

JFFS3 design issues

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Abstract

JFFS2, the Journalling Flash File System version 2, is widely used in the embedded systems world. It was designed for relatively small flash chips and has serious problems when it is used on large flash devices. Unfortunately, these scalability problems are deep inside the design of the file system, and cannot be solved without full redesign.

This document describes JFFS3 – a new flash file system which is designed to be scalable.

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1 JFFS2 overview

JFFS2, the Journalling Flash File System version 2 [1] is widely used in the embedded systems world. JFFS2 was originally designed for small NOR flashes (less than about 32MB) and the first device with JFFS2 file system was a small bar-code scanner. Later, when NAND flashes became widely used, NAND support was added to JFFS2. The first NAND flashes were also small enough, but grew in size very quickly and are currently much larger than 32MB (e.g., Samsung produces 2GB NAND flashes [4]).

JFFS2 has *log-structured* design, which basically means, that the whole file system may be regarded as one large log. Any file system modification (i.e., file change, directory creation, changing file's attributes, etc) is appended to the log. The log is the only data structure on the flash media. Modifications are encapsulated into small data structures called *nodes*.

So, JFFS2 is roughly a log, the log consists of nodes, each node contains a file system modification. And this is basically all JFFS2 file system is. It is very simple from the physical layout's standpoint. For more information about the design of JFFS2 and about the log-structured design, look at [1], [2], and [3].

It is not the goal of this chapter to delve into details of JFFS2 but it is still wanted to provide enough information to make it clear why JFFS2 has scalability problems and why JFFS3 is needed. To keep this chapter simple, terms *index* or *indexing information* are used.

The index is a crucial part of any file system as it is used to keep track of everything that is stored in the file system. For example, the index may help to quickly locate the addresses of physical blocks which correspond to the specified file at the specified offset, or it helps to quickly find all the directory entries in a specified directory and so on.

For example, in case of ext2, the inode table, the bitmap and the set of direct, indirect, doubly indirect and triply indirect pointers may be considered the index. In case of the FAT file system, the File Allocation Table may be considered as the index, etc.

In traditional file systems the index is usually kept and maintained on the media, but unfortunately, this is not the case for JFFS2. In JFFS2, *the index is maintained in RAM*, not on the flash media. And this is the root of all the JFFS2 scalability problems.

Of course, as the index is kept in RAM, JFFS2 achieves extremely high throughput, just because it does not need to update the index on flash after something has been changed in the file system. And this works very well for relatively small flashes, for which JFFS2 was originally designed. But as soon as one tries to use JFFS2 on large flashes (starting from about 128MB), many problems come up.

At first, it is obvious that JFFS2 needs to build the index in RAM when it mounts the file system. For this reason, it needs to scan the entire flash partition in order to locate all the nodes which are present there. So, the larger is JFFS2 partition, the more nodes it has, the longer it takes to mount it.

The second, it is evidently that the index consumes some RAM. And the larger is the JFFS2 file system, the more nodes it has, the more memory is consumed.

To put it differently, if S is the size of the JFFS3 flash partition ¹,

- JFFS2 mount time scales as $O(S)$ (linearly);
- JFFS2 memory consumption scales as $O(S)$ (linearly).

¹Note, all the symbols used in this document are summarized in section 9

So, it may be stood that JFFS2 *does not scale*. But despite the scalability problems, JFFS2 has many advantages, for example:

- very economical flash usage – data usually take as much flash space as it actually need, without wasting a lot space as in case of traditional file systems for block devices;
- admitting of "on-flight" compression which allows to fit a great deal of data to the flash; note, there are few file systems which support compression;
- very good file system write throughput (no need to update any on-flash indexing information as it simply does not exist there);
- unclean reboots robustness;
- good enough wear-leveling.

It is also worth noting here that there is a patch which is usually referred to as the "*summary patch*", that was implemented by Ferenc Havasi and was recently committed to the JFFS2 CVS. This patch speeds up the JFFS2 mount greatly, especially in case of NAND flashes. What the patch basically does is that it puts a small "*summary*" node at the end of each flash erasable block. This node, roughly speaking, contains the copy of headers of all the nodes in this eraseblocks. So, when JFFS2 mounts the file system, it needs to glance to the end of each eraseblock and read the summary node. This results in that JFFS2 only needs to read one or few NAND pages from the end of each eraseblock. Instead, when there is no summary, JFFS2 reads almost every NAND page in each eraseblock, because node headers are spread more or less evenly over eraseblocks.

Although the patch helps a lot, it is still a not scalable solution and it only relaxes the coefficient of the JFFS2 mount time liner dependency. Let alone that it does not lessen JFFS2 memory consumption.

2 JFFS3 Requirements

The following are the main user-level requirements JFFS3 has to meet.

- R01** JFFS3 memory consumption must not depend on the size of JFFS3 partition, the number of inodes in the file system, size of files, directories, and the like. Of course, JFFS3 must be able to use the advantage of the available RAM, but only for different kinds of *caches* which may be freed any time in case of memory pressure.
- R02** JFFS3 have to provide very fast file system mount without the need to scan the whole flash partition.
- R03** JFFS3 have to provide good flash wear-levelling.
- R04** JFFS3 must guarantee that unclean reboots cannot cause any file system corruption.
- R05** JFFS3 must provide good enough performance.
- R06** Unlike JFFS2, JFFS3 must implement write-behind caching for better performance.

- R07** JFFS3 must gracefully deal with different kinds of data corruptions (flash bit-flips, bad blocks may appear dynamically, etc).
- R08** In case of serious corruptions it should be possible to reconstruct all the data which were not damaged by means external tools like `ckfs.jffs3`.
- R09** All the JFFS3 characteristics ought to scale not faster the logarithmic function. JFFS2-like linear dependencies are not acceptable.
- R10** JFFS3 must support extended attributes.
- R11** JFFS3 must support the Access Control Lists feature (ACL).
- R12** JFFS3 have to support on-flight compression.
- R13** JFFS3 should provide good concurrency which means that it should be possible to read the file system during Garbage Collection and to read/write during the Journal Commit, read/write the file system simultaneously, etc.

3 Introduction to JFFS3

The main idea how to fix in JFFS2 to make it scalable is *to move the index from RAM to flash*. Unfortunately, this requires complete JFFS2 redesign and re-implementation and the design of JFFS3 is largely different to the design of JFFS2. This section discusses the base JFFS3 design ideas without any detailed description.

3.1 Indexing problem

There is a large difference between block devices and flash devices in how they allow to update the contents of a sector. Block devices admit of so-called "*in-place updates*", i.e. the update may be written straight to the sector. Flash devices do not allow this unless the whole eraseblock has been erased before.

Obviously, it is unacceptable to erase the whole eraseblock each time a sector is updated. Instead, so-called "*out-of-place updates*" technique is usually used. This simply means that no attempts to update sectors in-place are made but instead, updates are written to some other sector and the contents of the previous sector is afterwards regarded as garbage.

This "out-of-place writes" property of flash devices assumes that JFFS3 also has log-structured design as in JFFS3 any update is written out-of-place. And it seems that this is natural for any flash file system to have log-structured design.

It is interesting to notice that in log-structured file systems for block devices (like the one described in [2]) not any update is "out-of-place". There are always some fixed-position sectors present. These sectors usually refer the file system index, admit of quick file system mount and they are updated in-place.

But flash devices have limited number of erase cycles for each eraseblock and it is impossible to guaranty good wear-levelling if some eraseblocks are reserved for similar purposes. So, it is important that *in JFFS3 there are no in-place updates* as good wear-levelling is one of the main requirements to JFFS3 (see section 2).

The "out-of-place updates" property makes it difficult to maintain the index on the flash media. Figure 1 demonstrates why.

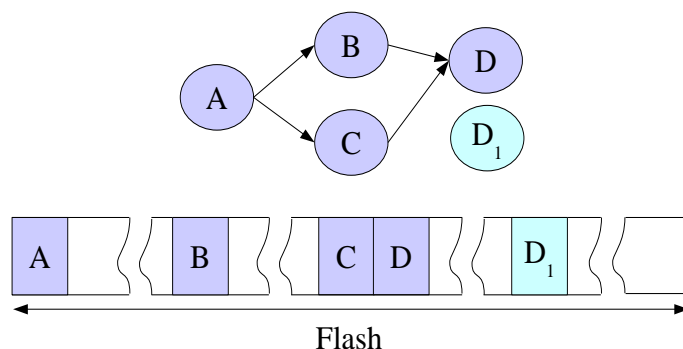


Figure 1: JFFS3 indexing problem example.

Suppose the index is kept and maintained on flash and it consists of 4 parts A , B , C , and D which refer each other: A refers B and C , B refers D , and C refers D . This means, that A contains the physical flash address of B and C and so on.

Suppose D should be updated. Since it is updated out-of-place, the newer version D_1 is written to some other place. But there are B and C which still refer D , not D_1 , and they ought to be updated as well. And when they are updated out-of-place, A will still refer the old B and C , and so on. Thus, it is not that trivial to store and maintain indexing information on the flash media.

3.2 Wandering trees

To address the above problem it is possible to use *wandering trees*. Figure 2 demonstrates how do wandering trees work.

1. Suppose that the index is a tree and it is stored and maintained on the flash media. The tree consists of nodes A , B , C , D , E , F , G , and H . Suppose node H should be updated.
2. At first, the updated version H_1 is written. Obviously, F still refers H .
3. Now the corresponding link in node F is changed and node F_1 is written to flash. F_1 refers H_1 . But as F_1 is also written out-of-place, A still refers the old node F .
4. Finally, the new root node A_1 is written and it refers F_1 .
5. Nodes A , F , H are now treated as garbage and the updated tree is composed by nodes A_1 , B , C , D , E , F_1 , G , and H_1 .

So, wandering trees is the base idea of how the indexing information is going to be maintained on the flash media in JFFS3. And it stands to reason that any tree may be called "wandering tree" if any update in the tree requires updating parent nodes up to the root. For example, it makes sense to talk about wandering Red-Black trees or wandering B^+ -trees and so forth.

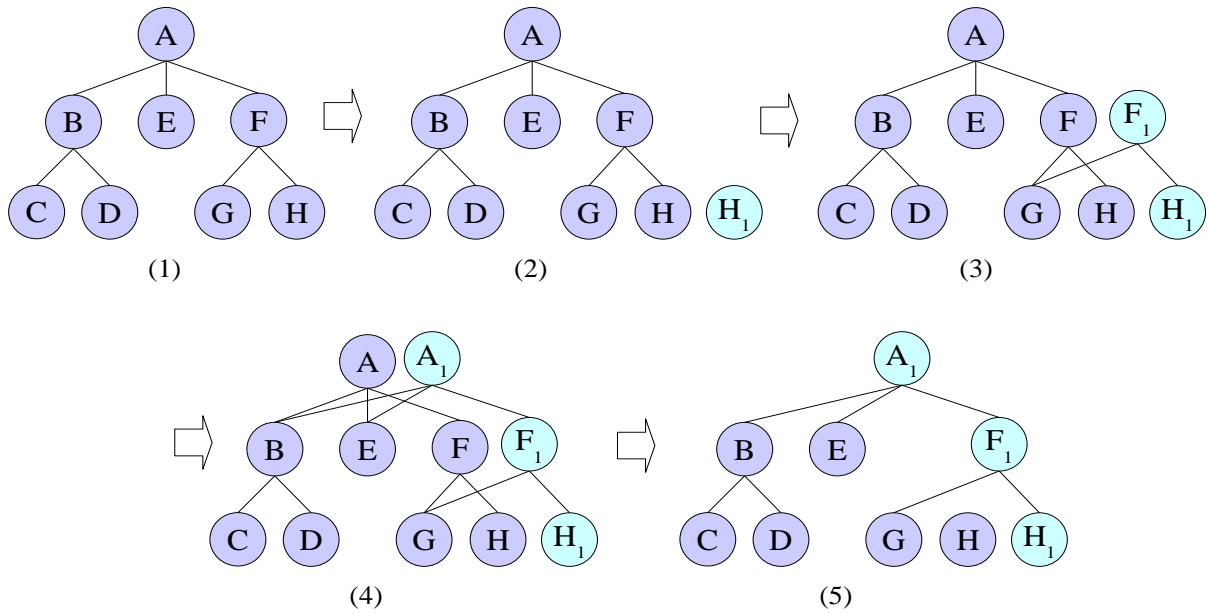


Figure 2: Wandering tree example.

3.3 B-trees

JFFS3 uses B^+ -trees and this subsection makes a short introduction to B^+ -trees. There is a plenty of books where one may find more information. There are also many on-line resources available, e.g. [6].

The inexact definition of B -tree may be formulated as a balanced search tree where each node may have many children. The *branching factor* or the *fanout* defines the maximal number of node's children. While B -trees may contain both useful data and *keys* and *links* in non-leaf nodes, B^+ -trees are B -trees which store data only in leaf nodes, while non-leaf nodes contain only keys and links.

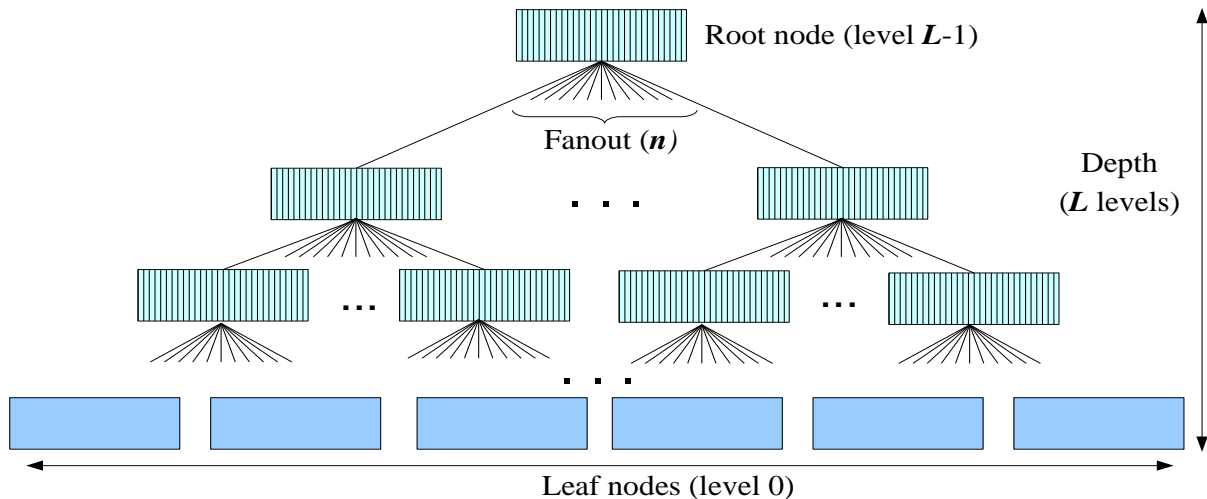


Figure 3: B^+ -tree example.

Figure 3 demonstrates a B^+ -tree with branching factor n and the number of level L .

Note, that in JFFS3 levels are numbered starting from *leaf* nodes (level 0) and ending at the *root* node (level $L - 1$).

Leaf nodes in the B^+ -tree contain data which are indexed by keys. Non-leaf nodes do not contain data, but contain only the indexing information, namely, *keys* and *links*.

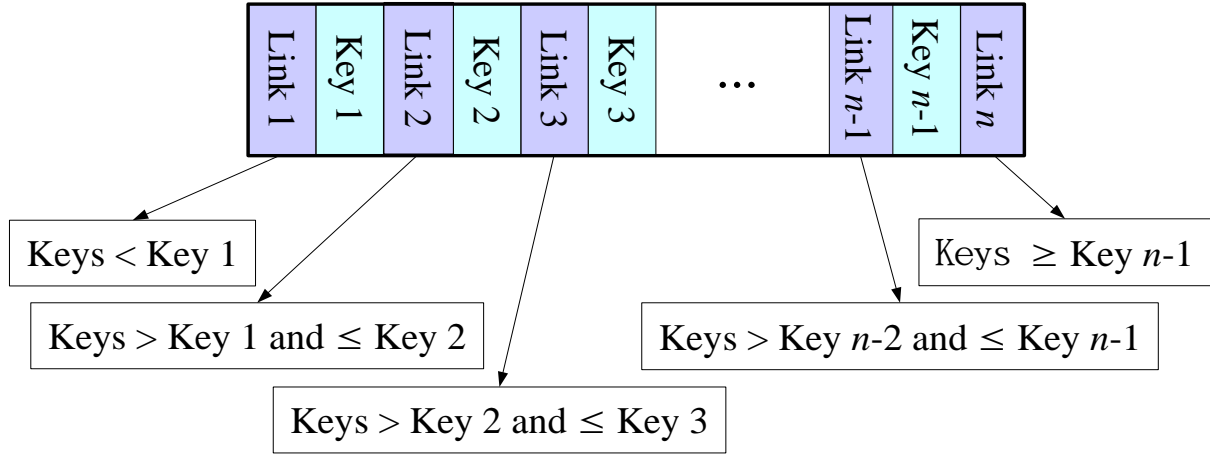


Figure 4: The structure of a non-leaf node in B^+ -tree.

Figure 4 depicts the structure of a non-leaf node. There are n links and $n - 1$ keys in the node. Links may point to either leaf nodes or other non-leaf nodes. In the former case, the leaf node will contain data which corresponds to the key which follows the link. In the latter case, the pointed non-leaf node (and the whole subtree with the root in this non-leaf node) will contain more keys in range ($Key 1, Key 2$].

Keys are sorted in the ascending order in non-leaf nodes, so it is not that difficult to lookup data corresponding to any key. Furthermore, the tree is balanced, so the the number of lookup steps does not depend on the key.

When objects are inserted or removed from the tree, re-balancing may be needed. The tree is re-balanced by means of splitting nodes or merging them and there is a simple enough algorithm exists. Please, refer to Donald Knuth's books for more information about re-balancing B^+ -trees.

B^+ -trees are widely used when working with block devices (e.g., hard drives). Indeed, these devices have a fixed input/output unit size (usually referred to as a *sector*) and it is natural to use B^+ -trees with node size multiple to the size of the sector in order to store information on such devices.

3.4 Indexing in JFFS3

The way how JFFS3 stores and indexes the file system is similar to the approach used by the *Reiser4* file system (see [5]). All the file system objects (inodes, files, directory entries, extended attributes, etc) are kept in one large B^+ -tree. Effectively, the whole JFFS3 file system may be regarded as one large B^+ -tree. This tree is further referred to just as "the tree".

Every object which is stored in the tree has a *key*, and objects are found in the tree by their keys. To make it clearer what are object keys, the following is an example of how they may look like:

- file data key: {inode number, offset};
- directory entry key: {parent directory inode number, dirent name hash} and the like.

The following are terms which are used in JFFS3 to refer nodes of different levels in the tree:

- nodes of level 0 are *leaf nodes*;
- nodes of level 1 are *twig nodes*;
- nodes which are not the root, not leaf, and not twig are *branch nodes*;
- no-leaf nodes (i.e., the root, branch and twig) are *indexing nodes*.

Note, the same terminology (except indexing nodes) is used in the Reiser4 file system [5].

Non-leaf nodes are called "indexing nodes" because they contain only indexing information, nothing else. No file system data is kept in the indexing nodes. Indexing nodes have fixed size which is equivalent to the flash *sector* size.

It is important to note that somewhat unusual terminology is used in this document. The smallest input/output unit of the flash chip is called a *sector*. Since JFFS3 mainly orients to NAND flashes, the sector is mostly the NAND page and is either 512 bytes or 2 Kilobytes. For other flash types the sector may be different. If flash's minimal input/output unit is very small (say, one bit as in case of NOR flash), there should be a layer which emulates larger sectors (say, 512 bytes).

In opposite to indexing nodes, leaf nodes have flexible size, just like nodes in JFFS2. So, roughly speaking, JFFS3 file system may be considered as JFFS2 file system (leaf nodes) plus indexing information (indexing nodes) (see figure 5).

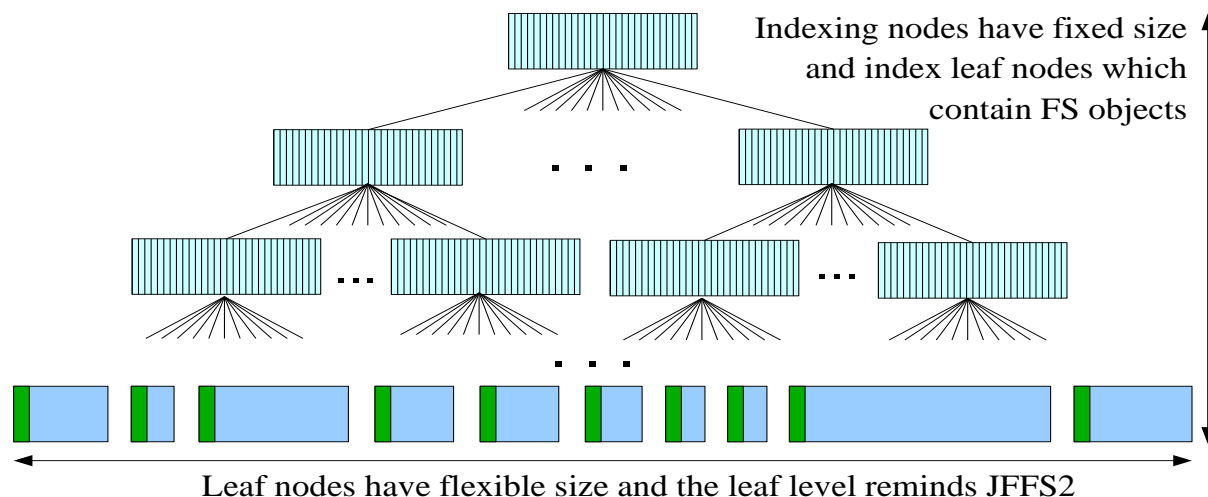


Figure 5: The JFFS3 tree.

Similarly to JFFS2, leaf nodes consist of *header* and *data*. The header describes the node data and contains information like the key of the node, the length, and the like.

Node data contains some file system data, for example a directory entry, file's contents, etc.

Leaf and indexing nodes are physically separated, which means that there are eraseblocks with only indexing nodes and with only leaf nodes. But of course, this does not mean that the whole flash partition is divided on two parts, this only means that the indexing and leaf nodes are not in one eraseblock. Figure 6 illustrates this.

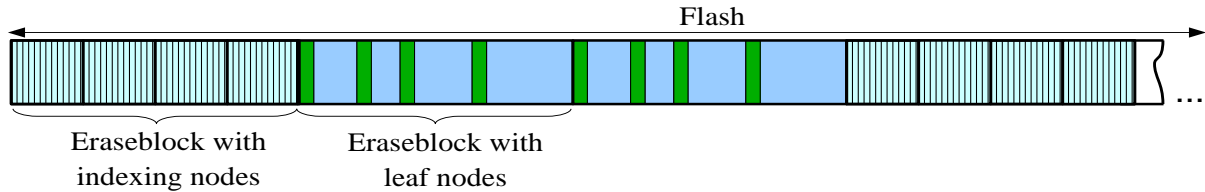


Figure 6: An illustration of leaf and indexing nodes separation.

Eraseblocks which contain only indexing nodes are called *indexing eraseblocks* and those with leaf nodes are called *leaf eraseblocks*.

The depth of the tree depends on how many objects are kept in the file system. The more files, directories, etc are present in the file system, the deeper is the tree. Fortunately, the number of tree levels grows very slowly with the growing number of file system objects and the tree lookup scales as $O(\log_n S)$ (logarithmically).

The following are advantages of the JFFS3 indexing approach.

- Many different key assignment schemes may be used and this gives a flexibility in how objects are sorted in the tree. Thus, one may optimize JFFS3 for specific workloads by means of changing the format of the keys.
- Leaf nodes may be compressed, so JFFS3 admits of the on-flight compression.
- In case of corruptions of the indexing information it is possible to re-create it by means of scanning leaf nodes' headers.
- There is a clear separation between data and indexing information. This implies that the indexing information and data may be cached separately, without overlapping in the same cache lines. This leads to better cache usage as described in the Reiser4 paper [5].

3.5 Indexing example

This section illustrates how does JFFS3 indexing work by means of a simple example. The example is very rough but it shows JFFS3 indexing in action. It is assumed that keys of direntries and data objects have the same layout that is mentioned in section 3.4.

Suppose that user does the following:

1. mounts JFFS3 file system to `"/mnt/jffs3"` directory;
2. issues `"ls /mnt/jffs3"` command;
3. reads the contents of `"/mnt/jffs3/my_file"` file.

The following are comments about what is going on in JFFS3 during the above steps.

1. During mount JFFS3 locates the position of the root node. This is done with help of the JFFS3 *superblock* which will be described later (see section 6).
2. To get the list of directory entries in the root directory, JFFS3 looks up all objects matching the $\{2, *\}$ key pattern. Indeed, direntry keys have $\{\text{parent inode \#, name hash}\}$ format, the root directory inode number is 2 (or another predefined constant). "*" means wildcard. Thus, JFFS3, $\{2, *\}$ will match to any direntry in the root directory.
3. To read the "my_file" file, JFFS3 first needs to find out its inode number. The inode number is stored in the directory entry object. Hence, JFFS3 reads my_file's direntry using $\{1, H(\text{"my_file"})\}$ key ($H()$ is the hash function).

Then JFFS3 searches for my_file's data objects using $\{I, \text{offset}\}$ keys. Depending on which part of file should be read, *offset* may take different values.

The above description is somewhat simplified e.g., JFFS3 also needs to read my_file's attr-data object to fetch the inode length from there (see section 4.1), etc. But the aim of the section is just to provide an idea of how JFFS3 indexing works.

3.6 The Journal

The JFFS3 tree is both B^+ -tree and wandering tree. Any file system change implies that a new node is written to the flash media, which in turn, assumes that a number of indexing nodes must be updated. Namely, the whole path of indexing nodes up to the root node should be updated (see section 3.2).

Evidently, it is very expensive to update several indexing nodes on each file system change and *the journal* provides a mechanism to avoid this.

The journal consists of a set of eraseblocks (the *journal eraseblocks*) which do not have a fixed location on flash and are not contiguous on flash. Any flash eraseblock may be used as an journal eraseblock.

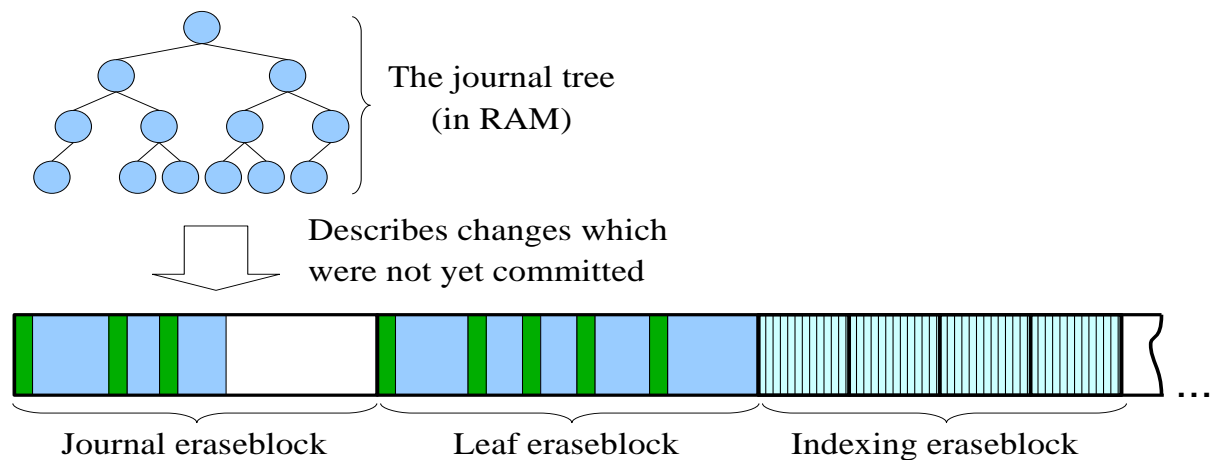


Figure 7: The JFFS3 journal.

When something is changed in the JFFS3 file system, the corresponding leaf node is written to the journal, but the corresponding indexing nodes are not updated. Instead, JFFS3 keeps track of file system changes in RAM in a data structure called *the journal tree* (see figure 7).

When something is read from the file system, JFFS3 first glimpses at the in-RAM journal tree to figure out if the needed data is in the journal. If the data are there, the journal is read, otherwise JFFS3 performs the usual tree lookup (see figure 8).

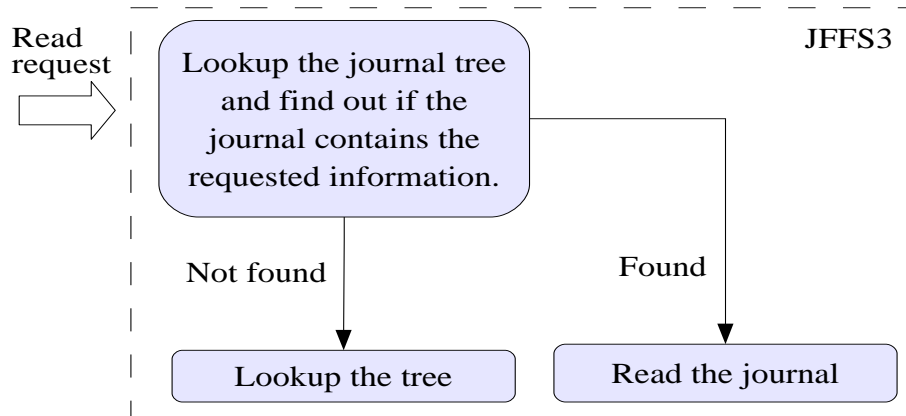


Figure 8: Read request processing in JFFS3.

The journal is *committed* when it is full or in some other appropriate for JFFS3 time. This means, that the indexing nodes corresponding to the journal changes are updated and written to the flash. The committed journal eraseblocks are then treated as leaf eraseblocks and new journal eraseblocks are picked by JFFS3 using the common JFFS3 wear-levelling algorithm.

The journal makes it possible to postpone indexing information updates to later and potentially more appropriate time. It also allows to merge many indexing node updates and lessen the amount of flash write operations.

When JFFS3 file system is being mounted, the journal should be read, "replayed" and the journal tree should be built. So, the larger is the journal, the longer it may take to mount JFFS3. From the other hand, the larger is the journal, the more writes may be deferred and the better performance may be achieved. By the other words, there is a trade-off between the mount time and the performance and one may vary these characteristics by means of changing the size of the journal.

3.7 Garbage collection

Garbage collection is a vital part of any log-structured file system. Over time, JFFS3 uses up all the flash free space and it needs to reclaim flash space occupied by garbage. And the goal of Garbage Collector is to recycle garbage and reclame flash space which it occupies. Since the only way to reclaim it is to erase the whole eraseblock, Garbage Collector works in terms of eraseblocks.

JFFS2 Garbage Collector is quite simple and works in several steps.

1. To reclaim dirt from an eraseblock, JFFS2 moves all valid nodes from this eraseblock to another eraseblock.

2. As nodes have changed their positions, the JFFS2 in-RAM index is adjusted.
3. The first eraseblock may be erased and re-used.

Note, JFFS2 (and JFFS3) always reserves several eraseblocks in order to guarantee that there are always some free eraseblocks available to perform garbage collection.

JFFS3 Garbage Collector is more complex. When valid data has been moved from an eraseblock, the corresponding indexing nodes must be updated as well. Depending on how many space Garbage Collector has reclaimed and how many space it has spent to update indexing nodes, it might be that Garbage Collector produces more garbage that it reclaims. This problem is demonstrated in figure 9.

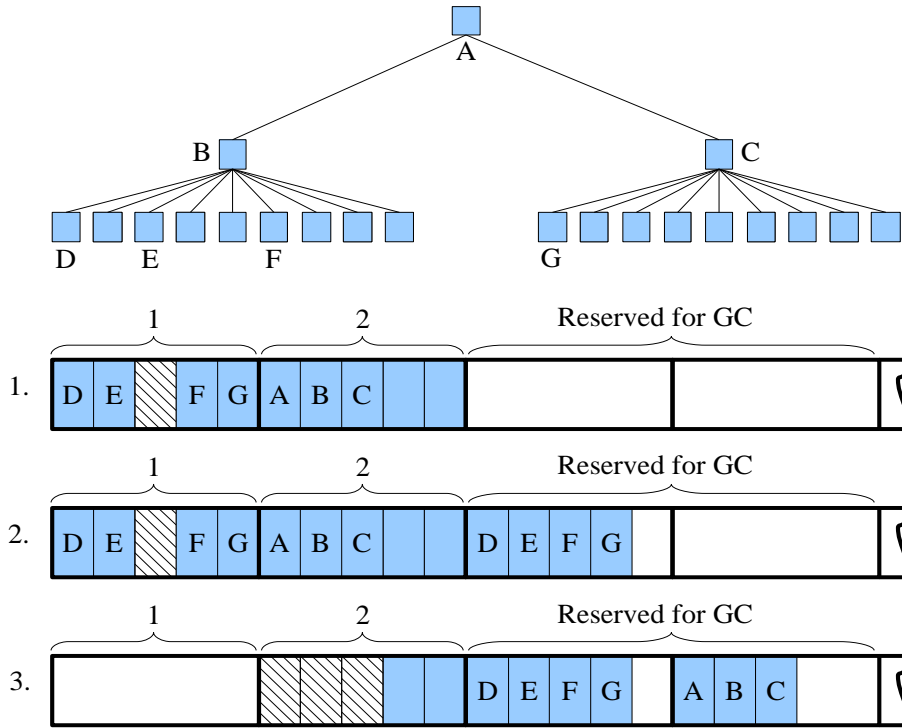


Figure 9: JFFS3 garbage collection problem illustration.

There is a subtree with root in node *A* depicted in the figure. At the beginning (snapshot 1), leaf nodes *D*, *E*, *F*, and *G* are situated in the eraseblock number 1. Indexing nodes *A*, *B*, and *C* are situated in the eraseblock number 2. There are also two reserved eraseblocks. Suppose all nodes have the same size equivalent to the size of sector which is 512 bytes in this example.

At snapshot 2 JFFS3 has decided to reclaim 512 bytes of dirty space form the eraseblock number 1. Garbage Collector moves all the valid nodes from the eraseblock number 1 to one of the reserved eraseblocks. But as indexing nodes *B* and *C* still refer old copies of the moved nodes in the eraseblock number 1, this eraseblock cannot be erased so far. Indexing nodes *A*, *B*, and *C* have to be updated first.

At snapshot 3 Garbage Collector has updated indexing nodes *A*, *B* and *C*, putting them to one of the reserved eraseblocks. From now on, old copies of nodes *A*, *B*, *C*, *D*, *E*, *F*, and *G* at eraseblocks 1 and 2 comprise garbage. The eraseblock number 1 was erased and is now free.

But unfortunately, the result is that Garbage Collector made more dirt than it reclaimed space. Indeed, GC reclaimed 512 bytes while produced three times greater amount of garbage (see the first three sectors at eraseblock 2, snapshot 3). Compare snapshots 1 and 2.

Hence, it is obvious that garbage collection in JFFS3 is must be more complex than in JFFS2. Chapter 5 discusses JFFS3 Garbage Collector in details.

3.8 The superblock

The JFFS3 *superblock* is a data structure that describes the file system as a whole and contains important information like the offset of the root node, the journal eraseblocks, etc. When the file system is being mounted, it first finds and reads the JFFS3 superblock.

In case of traditional file systems the superblock usually resides at a fixed position on the disk and may be found very quickly. Conversely, due to the "out-of-place write" flash property it is impossible to assign a fixed position for the JFFS3 superblock. Things are getting even more complex because of the need to provide good wear-levelling – it is incorrect to just reserve several erasable blocks for the superblock unless it is guaranteed that these eraseblocks will not be worn out earlier than the other eraseblocks.

We have the following two requirements that ought to be met in JFFS3:

- JFFS3 must be able to quickly find the superblock;
- the superblock management techniques must not spoil the overall flash wear levelling.

In the classical file systems the superblock usually contains a lot of static data which is rarely updated and the superblock may have any size. In JFFS3, the superblock must be updated quite often (e.g., each time the journal is committed). This means that to lessen the amount of I/O, the JFFS3 superblock should be as small as it is possible, namely, one sector. And there is no reason to keep any static data in the superblock (e.g., the size of the file system, its version, etc). For static data, JFFS3 reserves the first eraseblock of the JFFS3 partition.

Thus, the following terms are used in this document:

- *static superblock* – contains only static data which are never changed by JFFS3; the static superblock resides at the *static eraseblock*; the static eraseblock is the first non-bad eraseblock of the JFFS3 partition; it is supposed that the contents of the static eraseblock may only be changed by external user-level tools;
- *superblock* – contains only dynamic data, is changed quite often and requires special methods to deal with.

JFFS3 has a rather complicated superblock management scheme which makes it possible to quickly find the superblock without full flash scanning when the file system is being mounted. This scheme provides good flash wear-levelling. The superblock lookup should take few milliseconds and scale as $O(\log_2(S))$. For more detailed information about the superblock management scheme see section 6.1.

4 The tree

This chapter discusses the all the aspects related to the main JFFS3 entity – the tree. Please, refer to section 3.4 for basic information about the JFFS3 tree.

4.1 Objects

JFFS3 keeps file system objects in the leaf level of the tree (in leaf nodes) and the following is the list of supported objects.

1. *Data* objects contain files' data and are kept in *data nodes*. Each data node holds one RAM page bytes of data (i.e., `PAGE_SIZE` which is 4K on most 32-bit architectures). But of course, in case of small files (less then one RAM page bytes) and files' tails – less data data may be put to the data node.

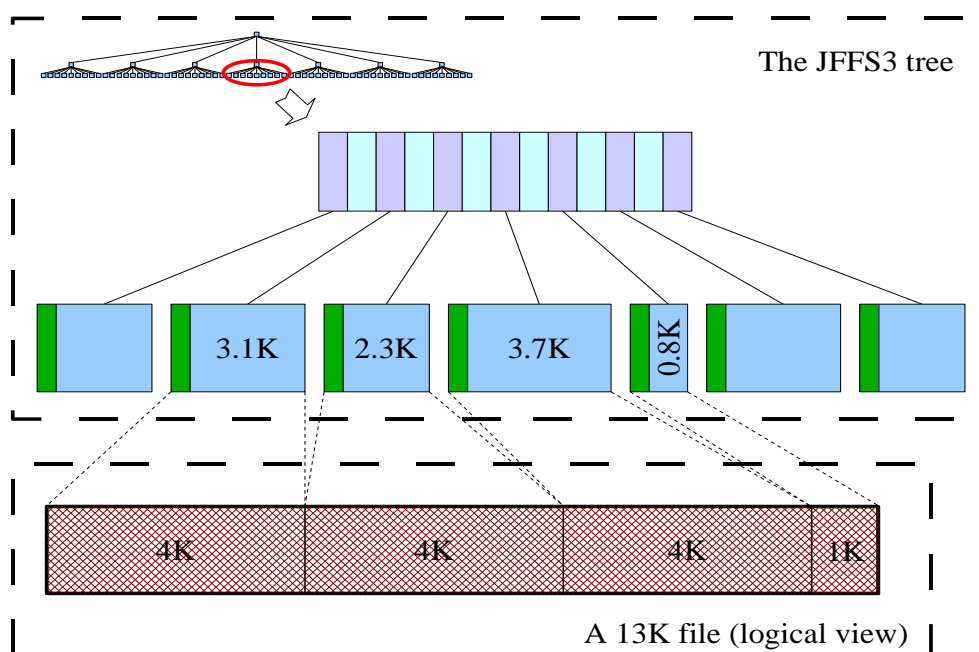


Figure 10: An illustration of files' data representation.

Figure 10 illustrates the correspondence between files' contents and data objects. Each RAM page-size piece of a 13K file corresponds to a data node in the JFFS3 tree. The 1K tail of the file also corresponds to a data node. But because of compression actual sizes of data nodes are less then the corresponding file fragments.

The division on RAM page-sized fragments relates to the Linux Virtual Memory Management architecture. Namely, the Linux *Page Cache* works in terms of RAM pages which means, that JFFS3 is always asked to read and write files' in units of RAM page size.

It is worth noting that in order to optimize flash utilization, JFFS3 may store multiple of RAM page bytes in one data node for static files. This admits of better compression and leads to several other benefits.

2. *Direntry* objects contain the correspondence between directory entry names and inode numbers. *Direntry* objects are stored in *direntry nodes*. Every directory entry in the file system has a corresponding *direntry* object.
3. *Attr-data* objects contain attributes of inodes – both standard Unix attributes like user ID, last modification time, inode length, etc and JFFS3-specific attributes like the type of compression, etc. Each inode has only one corresponding *attr-data* object.
4. *Xentry* objects contain the correspondence between names of extended attributes and *xattr IDs*. Every extended attribute in the file system has a corresponding *xattr* entry object. This is analogous to *direntry* objects, but *direntries* contain $\{\text{direntry name} \Rightarrow \text{inode number}\}$ mapping, instead of $\{\text{xattr name} \Rightarrow \text{xattr ID}\}$ mapping in *xentries*.

Each extended attribute in JFFS3 has its own unique number – *xattr ID*, just like every inode has its own unique inode number. And in fact, JFFS3 utilizes the same space of numbers to enumerate inodes and extended attributes.

Xentry objects are stored in *xentry nodes*.

5. *Xattr-data* objects contain the data of extended attributes. The way how *xattr-data* objects are kept in the tree is equivalent to the way how data objects are kept there. *Xattr-data* objects are stored in *xattr-data nodes*.
6. *Acl* objects contain Access Control Lists (ACL) of inodes (information about ACLs may be found out at [7]). *Acl* objects are stored in *acl nodes*.

In real-world systems a vast number of files have equivalent ACL while only few files have unique ACL. For the former group of files (or more strictly – inodes) JFFS3 makes use of *shared acl* objects. This means, that there is only one *acl* object instance for all of these inodes. Shared *acls* are referred to from *attr-data* objects of these inodes. If a *shared acl* is written to, a new *acl* object is created (copy-on-write mechanism). Conversely, for the latter group there is a distinct *acl* object per each inode.

4.2 Keys

Each object has its own key and may be quickly looked up in the tree by its key. As there are 6 object types in JFFS3, there are also 6 key types:

1. *data keys* – index data objects;
2. *direntry keys* – index *direntry* objects;
3. *attr-data keys* – index *attr-data* objects;
4. *xentry keys* – index *xentry* objects;
5. *xattr-data keys* – index *xattr-data* objects;
6. *acl keys* – index *acl* objects.

4.2.1 Trivial key scheme

Lets start discussing JFFS3 keys with an example of a simple key layout which is further referred to as the *trivial key scheme*. All keys in this scheme have the same 47-bit length (see figure 11).

- Data keys consist of the 32-bit inode number the data belongs to, the unique 3-bit key type identifier, and the 20-bit data offset.
- Direntry keys consist of the 32-bit parent directory inode number, the unique 3-bit key type identifier, and the 20-bit direntry name hash value.
- Attr-data keys consist of the 32-bit inode number the attributes belong to, and the unique 3-bit key type identifier.
- Xentry keys consist of the 32-bit inode number the extended attribute belongs to, the unique 3-bit key type identifier, and the 20-bit extended attribute name hash value.
- Xattr-data keys consist of the 32-bit xattr ID, the unique 3-bit key type identifier, and the 20-bit extended attribute data offset.
- Acl keys consist of the 32-bit inode number the acl object belongs to, and the unique 3-bit key type identifier.

The following is the list of key type identifiers.

1. Data keys – 0 (000 bin);
2. Direntry keys – 1 (001 bin);
3. Attr-data keys – 2 (010 bin);
4. Xentry keys – 3 (011 bin);
5. Xattr-data keys – 4 (100 bin);
6. Acl keys – 4 (101 bin);

Since data objects may only contain multiple RAM pages of data (excluding small files and files' tails) offsets in keys are always RAM page size-aligned. Assuming RAM page is 4K (12 bits), 20 bits is enough to refer up to 4GB of data. To put it differently, the trivial key scheme limits files' length to 4GB providing system's RAM page size is 4K.

It is also worth noting that several objects of the same type may have the same key. For example, in case of hash collision, two direntries may have equivalent keys. In this case objects may be distinguished by means of reading the corresponding leaf node headers.

data key:	inode # (32)	type (3)	offset (20)
direntry key:	parent inode # (32)	type (3)	name hash (20)
attr-data key:	inode # (32)	type (3)	offset (20)
xentry key:	inode # (32)	type (3)	name hash (20)
xattr-data key:	xattr ID (32)	type (3)	offset (20)
acl key:	inode # (32)	type (3)	unused (20)

Figure 11: The trivial key scheme.

4.2.2 Keys comparison

The important topic is how keys are compared as it defines the relative order of objects in the tree and is crucial for searching. Note, it only makes sense to compare keys of the same type.

JFFS3 keys are usually comprised of one or more fields, i.e., keys K_1 and K_2 may be represented as

$$K_1 = \{k_1^1, k_1^2, \dots, k_1^p\}, K_2 = \{k_2^1, k_2^2, \dots, k_2^p\},$$

where p is the number of components in keys of this type.

Keys K_1 and K_2 are considered to be *equivalent* if and only if all their fields are equivalent, i.e. $k_1^i = k_2^i, i = 1, 2, \dots, p$.

Keys are compared field-by-field starting from the first field. If on i 'th step $k_1^i > k_2^i$, then K_1 is considered to be *greater* than K_2 . Similarly, if on i 'th step $k_1^i < k_2^i$, then K_1 is considered to be *less* than K_2 .

4.2.3 Key schemes

Key schemes define layout of keys for all the 6 object types. Apparently, it would be too inflexible to hardcode JFFS3 to support only one fixed key scheme. Indeed, there may be a great deal of reasons why users may want to use different key schemes in different situations – some examples go bellow.

- The inode number is encoded by a 32-bit integer in the trivial key scheme which means that about 4 million inodes and extended attributes may exist on the file system simultaneously. But in some cases this may be insufficient or, conversely, too much and one may want to use less bits to encode inode numbers (say, only 24 bits), just for optimization.

- Similarly, offsets are encoded as 20-bit integers in the trivial key scheme which may be insufficient when huge files (larger than 4G) should be supported. So one may want to use more bits in certain cases.
- Depending on the concrete JFFS3 usage, different hash functions may be used in direntry keys. The length of hash values may also vary depending on how many directory entries are kept in directories. If there are huge directories with millions of files there, long hash values should be used to avoid massive hash collisions (say, 64-bit hash values). But if it is known in advance that there will be no too large directory entries, ² the length of hash values may be shorter.
- It also possible that one may want to use some tricky key layouts to achieve different kinds of optimization. For example, direntry keys may include the first 8 bytes (64 bits) of the direntry name (see figure 12). In this case the `getdents` ³ Linux system call will return direntries in "mostly" alphabetically sorted order and user-space programs will not spend much time to sort them. In fact this technique is used in the Reiser4 file system and it is claimed that slow sorting is a bottleneck in certain real-life workloads. And the like.
- Different keys compression methods may be used in different key schemes (see section 4.2.4 below).

parent inode # (32)	type (3)	name (64)	name hash (19)
---------------------	----------	-----------	----------------

Figure 12: Direntry key layout example.

So it is obvious why JFFS3 is not attached to a fixed key scheme but instead, admits of many different key schemes (one at a time of course) with a possibility to choose the best suited key scheme.

4.2.4 Keys compression

The index is the most frequently re-written part of JFFS3. Indeed, every single change at the leaf level of the tree requires re-writing $L - 1$ indexing nodes. The number of index updates is reduced by the write-behind cache and by the journal, but it is still changed very often. So, it is extremely important for JFFS3 to keep the tree as shallow as it is possible.

This means, that it makes sense to apply a sort of compression to keys in indexing nodes. There are several ways to compress keys and the following are examples of possible compression techniques.

Offsets coding. Offsets compression may be based on the observation that the overwhelming majority of files in many file systems are small files. This means, that it might makes sense to code smaller offsets by fewer bits.

²Note, when talking about directories, words "*large*" and "*small*" describe how many direntries are kept in these directories. The more direntries a directory contains, the larger is it.

³See `getdents` (2) Linux manual pages

Table 1 contains an example of how offsets may be encoded. For offsets in range 0KB–8KB only 3 bits are enough, so the bit sequence "000" will encode offset 0, and the bit sequence "001" will encode offset 4K⁴. Offsets in range 8KB–64KB are encoded by 6 bits and so on.

Offset range	Bits in range	Code prefix	Code length
0KB–8KB	3 bits	00	3 bits
8KB–64KB	6 bits	01	6 bits
64KB–1MB	10 bits	10	10 bits
1MB–128MB	18 bits	110	18 bits
128MB–4GB	23 bits	111	23 bits

Table 1: An example of offset coding.

Inode number coding. If the approximate number of inodes on the file system is known in advance, similar coding scheme may be exploited for inode numbers providing JFFS3 may reuse deleted files' inode numbers.

Common prefix compression. In case of the trivial key scheme the first field of any key is the inode number. Any other key scheme will likely also contain the inode number in keys. If the inode number is the first component of the key, all keys belonging to the same inode will go sequentially in indexing nodes. To put it differently, there will be sequences of keys prefixed by the same inode number in the tree.

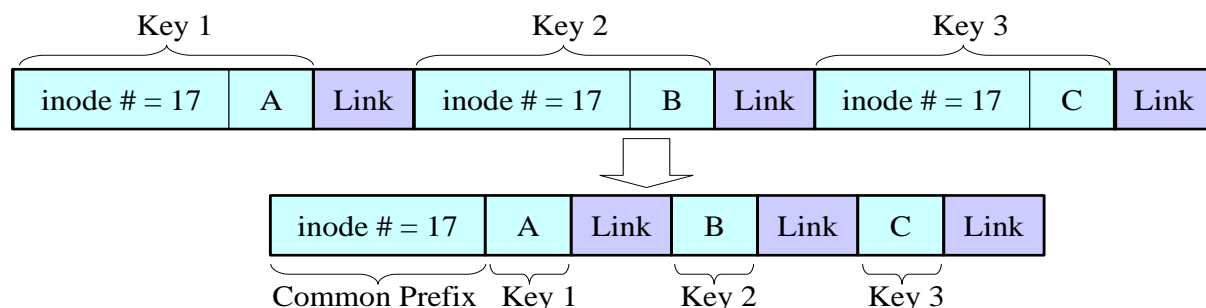


Figure 13: The common prefix compression idea illustration.

The evident compression method for these key sequences is to store the inode number only once as the common prefix for the entire key sequence, instead of duplicating it in every key. Figure 13 illustrates how does the prefix compression work.

Offsets sequence compression. In the trivial key scheme the last field of data keys is the offset. The offset is multiple of RAM page size. Obviously, indexing nodes will contain sequences of keys each of which describes data objects belonging to the same file but with different offsets. Moreover, the keys will be ordered in increasing key order.

⁴Recall, offsets in keys are RAM page-aligned and by default, the RAM page size is assumed to be 4K in this document

For sequences like this it is possible to only specify the starting offset, the ending offset and the number of keys in the sequence, instead of wasting space storing the offset in each key of the sequence.

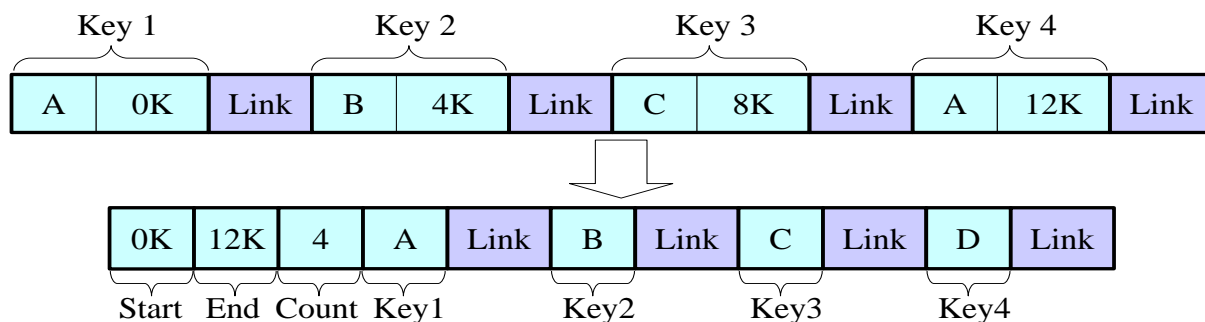


Figure 14: The Offsets sequence compression idea illustration.

Figure 14 presents an example of the offsets sequence compression method. Four consecutive keys which describe four data objects belonging to the same inode may be represented as a sequence of four keys without the offset field, but prefixed by the starting offset, the ending offset and the number of keys in the sequence.

Note, the above compression methods may be combined to achieve better compression.

Because of compression, JFFS3 keys have variable size which means, that it is impossible to directly apply the binary search algorithm to the contents of indexing nodes. In JFFS3, indexing nodes are decompressed when read and are cached in decompressed form. And after the indexing node has been decompressed, the binary search algorithm is applicable.

We believe that keys compression will considerably reduce the amount of on-flash indexing information and increase the overall performance just because the amount of Input/Output will lessen. But only actual fixed-size keys vs. variable-size keys tests will show if there is some real performance gain present.

4.3 Links

Links in JFFS3 have fixed length and are not compressed. The link width depends on the size of JFFS3 partition – the larger is JFFS3 partition, the wider are links. Instead of choosing a huge link width to suit the largest possible file systems (e.g. 64 bits), JFFS3 admits of flexible links width, depending on JFFS3 partition size.

As indexing nodes have fixed size equivalent to one sector, the width of links stored in branch nodes and in the root nodes is

$$w = \log_2 S - s.$$

Twig nodes refer variable-size leaf nodes so the width of links stored in twig nodes is

$$w = \log_2 S,$$

where S is the size of the JFFS3 partition and s is the size of sector.

5 Garbage Collection

Note! JFFS3 Garbage Collection is currently under development and this chapter may be changed. Any suggestions and ideas are welcome.

6 The superblock

6.1 The superblock management algorithm

To implement the superblock management scheme, JFFS3 reserves the second and the third good eraseblocks at the beginning of the flash partition (just next to the static eraseblock). These two eraseblocks are called *anchor eraseblocks*, or the *anchor area*.

Anchor eraseblocks contain references to *chain eraseblocks*. Chain eraseblocks may either refer other chain eraseblocks or the *super eraseblock* (see figure 15). The number of chain eraseblocks varies depending on the size of the JFFS3 partition. If there are k chain erase blocks, the anchor area will refer chain eraseblock 1, which will refer chain eraseblock 2, which will refer chain eraseblock 3 and so forth. The chain eraseblock k will refer the super eraseblock.

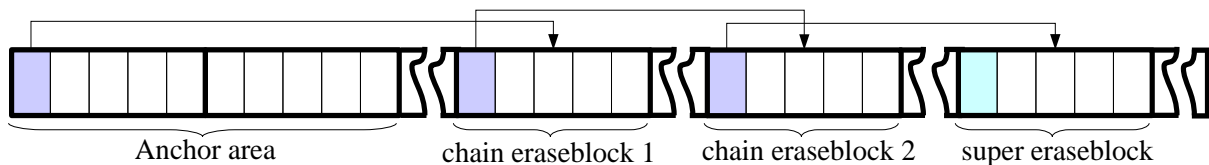


Figure 15: Types of eraseblocks involved to the superblock management scheme.

The super eraseblock contains the superblock which takes *one sector*. The chain eraseblocks contain references to the next chain eraseblock or to the super eraseblock.

The JFFS3 superblock management mechanisms work as follows. Suppose there are k chain eraseblocks in the current superblock management scheme. The superblock updates are written to consecutive sectors of the super eraseblock. When the super eraseblock has no more empty sectors, new super eraseblock is picked, the superblock update is written to the new super eraseblock, and new reference is written to the chain eraseblock k .

Similarly, when there is no space in the chain eraseblock k , new chain eraseblock k is picked and the corresponding reference is written to chain eraseblock $k - 1$, and so on. When there are no free sectors in the chain eraseblock 1, new chain eraseblock 1 is picked and the corresponding reference is written to the anchor area.

Figure 16 presents the example of the superblock management scheme ($k = 2$).

1. Initially, there are 2 chain eraseblocks (numbers 5 and 419) and the super eraseblock (number 501). There is a reference in the first sector of the anchor area which refers the chain eraseblock 1. The first sector of the chain eraseblock 1 refers the chain eraseblock 2, and the first sector of the chain eraseblock 2 refers the super eraseblock. The first sector of the super eraseblock contains the superblock.
2. After the superblock has been updated, the second sector of the super eraseblock contains the valid copy of the superblock and the first sector contains garbage.

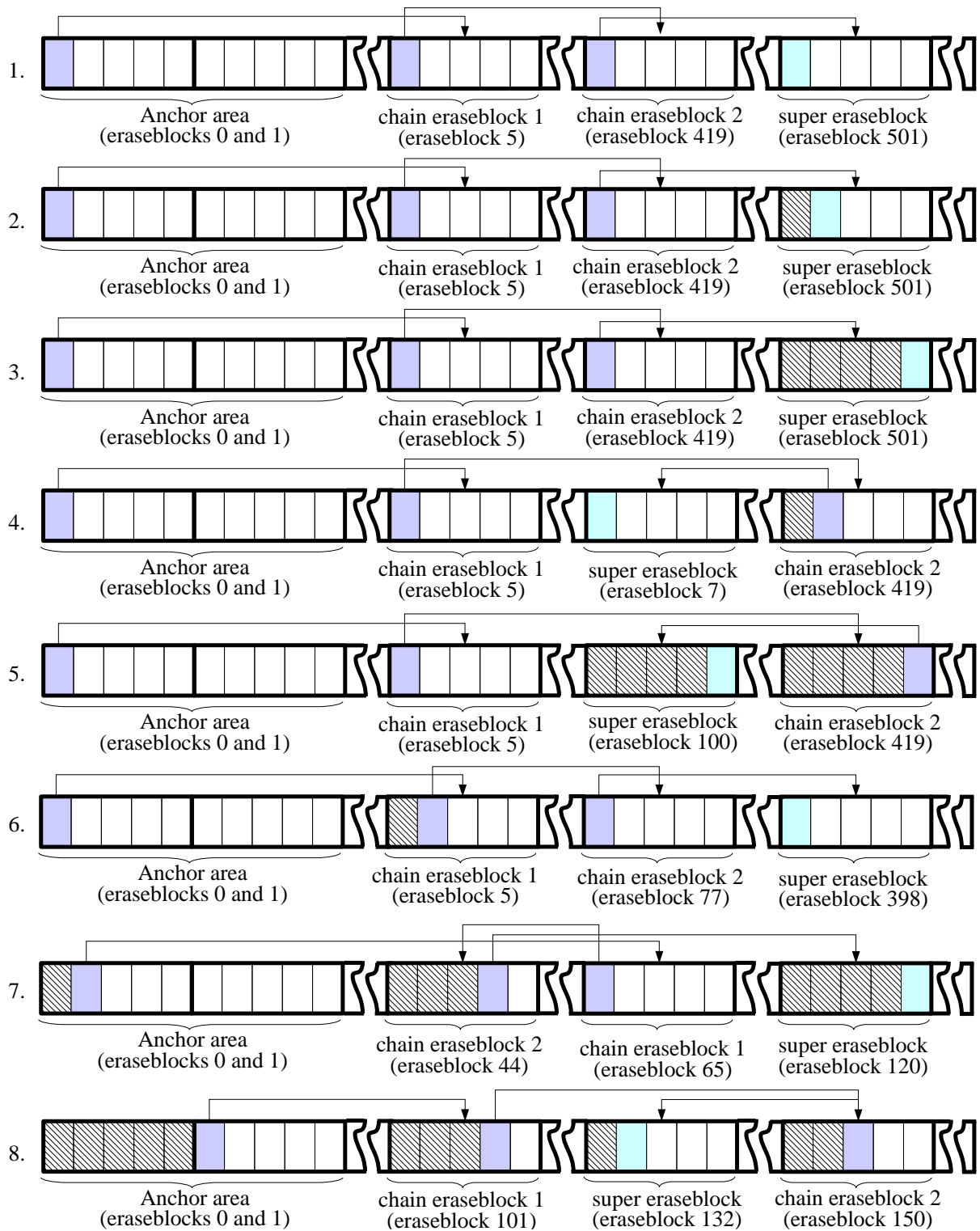


Figure 16: The superblock management example.

3. The superblock has been updated many times and the valid superblock is at the last sector of the super eraseblock while the other sectors of the super eraseblock contain garbage.

4. As there were no free sectors at the super eraseblock, new super eraseblock was chosen (eraseblock number 7) and the superblock update was written to the first sector of the new super eraseblock. As the super eraseblock changed its position, the corresponding reference at the chain eraseblock 2 was updated. It was updated out-of-place and now the first sector of the chain eraseblock 2 is dirty while the second sector contains the valid reference to the new super eraseblock.
5. The superblock has been updated many times and the super eraseblock changed its position many times and it is currently at the eraseblock number 100. The reference to the super eraseblock was also updated many times and at the moment the last sector of the chain eraseblock 2 contains the valid reference while the other sectors are obsolete. Similarly, the last sector of the super eraseblock contains valid superblock while the other sectors are obsolete.
6. When the next superblock update came, there were no free sectors at the super eraseblock and new super eraseblock was picked (eraseblock number 398) and the valid copy of the superblock is currently at the first sector of the eraseblock number 398. Also, there were no free sectors at the chain eraseblock 2 and new chain eraseblock 2 was picked (eraseblock number 77), so the first sector of the eraseblock 77 contains the valid reference to the super eraseblock. Since the chain eraseblock 2 changed its position, the corresponding reference at the chain eraseblock 1 was updated and at the moment the second sector of the chain eraseblock 1 contains the valid reference to the chain eraseblock 2 while the first sector is dirty.
7. And analogously, after many superblock updates, the chain eraseblock 1 was updated many times and when it became full it changed its position. Sure, the chain eraseblock 2 and the super eraseblock changed their positions many times as well. So, at the moment, the chain eraseblock 1 is at the eraseblock number 65, the chain eraseblock 2 is at the eraseblock 44 and the super eraseblock is at the eraseblock 120. When the chain eraseblock 1 changed its position, the corresponding reference at the anchor area was updated and currently the second sector of the anchor eraseblock 1 contains the valid reference to the chain eraseblock 1 while the first sector is dirty.
8. And even more superblock updates happened. The anchor area was updated many times. When there were no free sectors at the anchor eraseblock 1, the anchor eraseblock 2 was used. So, at the moment, the valid reference to the chain eraseblock 1 is at the first sector of the anchor eraseblock 2. From now on, the first anchor eraseblock may be erased and may be used again when the second anchor eraseblock is full.

The following are important notes about the JFFS3 superblock management.

- The superblock takes one sector so the super eraseblock may be updated at most N times (N is the number of sectors in the eraseblock).
- In case of NAND flash, the sector is the real minimal physical input/output unit, so only N updates are possible in anchor eraseblocks and in chain eraseblocks. But if the real input/output unit is smaller than the sector (i.e., if JFFS3 works on top of

NOR flash) the advantage of this may be used and more references may be packed into one anchor or chain eraseblock.

- When JFFS3 picks new chain/super eraseblock, the common JFFS3 wear-levelling scheme is utilized.
- Anchor area has 2 eraseblocks in order to ensure the tolerance to unclean reboots – one anchor eraseblock may be safely erased while the other is being used.
- When a new reference is written to anchor/chain eraseblocks, the previous reference becomes dirty and on mount JFFS3 should find the valid reference. To facilitate this, each reference has its version number. Each subsequent reference has higher version than the previous. Hence, JFFS3 may use the binary search algorithm to quickly find the valid reference.
- As unclean reboot may happen anytime, no anchor/chain/super eraseblocks are erased before the whole chain has been updated. This makes it possible to recover from unclean reboots if they happen while the chain of the superblock-related eraseblocks is being updated.

6.2 The length of the chain

The number of required eraseblocks in the superblock management scheme depends on the size of the JFFS3 partition. The larger the partition, the more levels are needed. This is determined by the need to ensure that the anchor area is not worn out earlier than the rest of the JFFS3 partition.

Denote the number of required chain eraseblocks plus one (the super eraseblock) m and calculate m assuming the worst case scenario: any file system data update requires the superblock update. This would correspond to synchronous JFFS3 operation mode with zero-length journal.

Obviously, what is wanted is to be sure that the anchor area is not worn out earlier than the data area, i.e. the following inequality should be true:

$$\frac{T_A}{T_D} \geq 1, \quad (1)$$

where T_A is the period of time of the total anchor area wear and T_D is the period of time of the total data area wear. Note, the whole JFFS3 partition excluding the static superblock and the anchor area is referred to as the *data area*.

If R_A is the average rate of the anchor area updates (sectors per second), R_D is the average rate of the data area updates and N is the number of sectors per the eraseblock, then the anchor area will be written to with rate R_A/N eraseblocks per second and the data area will be written to with the rate R_D/N eraseblocks per second. So, JFFS3 will need to erase R_A/N eraseblocks per second in the anchor area and R_D/N eraseblocks per second in the data area. Therefore, T_A and T_D may be expressed as

$$T_A = \frac{2D \cdot N}{R_A},$$

$$T_D = \frac{(M - 3) \cdot D \cdot N}{R_D},$$

where D is the maximum number of flash eraseblock erase cycles, and M is the number of non-bad eraseblock on the JFFS3 partition. We subtracted 3 from M to get the number of eraseblocks in the data area.

$$\frac{T_A}{T_D} = 2 \cdot \frac{R_D}{(M-3) \cdot R_A}. \quad (2)$$

If $m = 0$, i.e., there are no chain/super eraseblocks and the superblock is stored in the anchor area, then taking into account (2) and that in this case $R_A = R_D = R$, we have

$$\frac{T_A}{T_D} = \frac{2}{(M-2)}.$$

Suppose $m = 1$. i.e., there are no chain eraseblocks and only the super eraseblock is used. In this case each file system data update will require (a) the superblock update in the data area and (b) the anchor area update. Therefore, the anchor area will be written N times less frequently than when $m = 0$ and the data area will be written 2 times more frequently than when $m = 0$. This means, that $R_A = R/N$ and $R_D = 2R$ and from (2) we have

$$\frac{T_A}{T_D} = 2 \cdot \frac{2N}{M-3}.$$

When $m = 2$, i.e. the chain eraseblock 1 and the super eraseblock are used, the anchor area will be written N^2 times less frequently, while the data area will be written $2 + 1/N$ times more frequently than when $m = 0$ (one superblock update on each file system update and one chain eraseblock 1 update per N superblock updates). Therefore, $R_A = R/N^2$ and $R_D = (2 + 1/N) \cdot R$ and from (2) we have

$$\frac{T_A}{T_D} = 2 \cdot \frac{2N^2 + N}{M-3}.$$

For $m = 3$, analogously,

$$\frac{T_A}{T_D} = 2 \cdot \frac{2N^3 + N^2 + N}{M-3},$$

and for $m = 0, 1, 2, \dots$

$$\frac{T_A}{T_D} = 2 \cdot \frac{2N^m + N^{m-1} + \dots + N}{M-3}.$$

Consequently, from (1) we have the following inequality:

$$2 \cdot \frac{2N^m + N^{m-1} + \dots + N}{M-3} \geq 1,$$

or neglecting the minor components,

$$\frac{4N^m}{M-3} \geq 1,$$

or

$$m \geq \log_N \frac{M-3}{4}. \quad (3)$$

Thus, from (3) it is obvious that the JFFS3 superblock management scheme scales logarithmically.

Table 2 shows the value of m for different types of existing NAND flashes (see [10], [11], [12], and [13]).

Type	Size	Sect. size	M	N	m
Toshiba TC58DVM92A1FT	64MB	16KB	4096	32	2
Toshiba TH58NVG1S3AFT05	512MB	128KB	4096	64	2
ST Micro NAND08G-B	1GB	128KB	8192	64	2
Samsung K9K1G08X0B	2GB	128KB	16384	64	2

Table 2: The length of the JFFS3 superblock management chain for different types of existing NAND flashes.

Note, providing that $N = 64$, $m = 3$ is enough to guarantee acceptable anchor area wear leveling for up to 128GB flash, $m = 4$ – for up to 8TB flash (the inequality 3).

6.3 The superblock search

To find the superblock during mount, JFFS3 finds the valid reference in the anchor eraseblocks, then finds the valid reference in chain erase blocks 1, 2, ..., $m - 1$, and finally finds the valid superblock in the super eraseblock. Since JFFS3 assigns versions to records in anchor/chain/super eraseblocks and the versions are increased by one on every update, the binary search algorithm may be used to quickly find the valid sector.

The valid reference in the anchor area may be found after $\log_2(2N) + 2$ steps (one step involves one sector read operation), the reference in chain/super eraseblocks – after $\log_2(N) + 2$ steps. Thus, to find the superblock, JFFS3 must read

$$S = 2m + \log_2(2N) + (m - 1) \cdot \log_2(N)$$

sectors.

Table 3 contains the approximate superblock search time for different existing NAND flashes ⁵.

Type	Size	N	m	Sect. read	S	SB find
Toshiba TC58DVM92A1FT	64MB	32	2	$\sim 50\mu s$	22	$\sim 1.1ms$
ST Micro NAND08G-B	1GB	64	2	$\sim 130\mu s$	25	$\sim 3.3ms$
Samsung K9K1G08X0B	2GB	64	2	$\sim 70\mu s$	25	$\sim 1.6ms$

Table 3: The superblock search time for different existing NAND flashes.

⁵the calculated superblock search time does not contain the ECC/CRC checking overhead as well as any other CPU overhead.

For larger flash chips which would utilize the superblock management scheme with $m = 3$ (no such flashes exist at the moment), the superblock search time would be about 4.3ms, providing the flash characteristics are the same as ST Micro's (see table 3).

7 Issues/ideas/to be done

This section contains a temporary list of issues which should be solved, ideas which should be thought and analyzed deeper or things which were thought about but are not yet described in this document.

The following is the list of things which should be thought about more.

1. Quota support. Will quota be supported? How will it look like – lust generic linux quota or something better?
2. Transactions:
`transaction_open()/do_many_fs_modifications()/transaction_close()` semantics? Reiser4 pretends to support this via special `sys_reiser4()` syscall. Would be nice.
3. How can one select the compression mode on the per-inode basis? Xattrs with some reserved name?
4. Orphaned files.
5. Holes.
6. Direct I/O.
7. How to chose/add a key scheme?
8. Extents.

The following is the list of topics which should be highlighted in this document as well.

1. Garbage collection.
2. Tree balancing.
3. Tree locking.
4. Caching, write-behind cache.
5. An assumed flash model and the model of interactions between JFFS3 and the flash I/O subsystem.
6. How the track of eraseblocks will be kept? Space accounting, good/bad, erase count?
7. The wear-levelling algorithms.
8. The format of keys.

9. Branch nodes' links are sector numbers, twig nodes' links are absolute flash offsets. So, the length of twig and branch keys are different and branches have greater fanout.
10. Different optimizations may be achieved by means of changing the format of keys. So, JFFS3 should be flexible in this respect and have a mechanism to change/select the formats of keys.
11. The minimal amount of file's data in a node is `PAGE_SIZE`. No way to create smaller nodes as it is possible in JFFS2.
12. Portability (e.g., move FS between machines with different RAM page size, etc).
13. Errors handling.
14. Bad blocks handling.

The following is the list of ideas which were thought about but are not yet in the document.

1. If the compression is disabled for an inode, then its nodes are (`PAGE_SIZE` + header size) in size, i.e., they do not fit into integer number of flash sectors. For these nodes we may keep the header in the OOB area. In this case we should not mix compressed nodes and uncompressed nodes in one eraseblock.
2. For large files which are mostly read-only, we may fit more than one page of data in one node. This will make compression better. When the file is read, all the uncompressed pages are propagated to the page cache, like in the zisofs file system.
3. If there are few data in the superblock, we may keep this data in the root node. In this case the root will have smaller fanout than branches.

The "to do" list.

1. Re-calculate digits for SB search time and m .
2. For now only the idea of keys compression methods is provided. Would be nice to describe algorithms more strictly.

8 Definitions

1. **Access Control Lists, ACL** – a modern mechanism to control accesses to files which provides much more flexibility than the standard Unix mechanism of owner/group/others permissions, see [7] for more details.
2. **Acl** – an object in the tree containing inode's ACL. Refer to section 4.1 for more information.
3. **Acl key** – acl object's key.
4. **Acl node** – a leaf node containing an acl object.

5. **Anchor eraseblock, anchor area** – the second and the third *good* eraseblocks of the JFFS3 partition which are reserved for the superblock management. See section 6.1 for more details.
6. **Attr-data** – an object in the tree where inode’s attributes are stored (standard Unix attributes like creation time, owner ID, etc and other attributes like the type of compression, etc). Refer to section 4.1 for more information.
7. **Attr-data key** – attr-data object’s key.
8. **Attr-data node** – a leaf node containing an attr-data object.
9. **B-tree** – a balanced search tree where each node has many children. See section 3.3.
10. **B⁺-tree** – a B-tree where no data is stored in non-leaf nodes but instead, is stored only in leaf nodes.
11. **Branch node** – any node that is not leaf, not twig and not root.
12. **Branching factor** – the branching factor of the B-tree is the number of children of a node.
13. **Chain eraseblock** – an eraseblock containing references to other chain eraseblocks or to the super eraseblock. Chain eraseblocks facilitate quick SB searching and are the part of the JFFS3 superblock management scheme (see section 6.1). The main reason why chain eraseblocks are needed is the need to provide good flash wear-levelling.
14. **Clean eraseblock** – an eraseblock which contains no garbage, only valid information.
15. **Data area** – the whole JFFS3 partition excluding the static superblock and anchor eraseblocks.
16. **Data key** – data object’s key.
17. **Data node** – a leaf node with file’s data.
18. **Directory entry, direntry** – basically an association between the name and the inode number.
19. **Direntry key** – direntry object’s key.
20. **Direntry node** – a leaf node containing a direntry object.
21. **Dirt, dirty space** – information on flash which is not valid due to out-of-place updates or objects deletion. It is the aim if the Garbage Collector to reclaim the space occupied by dirt.
22. **Dirty eraseblock** – an eraseblock which contains some dirt along with valid nodes.
23. **Dirty sector** – a sector which contains dirt.

24. **Erasable block, eraseblock** – the minimal erasable unit of the flash chip from the JFFS3's viewpoint.
25. **Extended attributes, xattr** – an association between names and data for files and directories. See `attr(5)` Linux manual pages for more information.
26. **Fanout** – the same as **branching factor**.
27. **Free eraseblock** – an erased eraseblock (contains only `0xFF` words).
28. **Garbage** – the same as **dirt**.
29. **Garbage Collector** – a part of any Flash File System which is responsible for recycling dirty space and producing free eraseblocks.
30. **Indexing information, index** – data structures which do not contain any file system data (files, directories, extended attributes, etc) but instead, keep track of this data. For example, indexing information allows to quickly find all the directory entries for any specified directory. In case of the FAT file system, the File Allocation Table is may be treated as the index, in case of the ext2 file system the inode table, the bitmap and the set of direct, indirect, doubly indirect and triply indirect pointers may be considered as the index. In JFFS3, the index is comprised by the indexing nodes. See section 3.4 for more information.
31. **Indexing eraseblock** – an eraseblock which contains indexing nodes.
32. **Indexing node** – a non-leaf node. Indexing nodes have fixed size (one sector) and contain only keys and links.
33. **In-place updates, in-place writes** – a method of updating on-media data when the update is written to the physical position where the data resides (in opposite to out-of-place updates).
34. **Journal** – contains recent JFFS3 changes and all the file system updates first go to the journal. The purpose of the Journal is to accumulate a bunch of JFFS3 file system changes and to postpone updating the index. See section 3.6 for more information.
35. **Journal commit** – the process of re-building the indexing information for the data which is in the journal. After the journal has been committed the journal eraseblocks become just leaf eraseblocks.
36. **Journal eraseblock** – an eraseblock containing the journal data.
37. **Journal tree** – an in-memory tree referring Journal nodes which were not committed so far. When JFFS3 reads, it first looks up the journal tree to find out whether the searched information is there. See section 3.6 for more details.
38. **Key** – an identifier of objects in the tree.
39. **Key type** – an unique identifier of the key type. There are 6 key types in JFFS3 (see section 4.3).

40. **Leaf eraseblock** – an eraseblock containing leaf nodes.
41. **Leaf node** – any node from the leaf level of the tree (level 0). Leaf nodes contain only data and do not further refer other nodes. For more information see section 3.4.
42. **NAND page** – a basic input output unit of NAND flash chips. ECC is calculated on the per-NAND page basis. See any NAND flash manual for more details, e.g., 10.
43. **Node** – a pile of the tree (the tree consists of nodes) as well as the container for file system data. There are different types of nodes in JFFS3. For more information see section 3.4.
44. **Obsolete nodes/data/sectors** – the same as **dirty** nodes, data or sectors.
45. **Out-of-place updates, out-of-place writes** – a sort of data updates when the update is not written to the same physical position, but instead, is written to some other place and the previous contents is treated as garbage afterwards. Opposite to in-place updates.
46. **RAM page** – an unit of memory management in Virtual Memory Management subsystem of most modern operating systems (including Linux). See [9] for more information.
47. **Sector** – the smallest writable unit of the *flash chip* from JFFS3's viewpoint. May be equivalent to the minimal physical input/output unit (like in case of NAND flashes) or larger (like in case of NOR flashes).
48. **Shared acl** – an acl object which is shared by many inodes for optimization purposes. Refer to section 4.1 for more information.
49. **Static eraseblock** – the first good erasable block of the JFFS3 partition where the file system static data is stored. JFFS3 may only read it and it is created/changed by external formatting tools.
50. **Superblock** – a data structure which describes the whole JFFS3 file system. Only dynamic data is stored in the superblock, all the static data is kept in the static superblock. There is a comprehensive superblock management scheme in JFFS3, see section 6.1.
51. **Super eraseblock** – an eraseblock where the superblock is kept. See section 6.1 details.
52. **Target eraseblock** – the eraseblock which is currently being processed by the Garbage Collector, i.e., nodes are moved from the *target eraseblock* and it is erased afterwards.
53. **Quota** – a mechanism which allows to assign different limits on the file system (e.g., restrict users in the number of files they may create or in the amount of space they may consume, etc). See [8] for more details about quota support in Linux.
54. **Tree** – the main entity JFFS3 design revolves about. The JFFS3 tree is a wandering B^+ -tree where all the file system stuff (files, directories, extended attributes, etc) is stored.

55. **Twig nodes** – nodes which reside one level upper than leaf nodes (level 1).
56. **Valid nodes** – nodes which contain actual information, non-obsolete nodes.
57. **Wandering tree** – a method of updating trees when there is no possibility to perform in-place updates. The JFFS3 tree is a wandering B^+ -tree. See section 3.2 for more information.
58. **Xattr** – a widely used contracted form for **extended attributes**.
59. **Xattr-data** – an object in the tree containing the data of an extended attribute.
60. **xattr-data key** – xattr-data object's key.
61. **Xattr-data node** – a leaf node containing an attr-data object.
62. **Xattr ID** – an unique identifier of an extended attribute. Refer to section 4.1 for more information.
63. **Xentry** – an object in the tree which stores the association between the name of an extended attribute and its xattr ID. Refer to section 4.1 for more information.
64. **Xentry key** – xentry object's key.
65. **Xentry node** – a leaf node containing a xentry object.

9 Symbols

The following is the list of symbols which are used to denote different things throughout this document.

- D – the number of guaranteed erases of flash eraseblocks (typically $\sim 10^5$ for NAND flashes);
- $H()$ – the hash function JFFS3 uses to calculate names' hash for keys.
- I – inode number.
- K, K_x – tree's keys.
- k, k_x – keys' fields.
- L – the number of levels in the tree.
- m – the number of eraseblocks used in the superblock management scheme without the anchor eraseblocks, i.e. the number of chain eraseblocks plus one (the super eraseblock).
- M – the total number of non-bad eraseblocks on the JFFS3 partition.
- n – the branching factor (fanout) of the tree.
- N – the number of sectors per eraseblock.

- S – the size of the JFFS3 flash partition (assuming there are no bad block).
- s – the size of sector.
- w – the bit-width of links.

10 Abbreviations

1. **ACL** – Access Control List
2. **ECC** – Error Correction Code
3. **CRC** – Cyclic Redundancy Check
4. **JFFS2** – Journalling Flash File System version 2
5. **JFFS3** – Journalling Flash File System version 3
6. **MTD** – Memory Technology Devices
7. **RAM** – Random Access Memory
8. **VFS** – Virtual File System

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