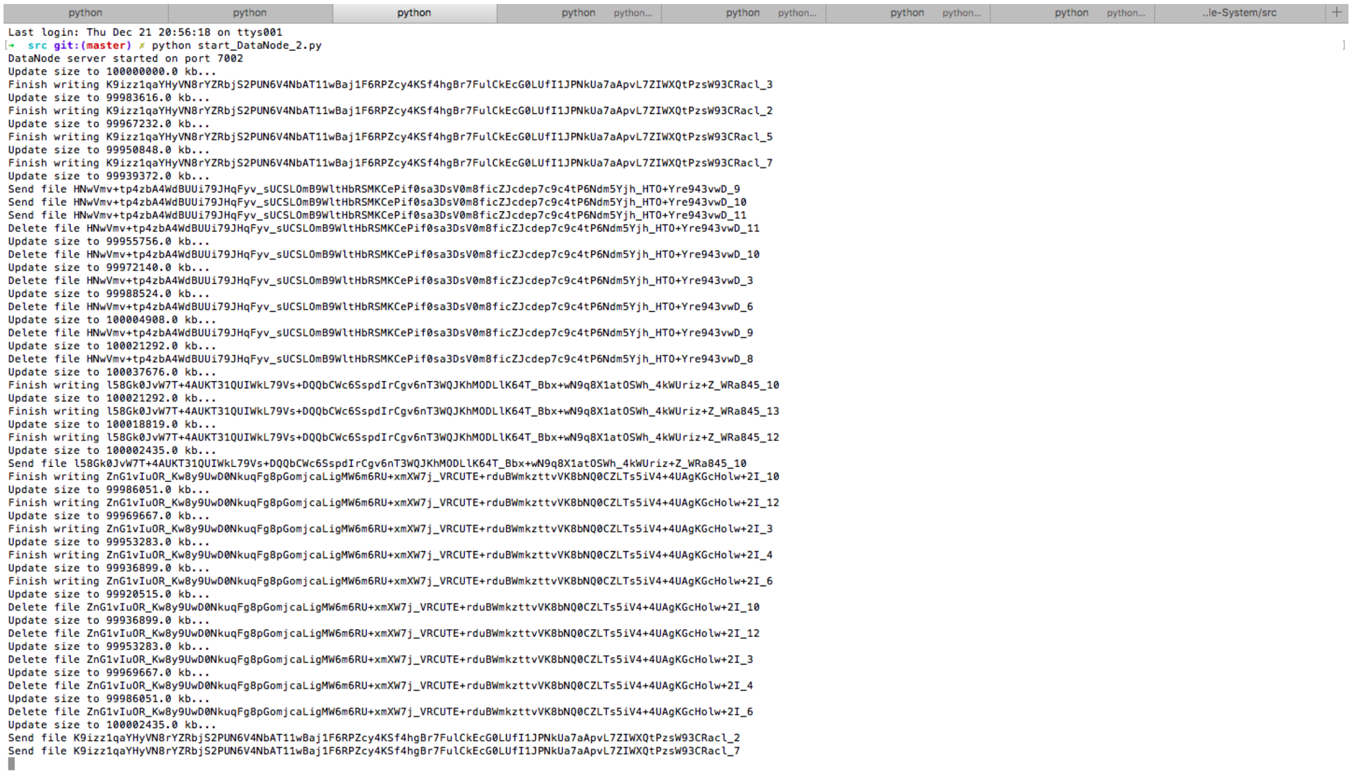

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Figure 9

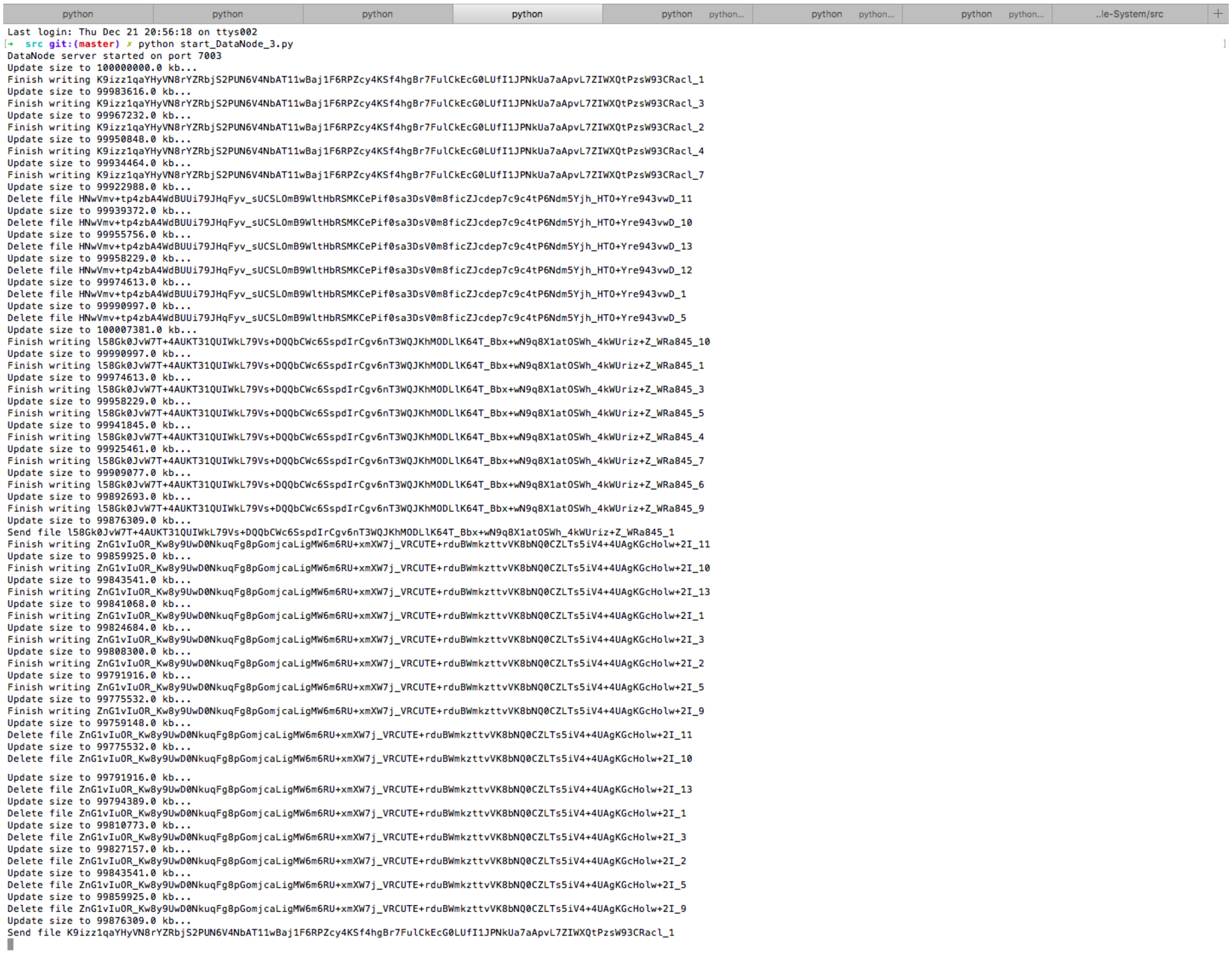
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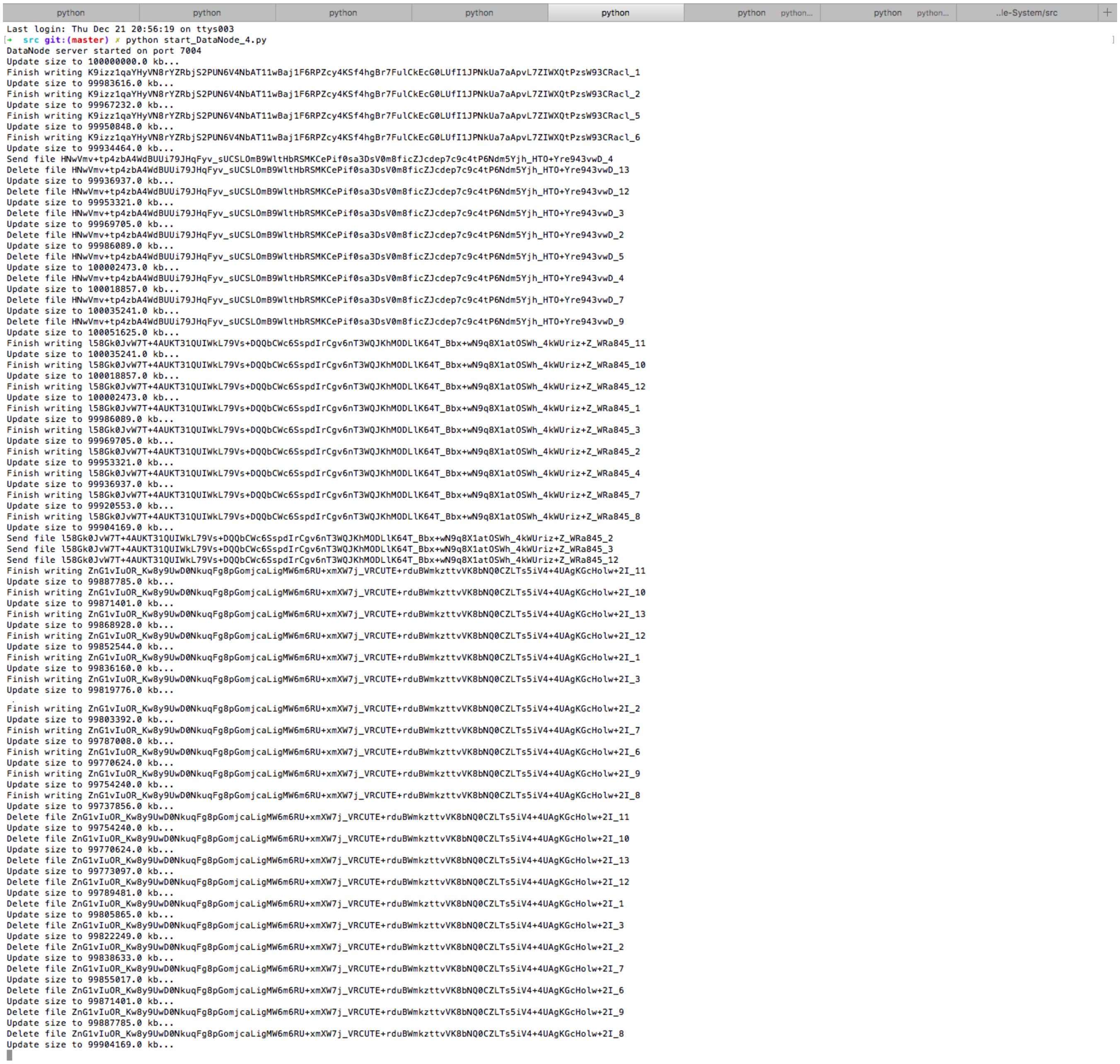
Figure 10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python python...
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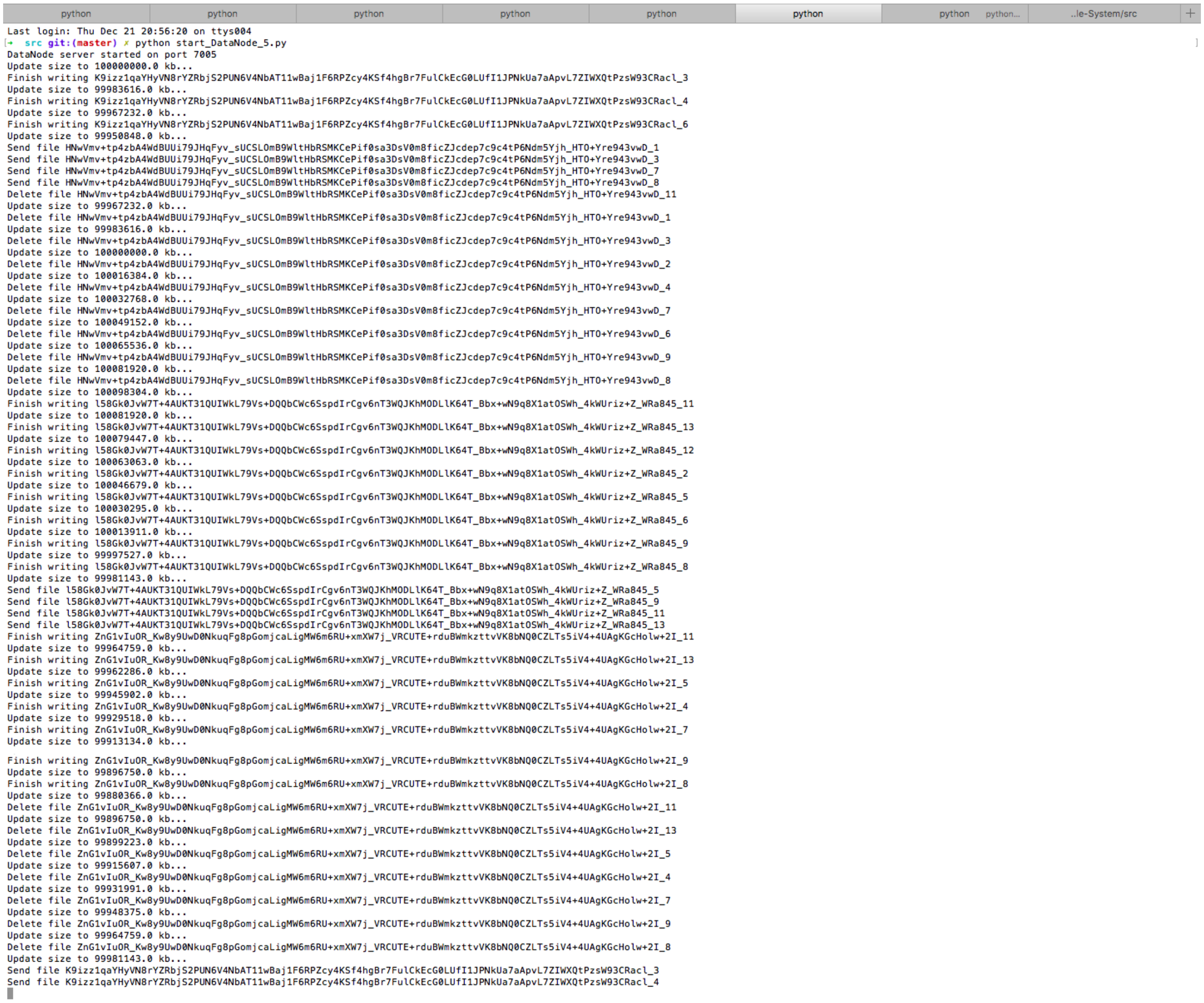
Figure 11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python...
...le-System/src
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→ src git:(master) ✗ python start_DataNode_5.py
DataNode server started on port 7005
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Figure 12