QEMU Copy-On-Write image file format specification

Analysis of the QCOW image format

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Summary

The QEMU Copy-On-Write (QCOW) image file format is used by the QEMU Open Source Process Emulator to store disk images.

This document is intended as a working document for the QCOW specification. Which should allow existing Open Source forensic tooling to be able to process this file type.

Document information

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Abstract: This document contains information about the QEMU Copy-On-Write file format.

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Version

Version	Author	Date	Comments
0.0.1	J.B. Metz	December 2010 January 2011	Initial version
0.0.2	J.B. Metz	May 2012	Small update.
0.0.3	J.B. Metz	April 2013 May 2013	Additional information regarding QCOW version 1, compression and encryption.
0.0.4	J.B. Metz	May 2013	Additional information regarding QCOW version 2.
0.0.5	J.B. Metz	December 2013	Additional information regarding compressed QCOW version 2.

Table of Contents

1. Overview

The QEMU Copy-On-Write (QCOW) image file format is used by the QEMU Open Source Process Emulator to store disk images (storage media).

The QCOW image file consists of:

- the file header
- the level 1 table (cluster aligned)
- the reference count table (cluster aligned)
- reference count blocks
- snapshot headers (8-byte aligned on cluster boundary)
- clusters containing:
  - level 2 tables
  - storage media data

The storage media data is stored in clusters. Each cluster is a multitude of 512 bytes. The level 1 (L1) table contains level 1 reference of level 2 (L2) tables. The level 2 tables contain level 2 references of the storage media clusters.

Characteristics	**Description**
Byte order	Big-endian in most cases, note that some values are in little-endian.
Date and time values	Number of seconds since Jan 1, 1970 00:00:00 UTC (POSIX epoch)
Character string	Narrow character strings assumed stored in UTF-8

1.1. Test version

The following version of programs were used to test the information within this document:

- QEMU

2. Encryption

The QCOW image format can encrypted the media data stored in the image format. Currently supported encryption methods are:

- AES-CBC 128-bit

If no encryption is used the encryption method in the file header is set to none (0).

It seems that compression and encryption at the same time is not supported, at least at the moment by qemu-img.

2.1. AES-CBC 128-bit

Both encryption and decryption use:

- AES-CBC with a 128-bits key decryption of sector data

The key is direct copy of the first 16 characters of a user provided (narrow character) password. If the password is smaller than 16 characters. The remaining key data is set to 0-byte values.

It is unclear which character sets are allowed and how characters outside the 7-bit ASCII set should be handled.

The initialization vector of the AES-CBC is using media data sector number (relative to the start of the disk) in little-endian format as the first 64 bits of the 128 bit initialization vector. The remaining initialization vector data is set to 0-byte values. The first sector number is 0 and the bytes per sector are 512.

3. File header

3.1. File header – version 1

The version 1 file header is 48 bytes of size and consist of:

offset	size	value	description
0	4	"QFI\xfb"	The signature (magic identifier) 0x51 0x46 0x49 0xfb
4	4	1	Version
8	8		Backing filename offset
16	4		Backing filename size
20	4		Modification date and time Contains a POSIX timestamp
24	8		Storage media size
32	1		Number of cluster block bits
33	1		Number of level 2 table bits
34	2		Unknown (empty values)
36	4		Encryption method
40	8		Level 1 table offset

The cluster block size is calculated as:

```
cluster block size = 1 << number of cluster block bits
```

The level table 2 size is calculated as:

```
level table 2 size = ( 1 << number of level 2 table bits ) * 8
```

The level 1 table size is calculated as:

```
level 1 table size = cluster block size
                   * ( 1 << number of level 2 table bits )

if( media size % level 1 table size != 0 )
{
        level 1 table size = ( media size / level 1 table size ) + 1
}
else
{
        level 1 table size = media size / level 1 table size
}
```

```
level 1 table size *= 8
```

The backing filename is set in snapshot image files and is normally stored after the file header.

3.2. File header – version 2

The version 2 file header is 72 bytes of size and consist of:

offset	size	value	description
0	4	“QFI\xfb”	The signature (magic identifier) 0x51 0x46 0x49 0xfb
4	4	2	Version
8	8		Backing filename offset
16	4		Backing filename size
20	4		Number of cluster block bits
24	8		Storage media size
32	4		Encryption method
36	4		Number of level 1 table references
40	8		Level 1 table offset
48	8		Reference count table offset
56	4		Reference count table clusters
60	4		Number of snapshots
64	8		Snapshots offset

The cluster block size is calculated as:

```
cluster block size = 1 << number of cluster block bits
```

The number of level 2 table bits is calculated as:

```
number of level 2 table bits = number of cluster block bits - 3
```

The level table 2 size is calculated as:

```
level table 2 size = ( 1 << number of level 2 table bits ) * 8
```

The level 1 table size is calculated as:

```
level 1 table size = number of level 1 table references * 8
```

The backing filename is set in snapshot image files and is normally stored after the file header.

3.3. Encryption methods

Value	Identifier	Description
0	QCOW_CRYPT_NONE	No encryption

Value	Identifier	Description
1	QCOW_CRYPT_AES	AES-CBC 128-bits encryption

4. Cluster blocks

4.1. Level 1 table

The level 1 table contains level 2 table references.

A reference value of 0 represents unused or unallocated and is considered as sparse or stored in a corresponding backing file.

4.1.1. Level 2 table reference – version 1

The level 2 table reference is 8-bytes of size and consists of:

offset	size	value	description
0.0	63 bits		Level 2 table offset Contains an offset value relative from the start of the file
7.7	1 bit		Is compressed flag (QCOW_OFLAG_COMPRESSED)

4.1.2. Level 2 table reference – version 2

The level 2 table reference is 8-bytes of size and consists of:

offset	size	value	description
0.0	62 bits		Level 2 table offset Contains an offset value relative from the start of the file
7.6	1 bit		Is compressed flag (QCOW_OFLAG_COMPRESSED)
7.7	1 bit		Is copied flag (QCOW_OFLAG_COPIED)

The is copied flag indicates that the reference count of the corresponding level 2 table is exactly one.

4.2. Level 2 table

The level 2 table contains cluster block references.

The level 2 table size is calculated as:

```
level 2 table size = ( 1 << number of level 2 table bits ) * 8
```

A reference value of 0 represents unused or unallocated and is considered as sparse or stored in a corresponding backing file.

4.2.1. Cluster block reference – version 1

The cluster block reference is 8-bytes of size and consists of:

offset	size	value	description
0.0	63 bits		Cluster block offset The offset is relative to the start of the cluster block
7.7	1 bit		Is compressed flag (QCOW_OFLAG_COMPRESSED)

4.2.2. Cluster block reference – version 2

The cluster block reference is 8-bytes of size and consists of:

offset	size	value	description
0.0	62 bits		Cluster block offset The offset is relative to the start of the cluster block
7.6	1 bit		Is compressed flag (QCOW_OFLAG_COMPRESSED)
7.7	1 bit		Is copied flag (QCOW_OFLAG_COPIED)

The is copied flag indicates that the reference count of the corresponding cluster block is exactly one.

4.3. Reference count table

The cluster data blocks are referenced counted. For every cluster data block a 16-bit reference count is stored in the reference count table.

The reference count table is stored in cluster block sizes. The file header contains the number of blocks (or reference count table clusters).

TODO

4.4. Retrieving a cluster data block

To retrieve a cluster data block corresponding a certain storage media offset:

Determine the level 1 table index from the offset:

```
level 1 table index bit shift =  number of cluster block bits
                               + number of level 2 table bits
```

Version 1

```
level 1 table index = ( offset & 0x7fffffffffffffffULL )
```

```
                    >> level 1 table index bit shift
```

Version 2

```
level 1 table index = ( offset & 0x3fffffffffffffffULL )
                    >> level 1 table index bit shift
```

Retrieve the level 2 table offset from the level 1 table. If the level table 2 offset is 0 and the image has a backing file the cluster data block is stored in the backing file otherwise the cluster block is considered sparse.

Read the corresponding level 2 table.

Determine the level 2 table index from the offset:

```
level 2 table index bit mask = ~( 0xffffffffffffffffULL
                              <<  number of level 2 table bits )
```

```
level 2 table index = ( offset >>  number of cluster block bits )
                    >> level 2 table index bit mask
```

Retrieve the cluster block offset from the level 2 table. If the cluster block offset is 0 and the image has a backing file the cluster data block is stored in the backing file otherwise the cluster block is considered sparse.

4.4.1. Uncompressed chunk data block

If the is compressed flag (QCOW_OFLAG_COMPRESSED) is not set:

```
cluster block bit mask = ~( 0xffffffffffffffffULL
                        <<  number of cluster block bits )
```

```
cluster block data offset = ( offset & cluster block bit mask )
                          + cluster block offset
```

Note that in version 2 the last cluster block in the file can be smaller than the cluster block size defined by the number of cluster block bits in the file header. This does not seem to be the case for version 1.

4.4.2. Compressed chunk data block

If the is compressed flag (QCOW_OFLAG_COMPRESSED) is set:

Compressed chunk data block – version 1

Version 1

```
compressed size bit shift =  63 - number of cluster block bits
```

```
compressed block size = ( ( cluster block offset & 0x7fffffffffffffffULL )
```

```
                    >> compressed size bit shift
```

```
compressed block offset &= ~( 0xffffffffffffffffULL
                        << compressed size bit shift )
```

Note that multiple compressed cluster data blocks seem to be always stored together in cluster block sizes. The compressed cluster data blocks are sector (512 bytes) aligned.

The compressed data uses a zlib inflate window bits value of -12

Compressed chunk data block – version 2

Version 2

```
compressed size bit shift =  62 - ( number of cluster block bits – 8 )
```

[MCLOUGHLIN08] describes the compressed block size calculation as:

```
compressed block size = ( ( ( cluster block offset & 0x3fffffffffffffffULL )
                    >> compressed size bit shift ) + 1 ) * 512.
```

Since the compressed block size is stored in 512 byte sectors this value does not contain the exact byte size of the compressed cluster block data. It sometimes lacks the size of the last partially filled sector and one sector should be added if possible within the bounds of the cluster blocks size and the file size.

```
cluster block offset &= ~( 0xffffffffffffffffULL
                    << compressed size bit shift )
```

Note that multiple compressed cluster data blocks seem to be always stored together in cluster block sizes. Although the file size does not seem to be strictly a multitude of the the cluster block size.

The compressed data uses a zlib inflate window bits value of -12

5. Snapshots

As of version 1 QCOW can use the backing filename in the file header to point to a parent image that contains the snapshot image where the current image only contains the modifications. Version 2 adds support to store snapshot inside the image.

5.1. Snapshot header - version 2

An in-image snapshot is created by adding a snapshot header, copying the L1 table and incrementing the reference counts of all L2 tables and data clusters referenced by the L1 table.

The snapshot header is variable of size and consists of:

offset	**size**	**value**	**description**
0	8		Level 1 table offset
8	4		Level 1 size

offset	size	value	description
12	2		Identifier string size
14	2		Name size
16	4		Date in seconds
20	4		Date in nano seconds
24	8		VM clock in nano seconds
32	4		VM state size
36	4		Extra data size
40	...		Extra data
...	...		Identifier string size
...	...		Name

TODO

6. Notes

6.1. Reference count table

reference count cluster block offset = cluster data block offset /
reference count table offset = cluster data block /

In order to obtain the reference count of a given cluster, you split the cluster offset into a refcount table offset and refcount block offset.

Since a refcount block is a single cluster of 2 byte entries, the lower cluster_size - 1 bits is used as the block offset and the rest of the bits are used as the table offset.

One optimization is that if any cluster pointed to by an L1 or L2 table entry has a refcount exactly equal to one, the most significant bit of the L1/L2 entry is set as a "copied" flag. This indicates that no snapshots are using this cluster and it can be immediately written to without having to make a copy for any snapshots referencing it.

Appendix A. References

[MCLOUGHLIN06]
Title: The QCOW Image Format
Author(s): Mark McLoughlin
Date: June 21, 2006
URL: http://people.gnome.org/~markmc/qcow-image-format-version-1.html

[MCLOUGHLIN08]
Title: The QCOW2 Image Format
Author(s): Mark McLoughlin
Date: September 11, 2008
URL: http://people.gnome.org/~markmc/qcow-image-format.html

[QEMU]
Title: QEMU Open Source Process Emulator
URL: http://wiki.qemu.org/Main_Page

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