Freescale MQX™
Flash File System User Guide

MQXFFSUG
Rev. 1.4
02/2014

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Document Number: MQXFFSUG
Rev. 1.4, 02/2014

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Chapter 1 Introduction

1.1 Purpose

This document describes the architecture of the MQX Wear Leveling module and its interface for the upper layer such as MFS and Read/Write raw operations.

As a result of significant differences between NAND flash memory and NAND controller in Freescale CPUs, this document only addresses a Wear Leveling solution for the CPU that is compatible with the NAND flash memory (NFC hardware).

The MQX Wear Leveling module currently supports all platforms on MQX RTOS that have the NAND flash device.

1.2 Wearout Problem on Flash Memory

Flash memory is a non-volatile memory that can be easily erased and reprogrammed when compared to some predecessor memories such as EEPROM. Flash memory is popular as a result of its small physical size, light weight, low power consumption, high shock resistance, and fast read performance. Currently there are two types of flash memory: NAND flash memory and NOR flash memory.

NAND flash memory is organized as an array of blocks. Each block contains 32 to 64 pages, where a page is the smallest unit for read and write operation. On the other hand, to erase, the input must be a block rather than a pages.

On the other hand, NAND flash memory has a limited number of program/erase cycles (typically known as P/E cycles). Today the most available flash products in the market are designed to endure around 100,000 P/E cycles before the cells become unreliable. This phenomenon is called memory wear or wearout.

1.3 Solution to Avoid Wearout Issues

To control the wear-out problem and to extend NAND flash lifetime, a method named *wear leveling* is used. Wear leveling tries to distribute every program/erase operations equally on each block in the flash drive. The equal distribution is done by an internal re-mapping mechanism between logical/physical block address and writing strategy. The wear leveling writes all new or updated data to a free block, which is picked from a head of the free block FIFO, then erases the old data block and eventually puts this erased block to the end of the free block FIFO. This process is done in the background and, for that reason, is completely transparent to the host system.

1.4 Outline

The outline of this document is as follows:

- Section 1 – Introduces the purpose of this project and the brief overview of NAND flash memory and wear leveling.
- Section 2 – Abbreviations and acronyms and reference are used in this document.
- Section 3 – Architecture overview.
- Section 4 – Using MQX NAND Flash Wear Leveling module.
- Section 5 – Functionalities of Wear Leveling module in this project.
- Section 6 – Internal software flow for Wear Leveling module.

Chapter 2 Abbreviations, Acronyms, and References

2.1 Abbreviations, Acronyms

Table 2-1. Acronyms and Abbreviations

Acronym	Description
API	Application Programming Interface.
BM	Bare Metal.
HW	Hardware.
IF	Interface.
App	Application.
NAND	In NAND flash memory, users access (read/write) through each page as a minimum unit and erase on each blocks.
NOR	NOR flash memory lets users be able to random-access in every bytes in flash memory.
Block	A smallest erasable unit in NAND device.
Page	A smallest programmable unit in NAND device.
Physical Block Address (PBA)	The address of physical block in memory.
Virtual Block Address (VBA)/Logical Block Address (LBA)	Since we used entire flash memory for wear leveling, the VBA is same as LBA. This address points to a logical address, which are mapped to specific PBA.
Wearout	A circumstance occurs when a block is uneraseable or a page cannot be written.
Wear leveling	Wear leveling is a process that helps reduce premature wear in NAND flash devices.
Bad Block	A block resist in NAND flash memories, that cannot be erase or write any more.
Metadata	Data is used by NAND driver to carry a specific information.
Sparedata	An area is typically used for ECC, wear leveling, and other software overhead functions.
NFC	NAND Flash Controller.
NAND driver	A driver which is responsible for initializing and handling read/write/erase through NAND memories.
ONFI	Open NAND Flash Interface.
Error Correcting Code – ECC	A code or checksum for automatically correcting purpose. An ECC stores in Metadata/sparedata of each pages.

Table 2-1. Acronyms and Abbreviations

Acronym	Description
M53015_Longjing	Evaluation Board for ColdFire MCF5301X CPU. This board contains 8M x 16 bit NOR flahs memory.
M54455_Redstrip	Evaluation Board for ColdFire MCF5445X CPU. This board contains 02 NOR flash memories (16 MB, 512 KB).
M54418_Modelo	Evaluation Board for ColdFire MCF5441X CPU. FSOFT uses TWR-MCF5441X for testing purpose, this board also contains 2Gb NAND flash memory.

2.2 References

Table 2-2. References

Serial No	Document Name	Version
1	MQX RTOS Source Code	4.0.2
2	Freescale MQX™ I/O Drivers User Guide	Rev. 9
3	MCF5441x Reference Manual	Rev. 4
4	K70P256M150SF3RM Reference Manual	Rev. 2
5	K60P144M150SF3RM Reference Manual	Rev. 2
6	Datasheet for 2Gb NAND Flash: 29F2G16AABWP	
7	Vybrid Reference Manual	

Chapter 3 Architecture Overview

3.1 Old NAND Flash Architecture

The current Freescale MQX NAND flash architecture contains two key components: NAND driver and NAND Flash Controller – NFC.

- NAND driver: Generally, this driver offers functions such as read, write, erase, raw and IOCTL operations for upper layer.
- NAND Flash Controller – NFC: This layer providers the NAND HW abstraction, which allows the hardware independent implementation of higher layers, that is, NAND driver.

The architecture of NAND flash driver in MQX can be seen in the figure below:

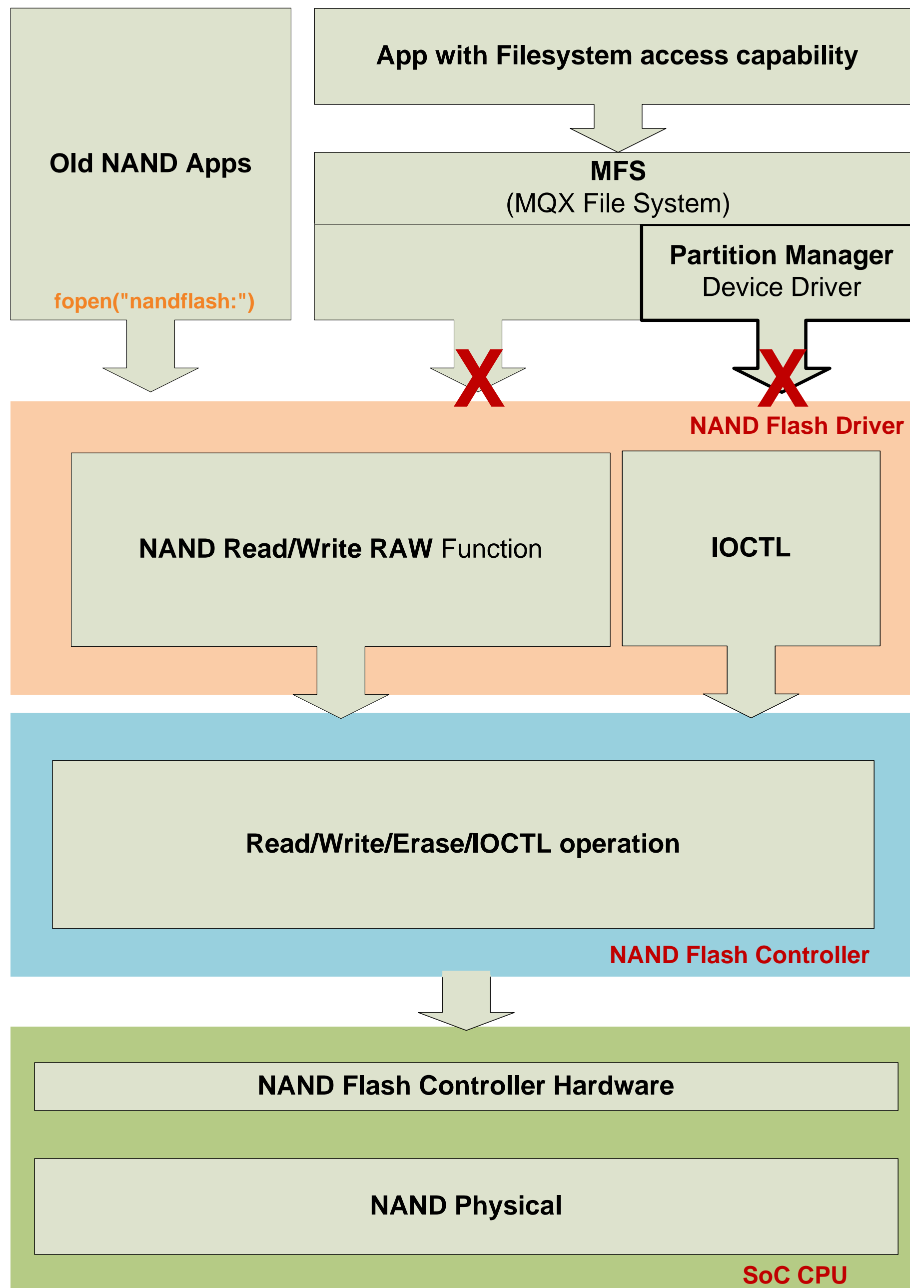


Figure 3-1. Old NAND Architecture

All NAND applications could be interactive with NAND flash driver through I/O driver with signature "nandflash:." The smallest unit that NAND apps can read/write is Virtual Page Address – VPA. The VPA points to exactly one physical address on NAND memory. However, a size of each page in NAND Apps/NAND driver is not the same as a page in NAND physical memory. The difference is a result of a divider in the NFC hardware. For example:

TWR-MCF54418 board uses MT29F2G16AABWP as NAND physical memory. The organization of NAND in this instance is as follows:

- Device size: 2Gb = 256MB
- Page size: 2112 bytes (2048 bytes for user's data + 64 bytes for spare data)
- Block size: 64 pages (135,168 bytes = 132KB)

By setting up the NFC HW register, the user can logically split the physical page size to a smaller one. This configuration can be done by modifying NFC_CFG[PAGECNT] register. For example: if we set NFC_CFG[PAGECNT] to 4, a physical page size will be divided into 4 virtual pages with size 2112B/4 = 528B in each. By doing so, user applications can handle smaller page size easily.

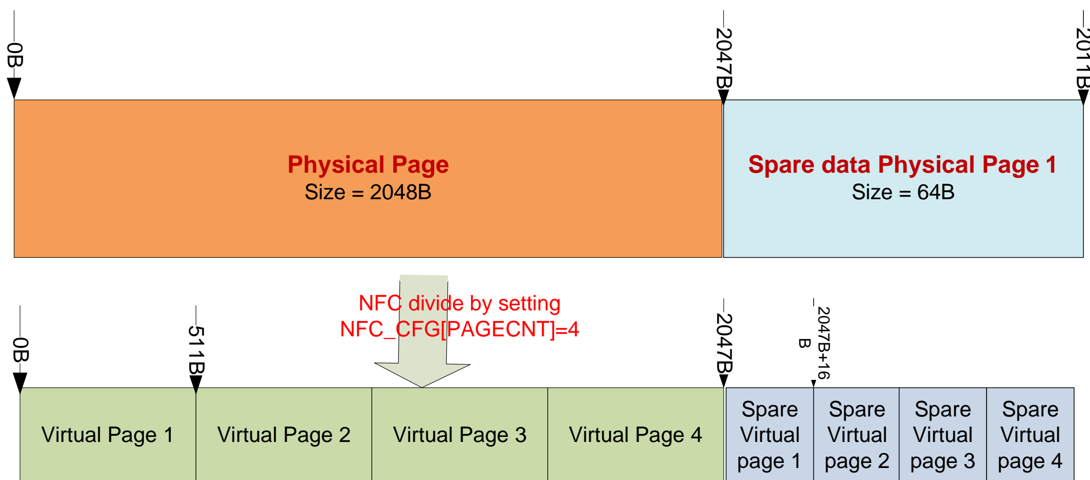


Figure 3-2. Difference between NAND Physical Organization and Virtual Organization

NAND driver currently does not support MQX MFS because of the follwing:

- Getting Block Size in IO_IOCTL_GET_BLOCK_SIZE command: NAND driver does not return a correct block size in bytes (MQX MFS needs a block size in bytes, which can be used for read/write operations).
- Identifying a total sector of storage devices through an IOCTL command (IO_IOCTL_GET_NUM_SECTORS): Currently, NAND driver does not implement this IOCTL command.

3.2 New Architecture with Wear Leveling – WL Capability

This solution focuses on a few modifications about MQX NAND flash driver and NAND Flash Controller. It helps MFS (MQX File System) to run on top of NAND flash memory device and makes NAND flash memory device not wear out too quickly. This solution also allows the new applications to run along with the old ones, which are used to access raw data on NAND physical.

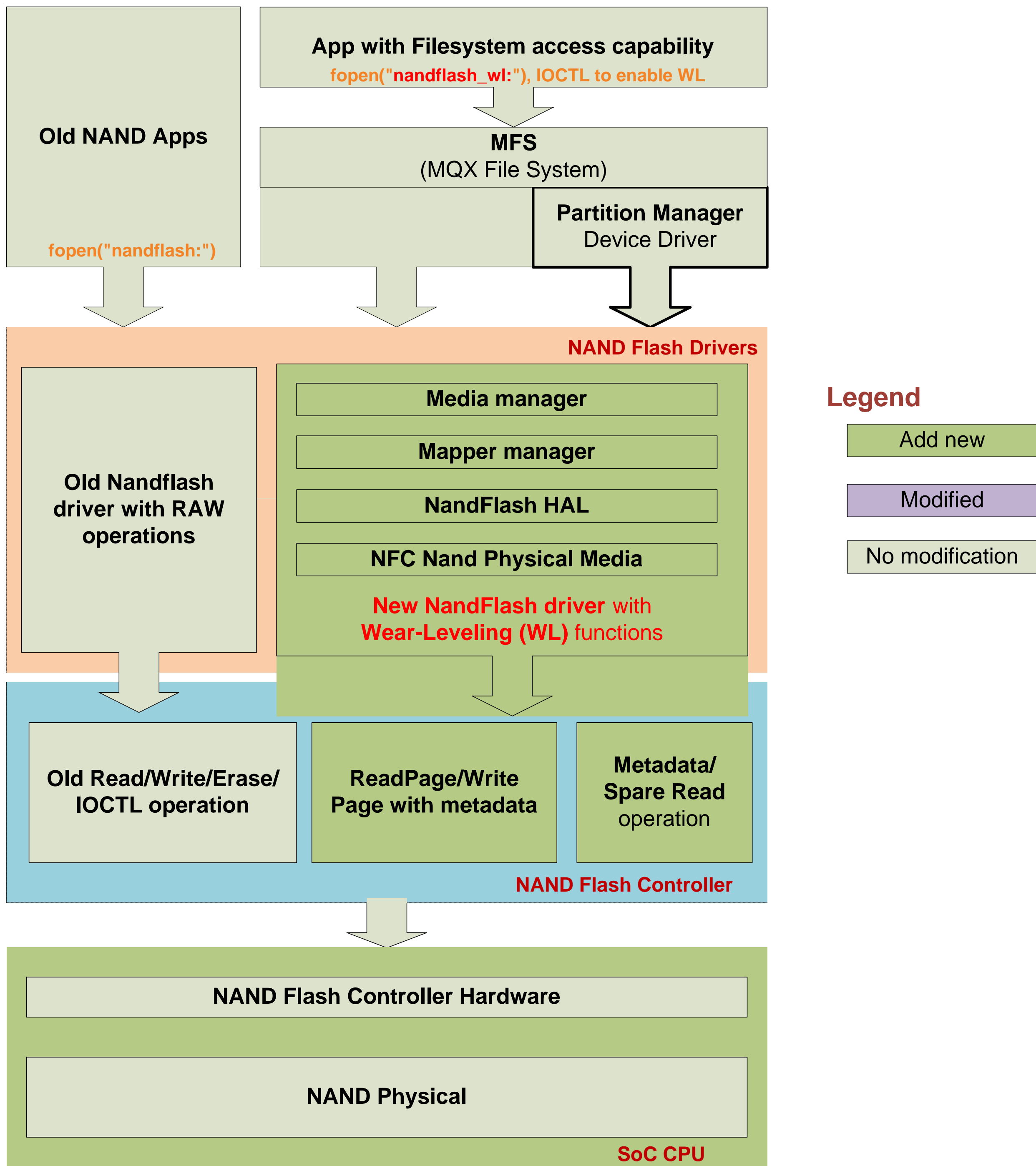


Figure 3-3. New NAND Architecture with Wear Leveling Capability

In this figure:

- NAND flash driver
  - Old NAND flash driver: provides read/write raw function for all legacy applications.

— New NAND flash driver with Wear Leveling: supplies read/write with wear-leveling capability for upper layers such as MFS.
  – Wear Leveling functions: this module contains all mapping mechanisms between Virtual Page Address and Physical Page Address. It also maintains mapping tables on flash memory and RAM.

• NAND Flash Controller (NFC)
  — Read/Write/Erase/IOCTL operation: old NFC's function for read/write/erase directly with NFC hardware. These functions work only with Virtual Page data.
  — ReadPage/WritePage with metadata: add new function for read/write page's data and metadata.
  — Metadata/Spare Read/Write operation: add new functions for handling spare data, which is used on Wear Leveling module. These functions simply read/write metadata of each pages from spare area.
  — In this new architecture, organization of virtual pages in physical pages is different with the old architecture.

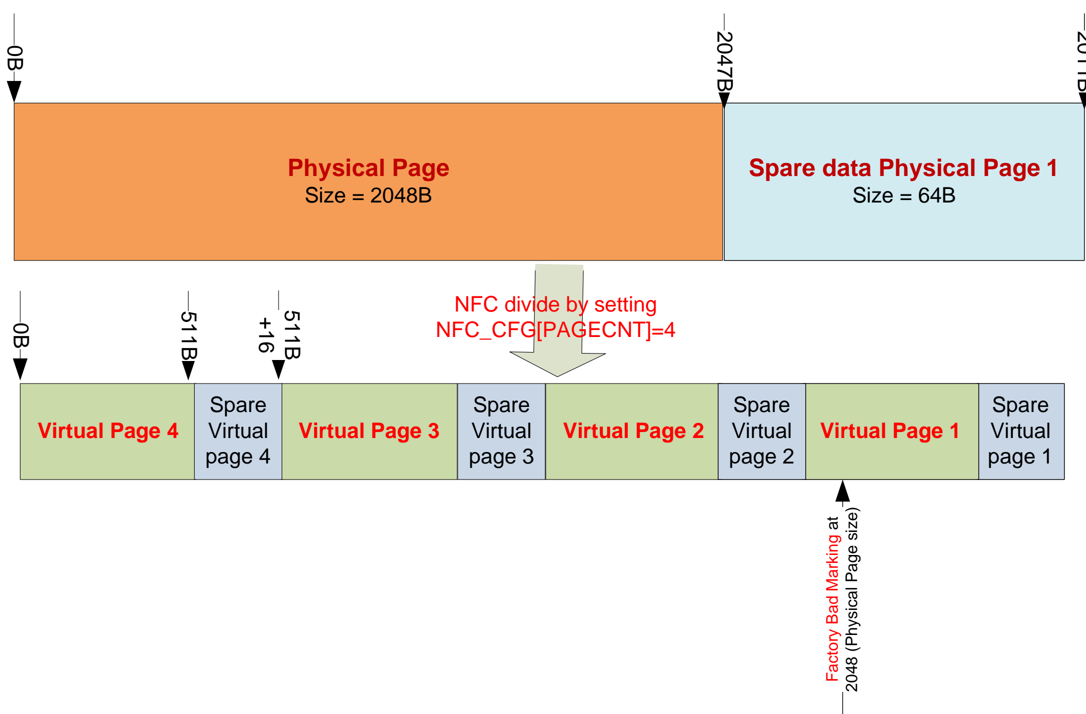


Figure 3-4. New Organization of Each Virtual Page in Physical Pages

By comparing Figure 3-2 and Figure 3-4, all virtual pages are placed in the reserved order. By doing so, we can preserve the location of Factory Bad Marking byte of NAND flash.

Chapter 4 Using MQX NAND Flash Wear Leveling Module

This chapter explains how a developer can initialize and work with MQX NAND Flash WL module:

- A pre-defined data driver layout must be declared in MQX NAND Flash WL module code before this module can initialize and start read/write on NAND physical device. The pre-defined layout is discussed in detail in section "4.1 Configure pre-defined data drive layout".
- After MQX NAND Flash WL is initialized successfully; upper layer can issue read/write operation by using standard FIO function such as read(), write(), seek(), and others. Section "4.6 MFS example user manual" demonstrates how to cooperate MFS with MQX NAND Flash WL module, which allows FAT file system to access on top of NAND Flash Wear Leveling module.
- Section "4.3 NFC Physical media" discusses a functionality of the NFC Physical Media class, which is a hardware dependent code in WL module.

4.1 Configure Pre-defined Data Drive Layout

One data drive is defined by default in the file given below:

```
<mqx>/source/io/nandflash_wl/nandflash_wl.h>.
```

Developer can use two macros, as shown below, to configure the start location and size for the first data drive.

```
#define NANDFLASH_1ST_DATA_DRIVE_SIZE_IN_BLOCK
#define NANDFLASH_1ST_DATA_DRIVE_START_BLOCK
```

For example:

```
#define NANDFLASH_1ST_DATA_DRIVE_SIZE_IN_BLOCK 90
#define NANDFLASH_1ST_DATA_DRIVE_START_BLOCK 110
```

In this example, the data drive size, in blocks, is 90. This data driver is expanded from 110th to 199th block.

If a developer wants to define data drivers manually (that is some data drivers are not placed continuously in NAND physical device), these data drivers can be declared in g_nandZipConfigBlockInfo variable in the file given below:

```
<mqx>/source/io/nandflash_wl/wearleveling/hal/ddi_nand_media_defination.cpp.
```

```
nand::NandZipConfigBlockInfo_t g_nandZipConfigBlockInfo =
{
        3,                      <- Number of drives
        {
                {
                        kDriveTypeData,
                        DRIVE_TAG_DATA,
                        10,
                        0,
                        0
                },
                {
                        kDriveTypeUnknown,
                        DRIVE_TAG_DATA,
                        10,
                        0,
                        10
                },
                {
                        kDriveTypeData,
                        DRIVE_TAG_DATA,
                        80,     <- Size of drive
                        0,
                        20      <- Start block of drive
                },
        }

};
```

In this sample, there are three drives, two are data type, one is unknown. It means the follwing:

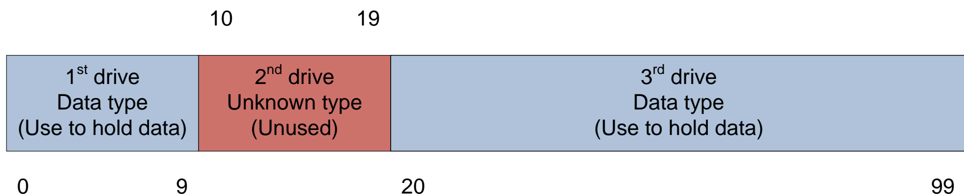


Figure 4-1. Manually Pre-defined 03 data Drivers

Drives could be the following types:

Enum LogicalDriveType_t	Description
kDriveTypeData	Public data drive
kDriveTypeSystem	System data drive
kDriveTypeHidden	Hidden data drive
kDriveTypeUnknown	Unknown data drive

In the current WL version, the WL only supports kDriveTypeData type. Other types with its block range are ignored.

4.2 NAND Flash WL API

NAND Flash WL driver provides an interface for upper layer such as MFS and read/write raw operations. Its prototypes are described as shown below.

4.2.1 _io_nandflash_wl_install

Description	This function is responsible for installing the main functions of nandflash memory. _io_nandflash_wl_open _io_nandflash_wl_close _io_nandflash_wl_read _io_nandflash_wl_write _io_nandflash_wl_ioctl _io_nandflash_wl_uninstall
Prototype	_mqx_uint _io_nandflash_wl_install (/* [IN] The initialization structure for the device */ NANDFLASH_INIT_STRUCT _PTR_ init_ptr)

4.2.2 _io_nandflash_wl_uninstall

Description	This function is used to uninstall the nandflash memory and free all unused allocated memory.
Prototype	_mqx_int _io_nandflash_wl_uninstall (/* [IN] The IO device structure for the device */ IO_DEVICE_STRUCT_PTR io_dev_ptr)

4.2.3 _io_nandflash_wl_open

Description	This function is used to open and initialize nand flash driver supported wear leveling feature. Depending on the input argument, the core of the driver is either built or ignored.
Prototype	_mqx_int _io_nandflash_wl_open (/* [IN] the file handle for the device being opened */ MQX_FILE_PTR fd_ptr, /* [IN] the remaining portion of the name of the device */ char_ptr open_name_ptr, /* [IN] the flags to be used during operation: */ char_ptr flags)

4.2.4 _io_nandflash_wl_close

Description	This function is used to close nand flash driver.
Prototype	_mqx_int _io_nandflash_wl_close (/* [IN] the file handle for the device being closed */ MQX_FILE_PTR fd_ptr)

4.2.5 _io_nandflash_wl_read

Description	Modules of upper layers use this function to read a logical sector from nand flash memory device via core and NFC Physical media.
Prototype	_mqx_int _io_nandflash_wl_read (/* [IN] the file handle for the device */ MQX_FILE_PTR fd_ptr, /* [IN] where the data is to be stored */ char_ptr data_ptr, /* [IN] the number of pages to input */ _mqx_int num)

4.2.6 _io_nandflash_wl_write

Description	Modules of the upper layers use this function to write a logical sector from nand flash memory device via core and NFC Physical media.
Prototype	_mqx_int _io_nandflash_wl_write (/* [IN] the file handle for the device */ MQX_FILE_PTR fd_ptr, /* [IN] where the data is stored */ char_ptr data_ptr, /* [IN] the number of pages to output */ _mqx_int num)

4.2.7 _io_nandflash_wl_ioctl

Description	This function contains a useful control command to communicate with low layer hardware.
Prototype	_mqx_int _io_nandflash_wl_ioctl (/* [IN] the file handle for the device */ MQX_FILE_PTR fd_ptr, /* [IN] the ioctl command */ _mqx_uint cmd, /* [IN/OUT] the ioctl parameters */ pointer param_ptr)

4.2.8 _io_nandflash_wl_internal_read_metadata

Description	This function is responsible to read only data of the spare area. It’s called from _io_nandflash_wl_ioctl function by the input command.
Prototype	_mqx_int _io_nandflash_wl_internal_read_metadata (/* [IN] the file handle for the device */ MQX_FILE_PTR fd_ptr, /* [IN] where the data is to be stored */ char_ptr data_ptr, /* [OUT] the error is returned */ uint_32_ptr ret_err)

4.2.9 _io_nandflash_wl_internal_read_with_metadata

Description	This function is used to read all data in a sector. It's called from _io_nandflash_wl_ioctl function by the input command.
Prototype	_mqx_int _io_nandflash_wl_internal_read_with_metadata (/* [IN] the file handle for the device */ MQX_FILE_PTR fd_ptr, /* [IN] where the data is to be stored */ char_ptr page_struct_ptr, /* [IN] the number of pages to input */ _mqx_int num, /* [OUT] the error is returned */ uint_32_ptr ret_err)

4.2.10 _io_nandflash_wl_internal_write_with_metadata

Description	This function is used to write data to a sector, and metadata in the spare area.
Prototype	_mqx_int _io_nandflash_wl_internal_write_with_metadata (/* [IN] the file handle for the device */ MQX_FILE_PTR fd_ptr, /* [IN] where the data is stored */ char_ptr page_buff_struct, /* [IN] the number of pages to output */ _mqx_int num, /* [OUT] the error is returned */ uint_32_ptr ret_err)

4.3 NFC Physical Media Class

- NFC Physical Media class, which is a subclass of the NandPhysicalMedia abstract class, is a hardware dependent code that is responsible for bridging between WL module and specific hardware NAND Flash Controller (NFC). This class prototype is discussed in detail in subsequent section.

NOTE

WL can support a new NAND Flash Controller (that is CPU does not have NFC hardware) by simply creating a new class, which is based on NandPhysicalMedia, and initializing it properly in NandHal class.

NFC physical media is located as shown below:

`<mqx>/source/io/nandflash_wl/wearleveling/hal/ddi_nand_hal_nfcphymedia.cpp.`

4.3.1 NFCNandMedia::NFCNandMedia

Description	This is a constructor of the NFC Physical media module.
Prototype	NFCNandMedia::NFCNandMedia (/* [IN] chip number for enabling */ uint32_t chipNumber)

4.3.2 NFCNandMedia::initChipParam

Description	This function initializes all chip parameters such as pages per block, page size, etc.
Prototype	void NFCNandMedia::initChipParam()

4.3.3 NFCNandMedia::readPage

Description	This function reads data and its metadata on a given physical sector number# from a physical sector in nand flash memory device.
Prototype	RtStatus_t NFCNandMedia::readPage (/* [IN] Sector number for reading */ uint32_t uSectorNumber, /* [OUT] Return read data buffer */ SECTOR_BUFFER * pBuffer, /* [OUT] Return read auxiliary(metadata) buffer */ SECTOR_BUFFER * pAuxiliary)

4.3.4 NFCNandMedia::writePage

Description	This function reads data and its metadata on given physical sector number# from a physical sector in the nand flash memory device.
Prototype	RtStatus_t NFCNandMedia::readPage (/* [IN] Sector number for reading */ uint32_t uSectorNumber, /* [OUT] Return read data buffer */ SECTOR_BUFFER * pBuffer, /* [OUT] Return read auxiliary(metadata) buffer */ SECTOR_BUFFER * pAuxiliary)

4.3.5 NFCNandMedia::eraseBlock

Description	This function is used to erase a given physical block number#.
Prototype	RtStatus_t NFCNandMedia::eraseBlock (/* [IN] Given block for erase request */ uint32_t uBlockNumber)

4.3.6 NFCNandMedia::eraseMultipleBlocks

Description	This function is used to erase a range of physical blocks.
Prototype	RtStatus_t NFCNandMedia::eraseMultipleBlocks (/* [IN] Start block No# for erase request */ uint32_t startBlockNumber, /* [IN] Number of block for erase request */ uint32_t requestedBlockCount, /* [OUT] Actual erased block */ uint32_t * actualBlockCount)

4.3.7 NFCNandMedia::copyPages

Description	This function is used to copy data of multiple physical sectors (data and metadata) from a source device to a target device.
Prototype	RtStatus_t NFCNandMedia::copyPages (/* [IN] Target Nand is request for copy to */ NandPhysicalMedia * targetNand, /* [IN] Start from sector No# */ uint32_t wSourceStartSectorNum, /* [IN] Copy to target's sector No# */ uint32_t wTargetStartSectorNum, /* [IN] Number of sector for copying */ uint32_t wNumSectors, /* [IN] The temporary sector buffer */ SECTOR_BUFFER * sectorBuffer, /* [IN] The temporary auxilary buffer */ SECTOR_BUFFER * auxBuffer, /* [IN] For copy filtering purpose */ NandCopyPagesFilter * filter, /* [OUT] Actual number of copied pages */ uint32_t * successfulPages)

4.3.8 NFCNandMedia::isBlockBad

Description	This function checks whether a given block is bad.
Prototype	bool NFCNandMedia::isBlockBad (/* [IN] Given block No# */ uint32_t blockAddress, /* [IN] The temporary sector buffer */ SECTOR_BUFFER * auxBuffer, /* [IN] Indicate whether we should check the factory marking position, ** NFCNandMedia currently does implement in lower layer */ bool checkFactoryMarkings, /* [OUT] Read status */ RtStatus_t * readStatus)

4.3.9 NFCNandMedia::markBlockBad

Description	This function is used to mark a block as bad.
Prototype	RtStatus_t NFCNandMedia::markBlockBad (/* [IN] Given block No# */ uint32_t blockAddress, /* [IN] The temporary sector buffer */ SECTOR_BUFFER * pageBuffer, /* [IN] The temporary sector auxiliary buffer */ SECTOR_BUFFER * auxBuffer)

4.4 Memory Management

Memory management is a useful module to manage/profile allocated memory. It enables both the developer and the user to know the amount of allocated/free and leaked memory.

This module can be easily turned off by changing the definition: NANDWL_MEM_LEAK_DETECTION to zero. When the definition is zero, the NAND Flash WL module uses MQX standard allocator/free memory – mem_alloc()/free() function instead of NAND Flash WL's function – mm_alloc()/mm_free().

This memory management module is located as shown below:

`<mqx>/source/io/nandflash_wl/wearleveling/rtos/mqx/mem_management.cpp.`

4.4.1 mm_alloc

Description	This function allocates a buffer with a given size. Each buffer includes two signatures, at head and tail, to trace their status. To manage memory, it's better to implement this function, in place of using standard functions.
Prototype	pointer mm_alloc (/* [IN] size of requested buffer */ _mem_size request_size, /* [IN] file name which requests buffer */ const char* file_name, /* [IN] Location in file_name */ int file_loc, /* [IN] Should zero buffer after allocated */ boolean isZero, /* [IN] Is this buffer requested from new operator */ boolean is_from_operator)

4.4.2 mm_free

Description	This function is used to free allocated memory. It will check the signature included and alert invalid allocated buffer.
Prototype	_mqx_uint mm_free (/* [IN] pointer to head of allocated buffer */ pointer buf)

4.5 WL Debug

WL Debug is designed to support developers to debug each sub module or all sub modules of the NAND Flash WL core. If a debug module is enabled, all messages of verbose module will be printed out by using WL_LOG statement. The syntax is shown below:

```
WL_LOG(<WL_Module>, <Log_type>, <Message>);
```

```
/* Try to load the zone and phy maps from media. */
WL_LOG(WL_MODULE_MAPPER, WL_LOG_INFO, "Loading maps from media\n");
```

```
#if  ( (WL_DEBUG))
uint_32 g_wl_log_module_attributes =
    WL_MODULE_GENERAL
    /*| WL_MODULE_HAL*/                 <-- Disabled debug module
    | WL_MODULE_MAPPER
    | WL_MODULE_MEDIA
    | WL_MODULE_LOGICALDRIVE
    | WL_MODULE_DEFEERREDTASK           <-- Enabled debug modules
    | WL_MODULE_MEDIABUFFER
    | WL_MODULE_NANDWL
    | WL_MODULE_NANDWL_TESTING
;
```

This module is located as shown below:

<mqx>/source/io/nandflash_wl/wearleveling/wl_common.cpp.

4.6 MFS Example User Manual

4.6.1 User Interface

```
COM1:57600baud - Tera Term VT
File  Edit  Setup  Control  Window  Help
NAND Flash demo
If this is the first time you use the demo, you should run "nanderasechip" first.

Shell (build: Jan  9 2012)
Copyright (c) 2008 Freescale Semiconductor;
shell>
shell> help
Available commands:
   cd <directory>
   copy <source> <dest>
   create <filename> [<mode>]
   del <file>
   disect <sector> [<device>]
   dir [<filespec>] [<attr>]]
   di <sector> [<device>]
   exit
   format <drive:> [<volume label>]
   help [<command>]
   mkdir <directory>
   pwd
   read <filename> <bytes> [<seek_mode>] [<offset>]
   ren <oldname> <newname>
   rmdir <directory>
   sh <filename>
   type <filename>
   write <filename> <bytes> [<seek_mode>] [<offset>]
   fsopen
   fsclose
   nanderase
   nandrepair
   nanderasechip
   ?
shell>
```

Figure 4-2. MFS example user interface

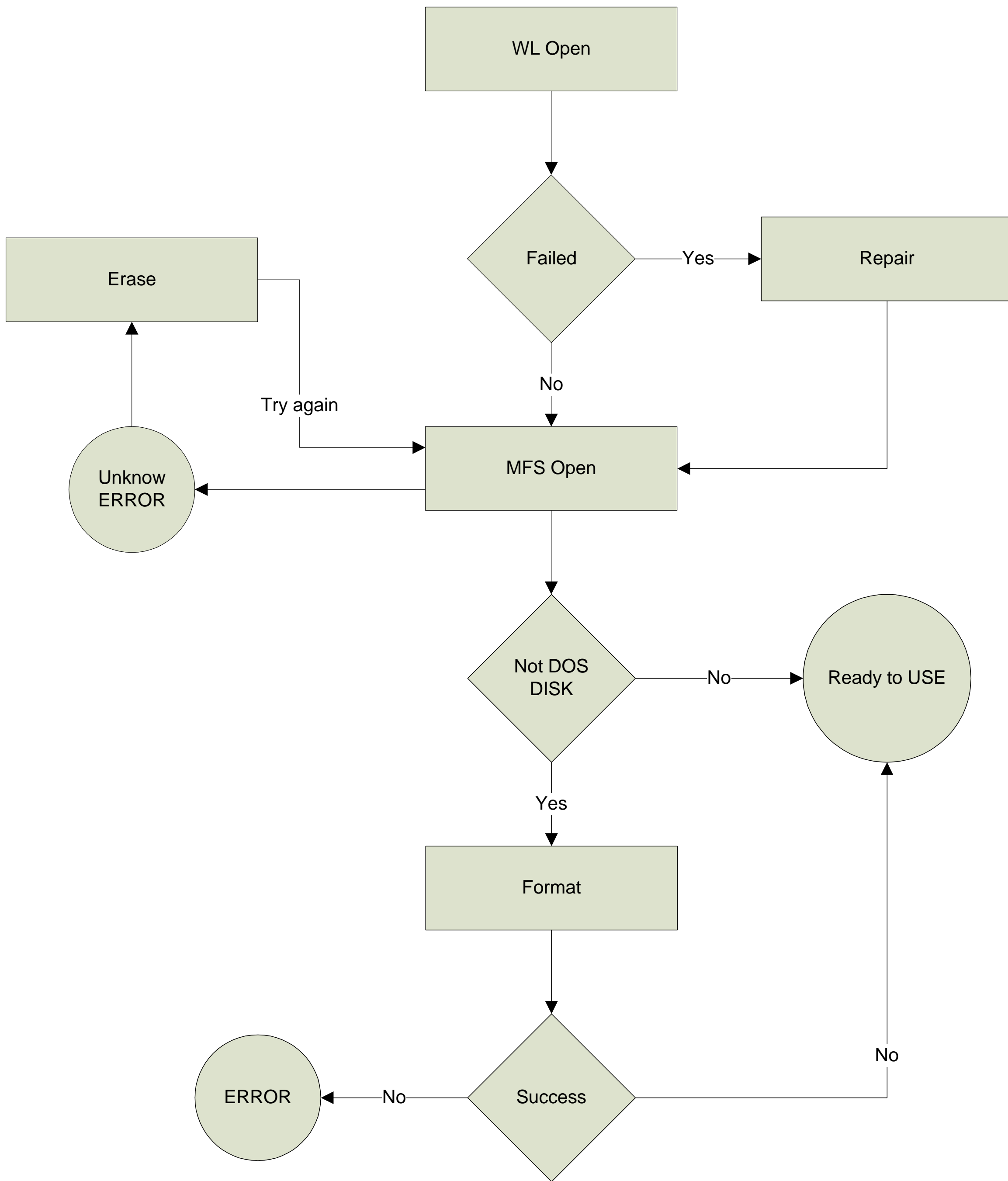
4.6.2 New Shell Commands

This example is based on existing MFS SD Card example. Therefore, it has common shell commands and some new commands, which are only used for FFS.

New shell commands are:

- fsopen
- fsclose
- nanderase
- nandrepair
- nanderasechip

These commands are shown in the diagram below:



4.6.2.1 “fsopen” Command

This command is used to open NAND flash memory with wear leveling. Each sub module (Media, DataDrive, Mapper…) is initialized in order.

4.6.2.2 “fsclose” Command

This command is used to close NAND flash memory and shutdown initialized wear leveling module.

4.6.2.3 “nanderase” Command

This command is used to erase all blocks, which are defined as Data drive. These blocks are erased by wear leveling module, not NFC directly.

4.6.2.4 “nandrepair” Command

This command is used to repair all blocks in defined Data drive. Random data will be written to these blocks (included the spare area) and their status is also checked. The wear leveling module will rebuild necessary maps because they were erased while the Data drive is being repaired.

4.6.2.5 “nanderasechip” Command

This command is used to erase all blocks in NAND flash memory. These blocks are erased directly by the NFS ioctl. The wear leveling module is not installed.

NOTE

- First time users of the MFS NAND Flash example, should run “nanderasechip” command first. If the data in the spare area, which holds metadata of each sector, is cluttered, it will cause the core to malfunction. With incorrect data, the core will build incorrect maps and critical errors may occur.
- To change the size of the default data drive or the structure of the NAND media, please make sure they were declared in g_nandZipConfigBlockInfo variable.

Chapter 5 MQX Wear Leveling Internal Functionality

This section describes the functionalities of Wear Leveling module in NAND flash driver.

5.1 Role of WL Module in NAND Driver

This module is mainly responsible for mapping from a virtual page address to a physical page address. By doing so, the wear leveling works transparently with the upper layer such as MQX MFS. Applications in the upper layer pass a logical sector (or virtual page address) to WL's module resists inside NAND driver. After that, the WL mechanism searches its internal mapping table on RAM or flash memory to find the desired physical page address.

There are a few existing mapping tables, namely PhyMap, ZoneMap, and NonSequentialSectorMap, maintained in the WL module. In the initialization step, WL tries to build up the PhyMap and ZoneMap by scanning all blocks in the reserved area on NAND physical to find the suitable map structure. NonSequentialSectorMap is built from metadata in every physical page.

If NAND memory is fresh or does not contain WL information, these maps will initialize with default parameters. On each read/write operation from the upper layer, these maps will update by getting rid of a non-existing entry and fetching a new one from the flash memory. Finally, when upper layer closes the flash driver, all map data will be flushed to the physical pages encapsulated in a special structure.

In addition, WL map retains all good blocks and bad blocks on NAND flash memory. If WL catches an error related to the writing or erasing operation on a specific block, it marks the block as bad and avoids it in the future allocation.

5.2 Input and Output of WL Module

The following figure depicts WL input and output parameters that are passed between each module and function.

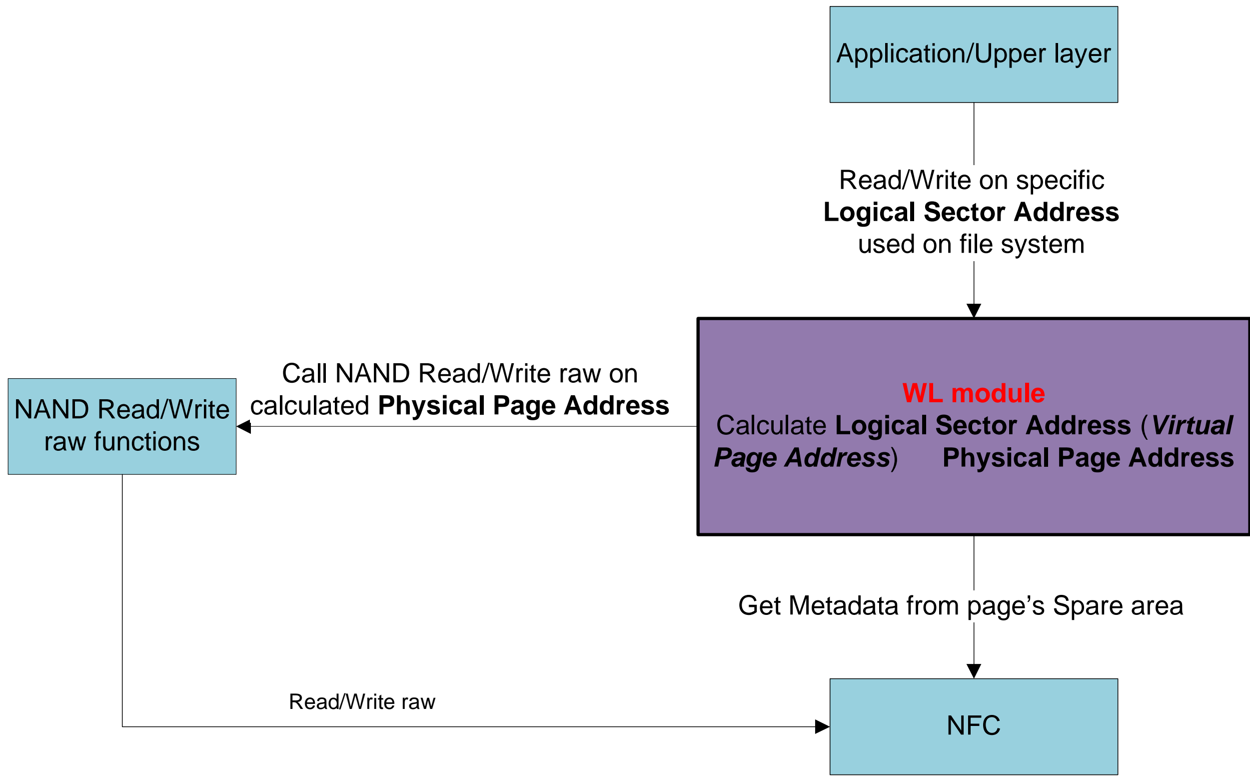


Figure 5-1. Input/Ouput Parameters of WL Module

5.3 Internal Mechanism inside WL Module

The most important task for WL module is to get essential information from maps or flash memory and calculate the physical page address from Logical Sector/Page Address to Physical Page Address. To do so, WL must cooperate with maps as shown in the figure below:

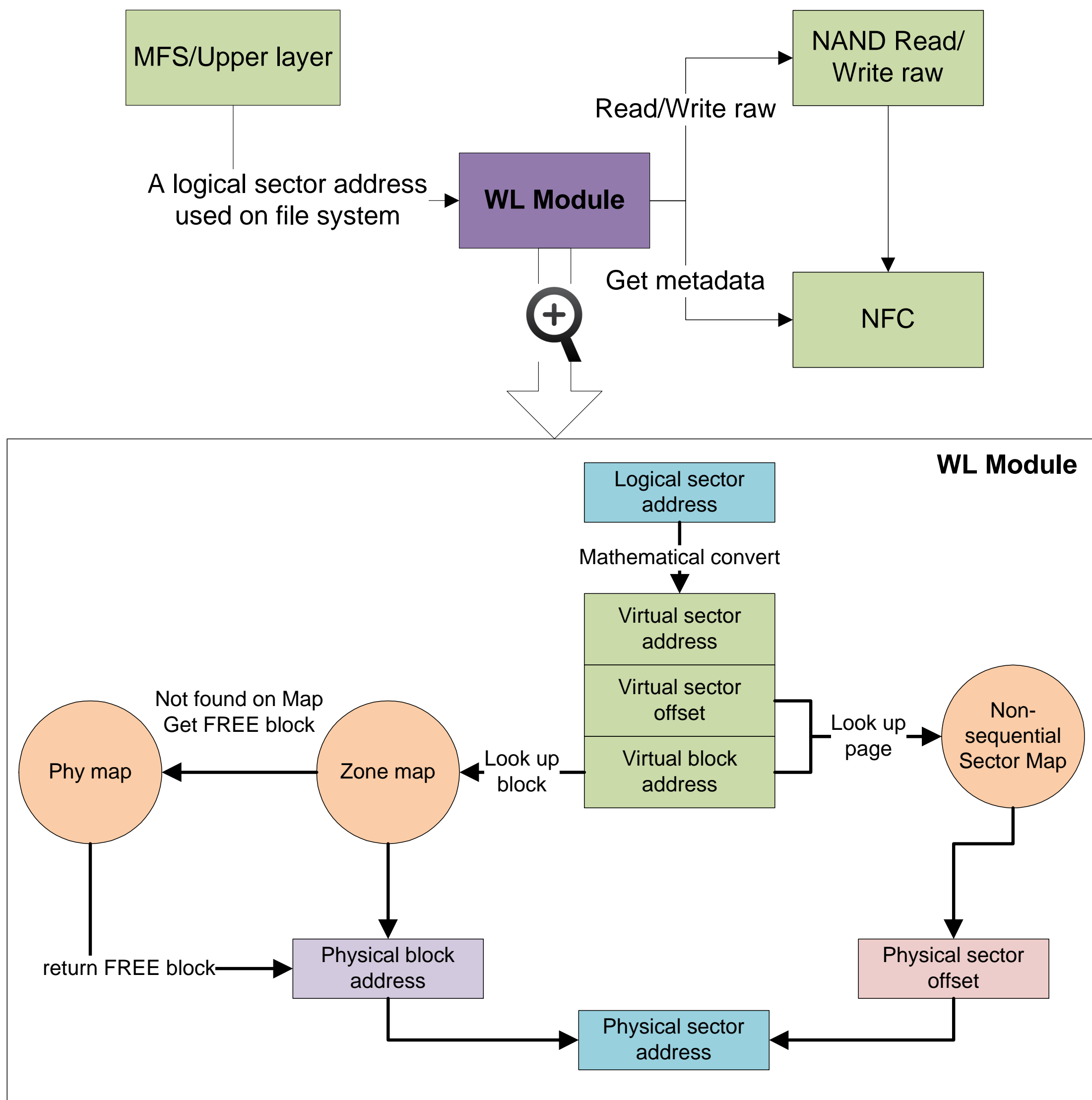


Figure 5-2. Internal Mechanism inside WL Module

In this figure:

- Phy Map: holds a bitmap table that indicates the status of each block in the flash memory.
- Zone Map: stores a look up table for mapping the Vritual Block Address to the Physical Block Address.
- Non-Sequential Sector Map (NSSM): supplies a map to convert the logical sector offset to the physical sector offset in a Virtual Block. One important aspect of the NSSM is that each NSSM is associated with a virtual block number, not with a physical block. This allows the data associated with the virtual block to move around the media as necessary.

As mentioned in the previous section, the three maps (Phy map, Zone map, and Non-sequential sector map) are both stored in RAM and preserved on flash memory for future re-building purpose.

Chapter 6 MQX Wear Leveling Internal Software Flow

This section describes software flow inside the WL Module.

6.1 Initialize Flow

Initialization steps are as shown below:

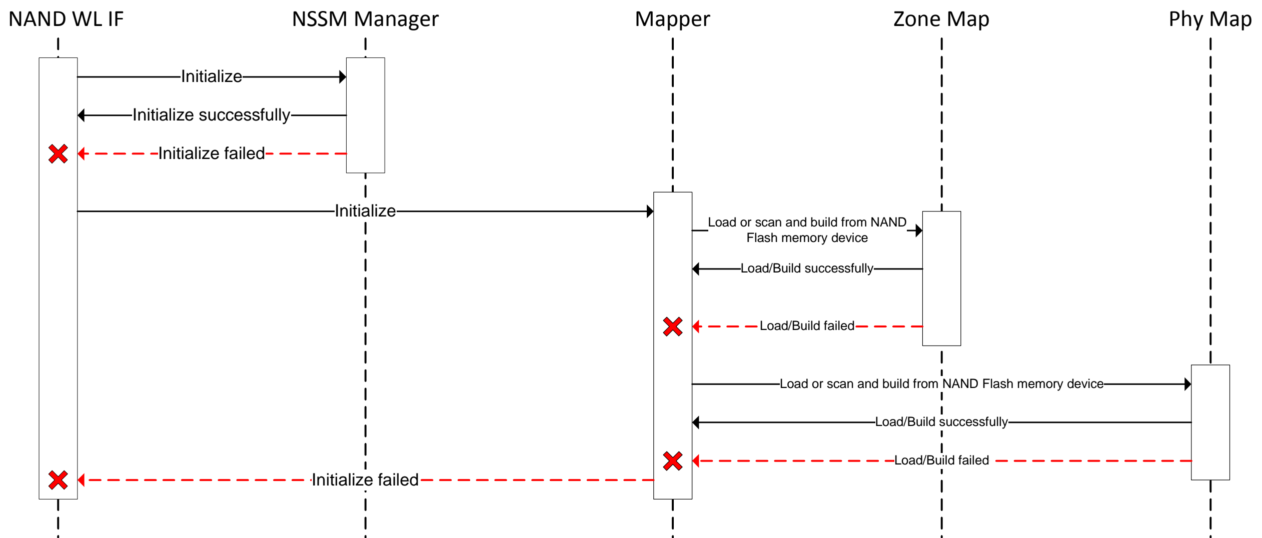


Figure 6-1. WL Initialization Sequence Diagram

In this sequence diagram:

- NAND WL IF : is an interface for WL module. It is responsible for initializing all maps and for interacting with upper layers.
- NSSM Manager: manages all Non-sequential Sector maps in the Red Black tree structure and LRU list.
- Mapper: manages Zone Map and Phy Map.

6.2 Read Sector Flow

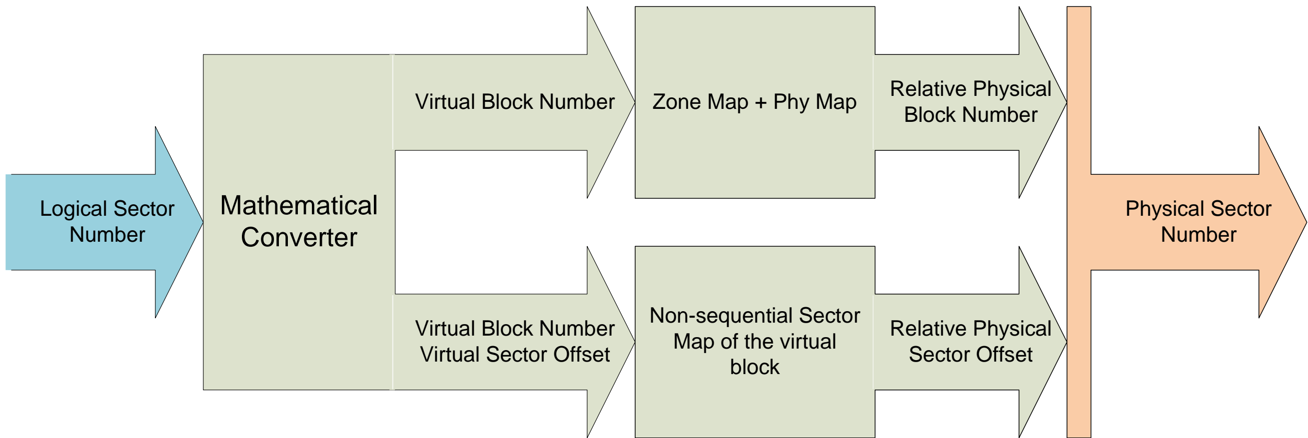


Figure 6-2. WL Read Sector Flow

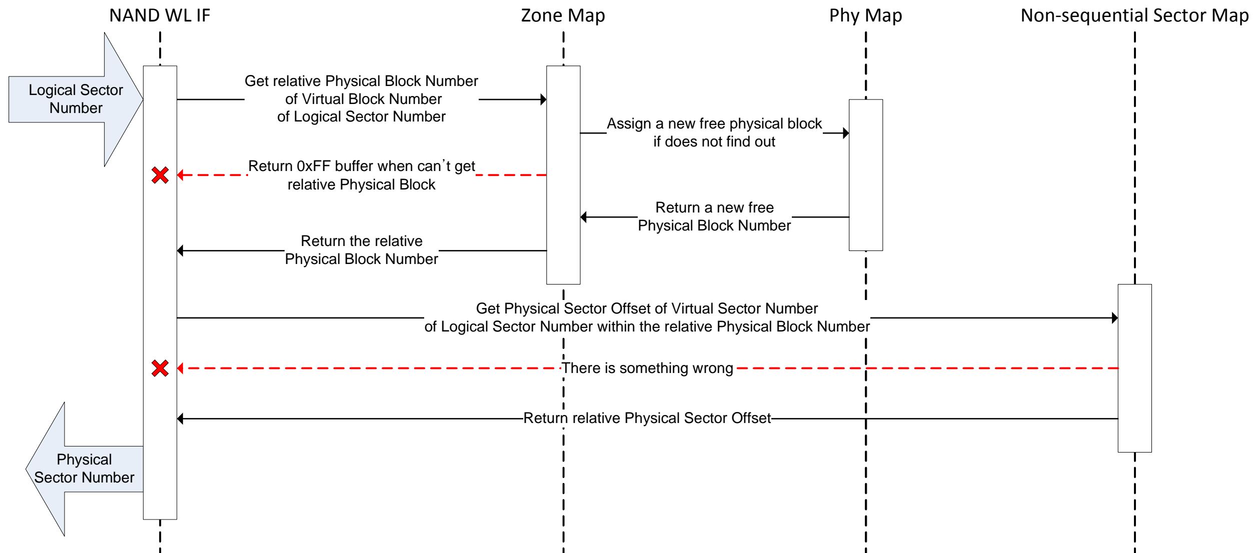


Figure 6-3. WL Read Sector Sequence Diagram

In this sequence diagram:

- Step 1: If MFS wants to read data from a logical sector, it passes a logical sector address to the NAND WL IF of the NAND driver. WL needs to make sure that a given logical sector is not out of bounds.
- Step 2: The NAND WL IF converts the input logical sector number mathematically into a virtual block number and a virtual block offset.
- Step 3: If the Zone map object is loaded or built from the initialization phase, the NAND WL IF searches the map to figure out a relative physical block of this virtual block. If the physical block cannot be found, that means that no physical block was assigned to this virtual block, and that a

free physical block that is available in Phy map is assigned and a buffer filled with 0xFF sent back to MFS.

- Step 4: The NAND WL IF scans all entries in Non-sequential Sector Map of the virtual block to get location (offset) of the virtual sector in the block which it belongs to. If the Non-sequential Sector Map was not loaded to SDRAM, each sector of the relative physical sector is scanned to read metadata and Non-sequential Sector Map is built.
- Step 5: If WL has the physical sector number and the physical sector offset number, it knows exactly which physical sector must be sent to the NFC. However, WL also needs to confirm whether the sector is written or not. If it is not written, it returns an 0xFF buffer.

6.3 Write Sector Flow

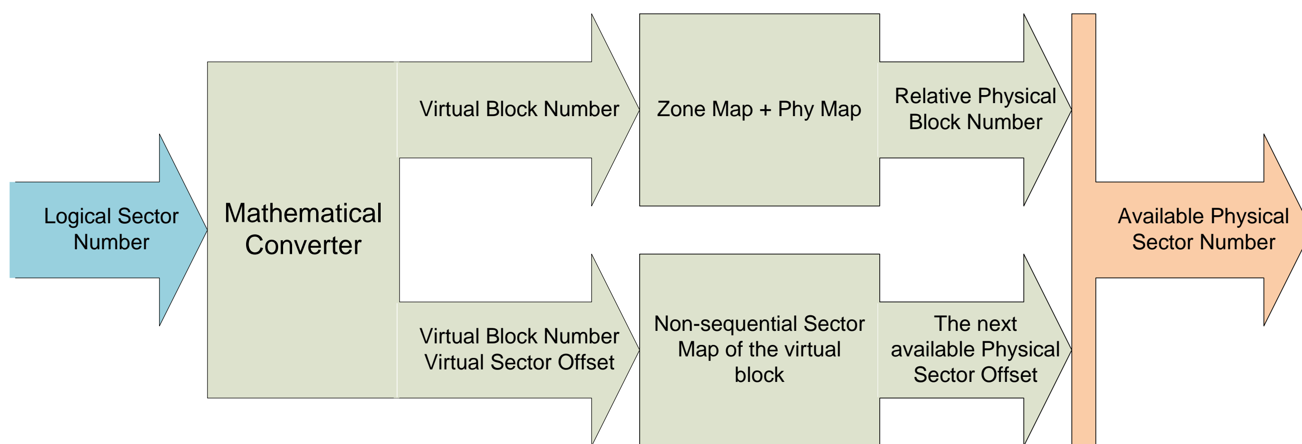


Figure 6-4. WL Write Sector Flow

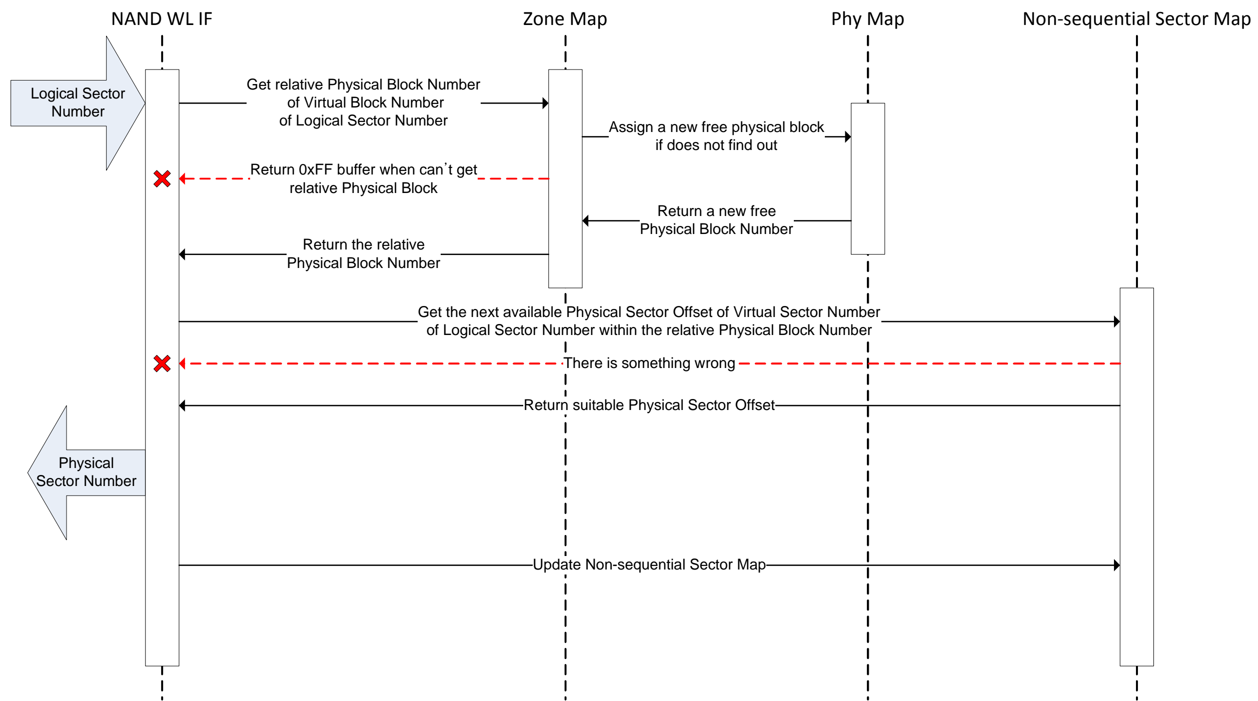


Figure 6-5. WL Write Sector Sequence Diagram

In this sequence diagram:

- Step 1: If the MFS wants to write data to a logical sector, it transfers a logical sector address to the NAND WL IF of the NAND driver. WL needs to make sure that a given logical sector is not out of bounds.
- Step 2: The NAND WL IF converts the input logical sector number mathematically into a virtual block number and a virtual block offset.
- Step 3: If the Zone map object is loaded or built from the initialization phase, the NAND WL IF searches the map to figure out the relative physical block of this virtual block. If the physical block cannot be found, that means that no physical block is assigned to this virtual block, and that a free physical block, which is available in Phy map, is assigned.
- Step 4: The NAND WL IF scans all entries in the Non-sequential Sector Map of the virtual block to get location (offset) of the next available virtual sector in the block to which it belongs. If the Non-sequential Sector Map was not loaded to SDRAM, each sector of the relative physical sector is scanned to read metadata and Non-sequential Sector Map is built later.
- If the next available virtual sector is out of bounds because the physical block is full, WL marks that physical block as a backup block and gets a new free block to write data. Old backup block needs to be erased and marked as free.
- Step 5: If WL has the physical sector number and the physical sector offset number, WL knows exactly which physical sector must be sent to the NFC. However, if an error occurs when writing and the NFC cannot fix that error, WL has to copy content of the physical block to another free block and mark the previous block as bad. The NFC continues writing on the new block.

- Step 6: After the NFC writes successfully, the Non-sequential Sector Map of the physical block needs to be updated.

6.4 Shutdown Flow

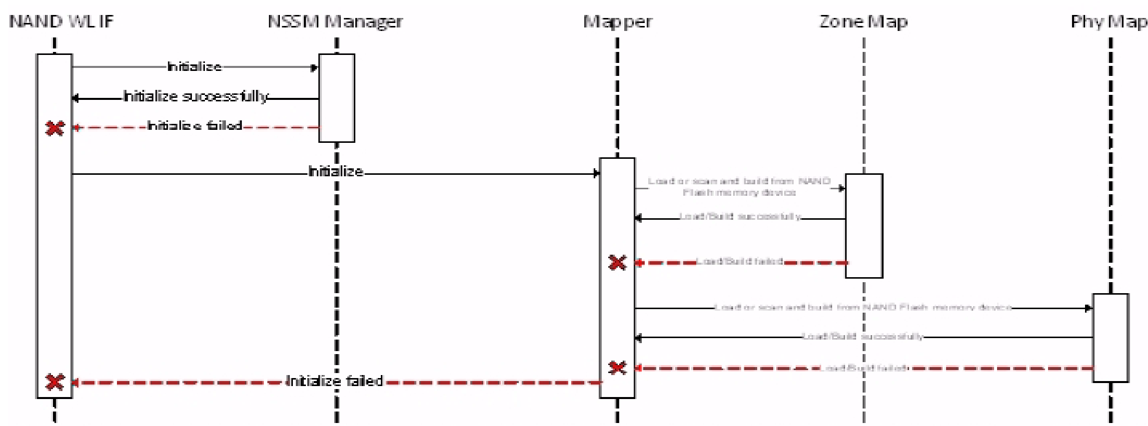


Figure 6-6. WL Shutdown/Flush Sequence Diagram

Before releasing all variable that is allocated on memory, WL needs to flush all Non-sequential Sector Maps by merging the backup block and the primary block to free the unused block, and write Zone map and Phy map on NAND flash memory device if they are not saved.

6.5 Zone Map, Physical Map, and Non-sequential Sector Map Structure

Zone Map and Physical Map are organized inside the flash memory as shown in the figure below:

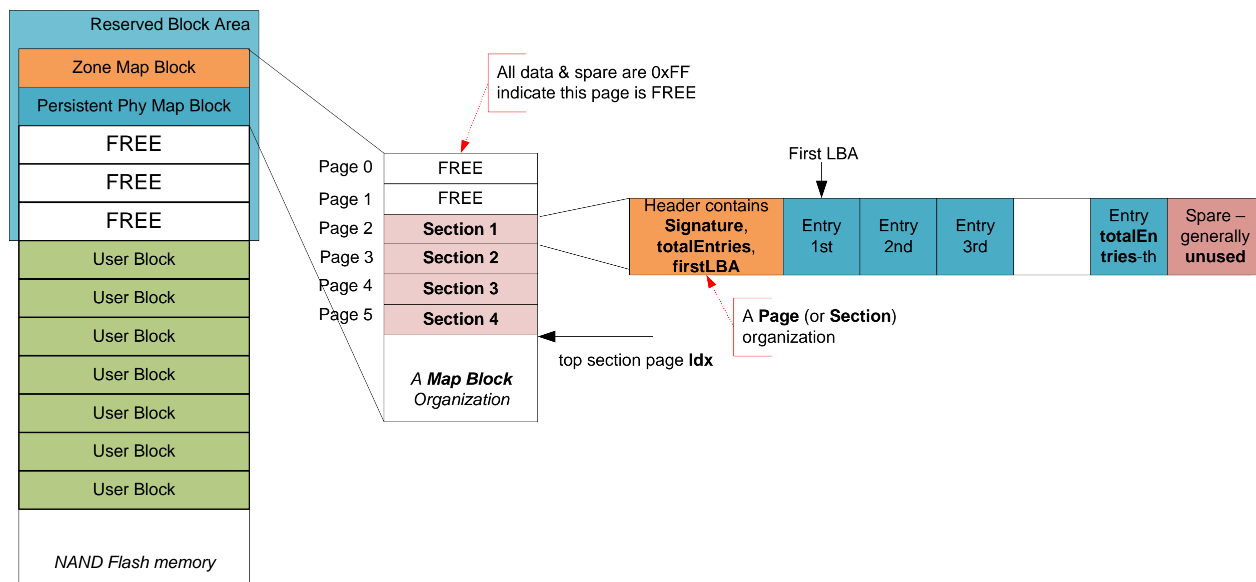


Figure 6-7. Zone Map and Phy Map Organization in Flash Memory

Maps are located in a Reserved Area Block that the user's data cannot touch. Each map occupies one block and the others are backups. One map block contains multiple sections that are spread continuously in virtual pages on the flash memory. To slow down the premature wear-out on this map block, whenever WL adds new section number to flash memory, it always writes to the first available virtual page (indicated by top section page index). By using this strategy, WL regularly touches all virtual pages in this block.

Every section contains a header on the first page data. The most important fields in each header are:

- Signature: for identifying a Zone Map or Phy Map
- firstLBA: Logical Block Address of first entry
- totalEntries: total number of entries in this section

The assumption is that, with one physical block (64*4 virtual pages, 512 byte in each page), it is possible to preserve all mapping information for physical NAND memory. For example:

- For storing Phy Map:
  — Virtual page size = 512 bytes and a block contains 64*4 virtual pages
  — Section header = 24 bytes
  — 02 bits are used for indicating a block's status
  — A block can present status of maximum ((512 bytes-24 bytes)*8bit)/(2 bit) * 64*4 pages = 499,712 blocks (~ 499,712 * 128KB in each block = 61GB NAND flash device)
- For storing Zone Map:
  — Virtual page size = 512 bytes and a block contains 64*4 virtual pages
  — Section header = 24 bytes
  — Each entries contain a 24-bit physical block address

— A block can hold a maximum of ((512 bytes-24 bytes)*8bit)/(24 bit) * 64*4 pages = 41,642 physical block address (~ 41,642 * 128KB in each block = 5GB NAND flash device)

NOTE

When the top section page index reaches the total virtual page in a block (64*4), it means that this map block is completely full. WL relocates this block to the new one (still in reserved area block). This process is called consolidation.

Compared to the Zone and Phy Map, a Non-sequential Sector map is distributed in every virtual page spare area.

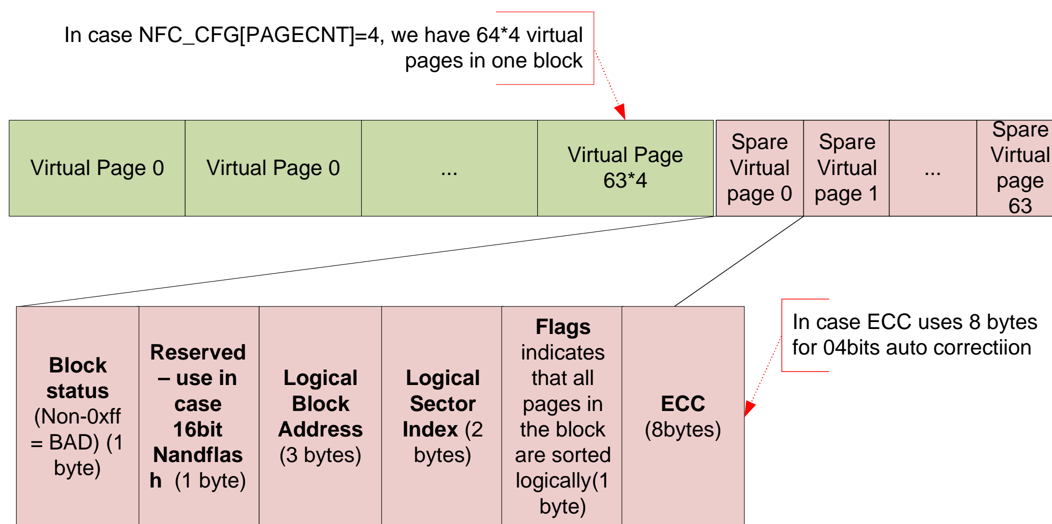


Figure 6-8. Organization of Non-sequential Sector Map in Virtual Page Spare Area

NOTE

Generally, the reserved block area (RBA) is expandable if there are bad blocks inside this area. In this instance, the reserved block area moves toward the higher block address and relocates any non-map blocks which reside in RBA.

6.5.1 Phy Map

Phy map is responsible to get/set a status of the specific physical block. It stores the status of each block in the flash memory by using a bitmap entry. Each entry in this map uses 01 bit to represent three different states of a block:

- Block is used (occupied or bad)
- Block is free

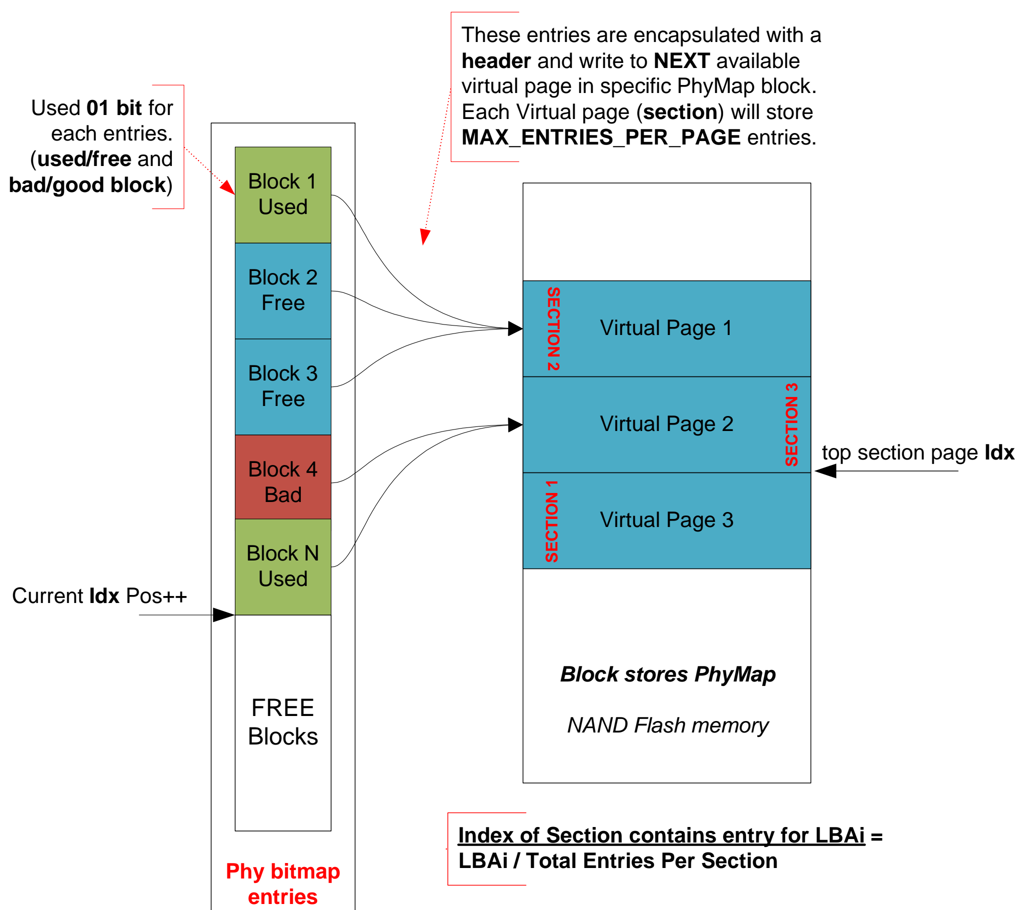


Figure 6-9. Phy Map Organization in Memory and Flash

In this figure:

- Each Physical Virtual Page stores a maximum of MAX_ENTRIES_PER_PAGE entries. WL encapsulates these entries into a section by padding a header before flushing to flash memory.
- Current index position indicates that the next free non-map block can be allocated. This position is helpful whenever a user wants to request a new block for writing.
- Top section page index indicates the section of the next free virtual page that can be stored. This index continuously increments toward the higher address; when it reaches a total page number, WL will consolidate all sections of this map into the next free block in RBA.

NOTE

A trust number (TN), informs that all maps have been flushed into the flash memory successfully. It is located in the last two bytes of metadata (byte 7 and byte 8) of every map block. Normally, the TN in Zone and Phy maps should be as follows:

- $TN_{ZoneMap}$ = 16 bit random number
- $TN_{PhyMap} = TN_{ZoneMap} + 1$ *(the Phy Map is always written to NAND flash before ZoneMap)*

6.5.1.1 Phy Map initialization

Normally, WL checks the trust number to find out whether all maps have been flushed. If so, WL will scan all blocks in RBA in flash memory to locate the block that holds the PhyMap table during initialization phase. A valid PhyMap Block should have a valid signature and a consistent structure on each page. If WL does not find a good Phy Map block, it scans all blocks to build a new one.

6.5.1.2 Phy Map preservation

Whenever the Phy Map changes, (it is dirty),WL flushes it to the flash memory.

6.5.2 Zone Map

Zone map contains a mapping table between Logical Block Address and Physical Block Address.

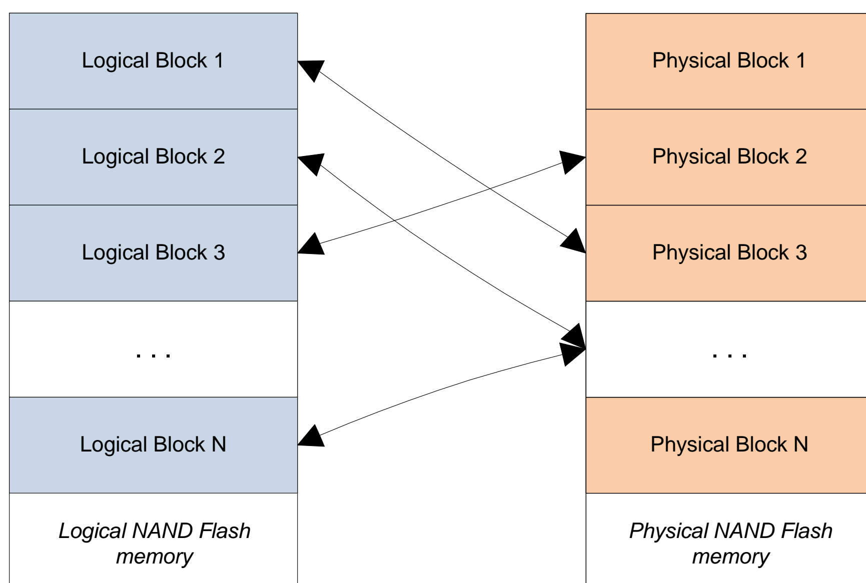


Figure 6-10. Zone Map - Mapping Table between Logical Block Address and Physical Block Address

WL splits this map into many sections and writes to flash memory. Each section contains entries whereby each entry stores 16 or 24 bits physical block address.

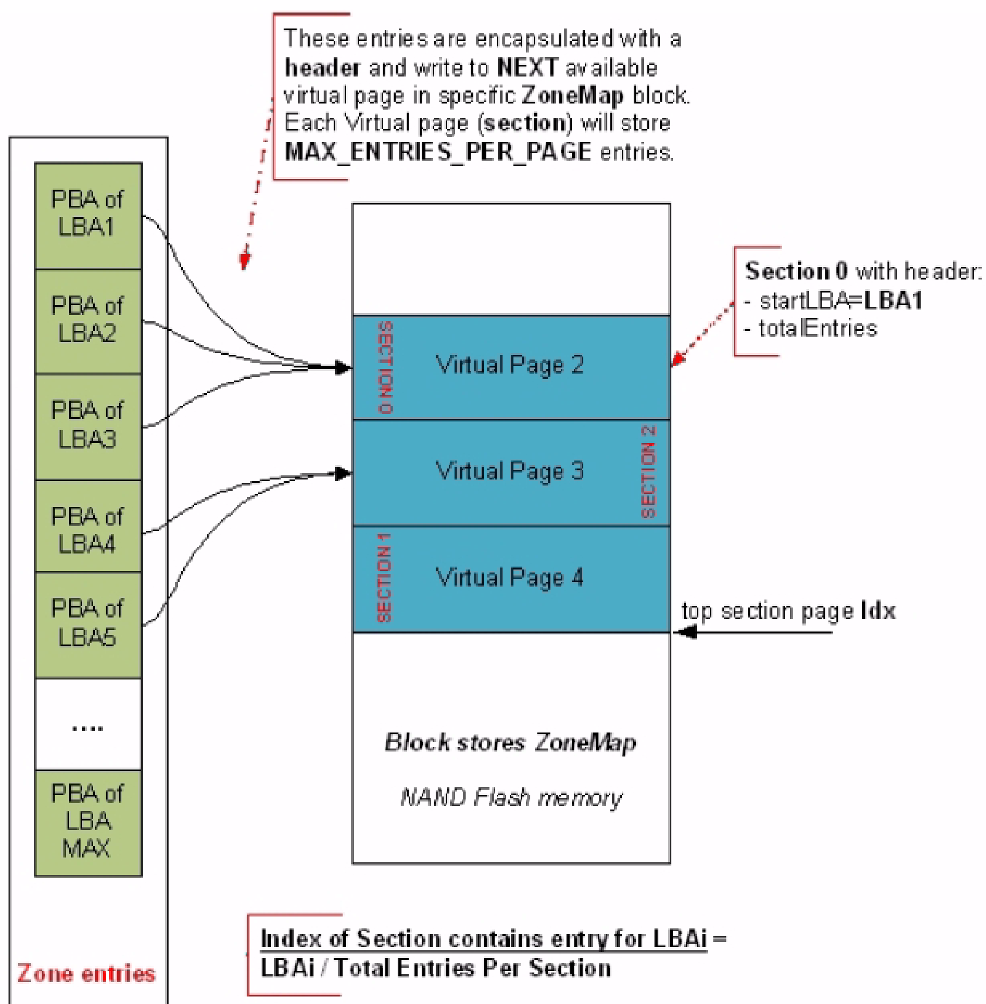


Figure 6-11. Zone Map Organization In memory and Flash

WL maintains this map in flash memory the same way as it does the Phy Map. However, it is difficult to load the entire Zone Map to memory beacause of the limited RAM . As a result, only some sections of the zone map are loaded into a cache array for fast look up. If the cache array is full, WL uses the Least Recently Used (LRU) strategy to remove and fetch a new one from flash memory.

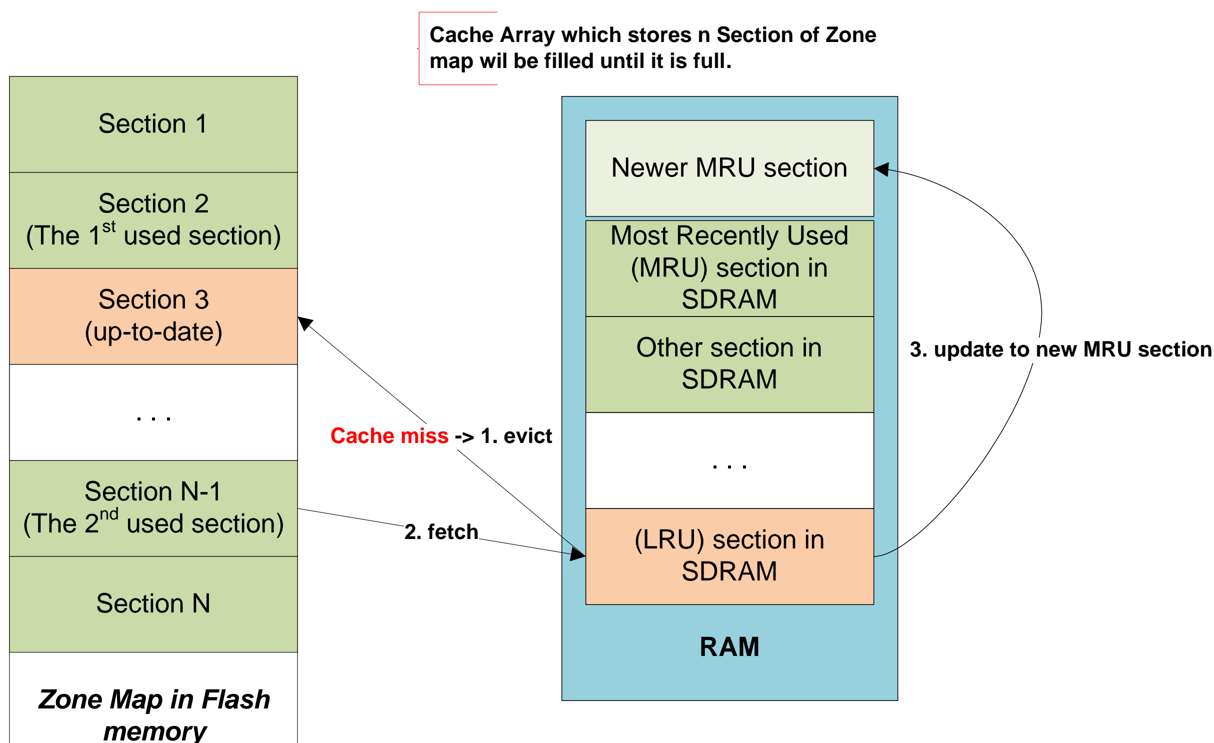


Figure 6-12. Cache Array for Zone Map

6.5.3 Non-sequential Sector Map

The Non-sequential sector map (NSSM) is responsible for tracking the block's logical sectors within the physical location of a block. It also manages the mechanism which updates the block contents in an efficient manner. All upper layer sectors reading and writing must utilize a non-sequential sector map to either find the physical location of a logical sector, or to get the page where a new sector should be written.

The NSSM is composed of two key components. First, it has a map which explains the relationship of the logical sector to a physical page within a block. This allows logical sectors to be written to the block in any order, which is important for ensuring that pages are only written sequentially within the block as required by NAND. The map also enables logical sectors to be written to the block more than once, with the most recent copy taking precedence.

The second element is a backup block. The backup block contains previous contents of the block and allows only new sectors to be written to the primary block. If a logical sector is not present in the primary block, it can be read from the backup block. When the primary block becomes full, the primary and backup are merged into a new block. Merging takes the most recent version of each logical sector from either the primary or backup and writes it to the new block.

Another important aspect of the NSSM is that each NSSM is associated with a virtual block number, not a physical block. This allows the data associated with the virtual block to move around on the media as necessary.

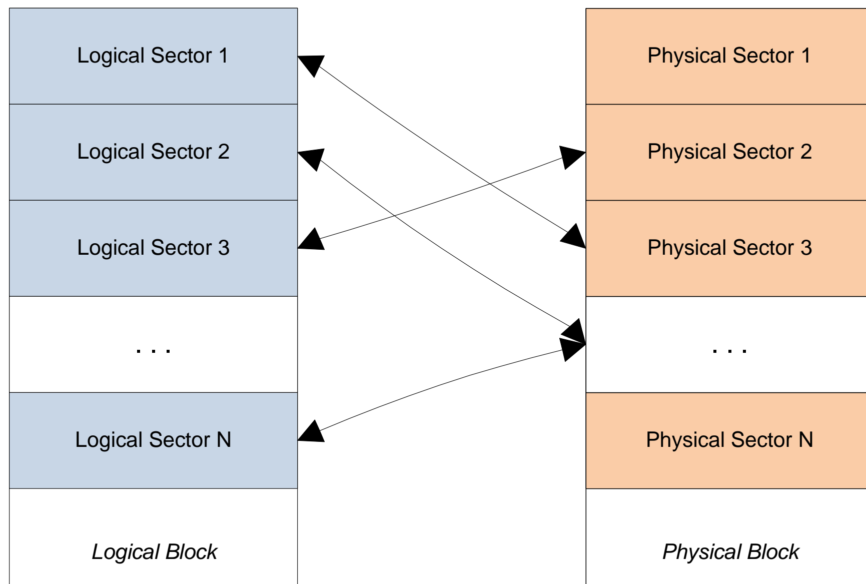


Figure 6-13. Mapping between Logical Sector <-> Physical Sector

Each block holds a non-sequential map in the spare area of every page. Whenever upper layer requests to read or write on a given sector, WL will calculate a virtual block that contains a sector. After that, WL scans the spare area of all pages of this virtual block to build up a non-sequential sector map.

To boost performance, WL uses specific caching mechanism to improve speed when looking up a logical sector in one block. Similar to Zone Map, only a few maps are loaded into memory. WL uses LRU strategy for every cache-missed map. In addition, to enhance the search time, a Red-black tree is used to hold the non-sequential maps. Each node of the tree is a non-sequential map whereby the key is related to the Virtual Block Address (VBA) of that map. Since a Red-black tree is a self-balancing binary search tree, searching-time is optimized.

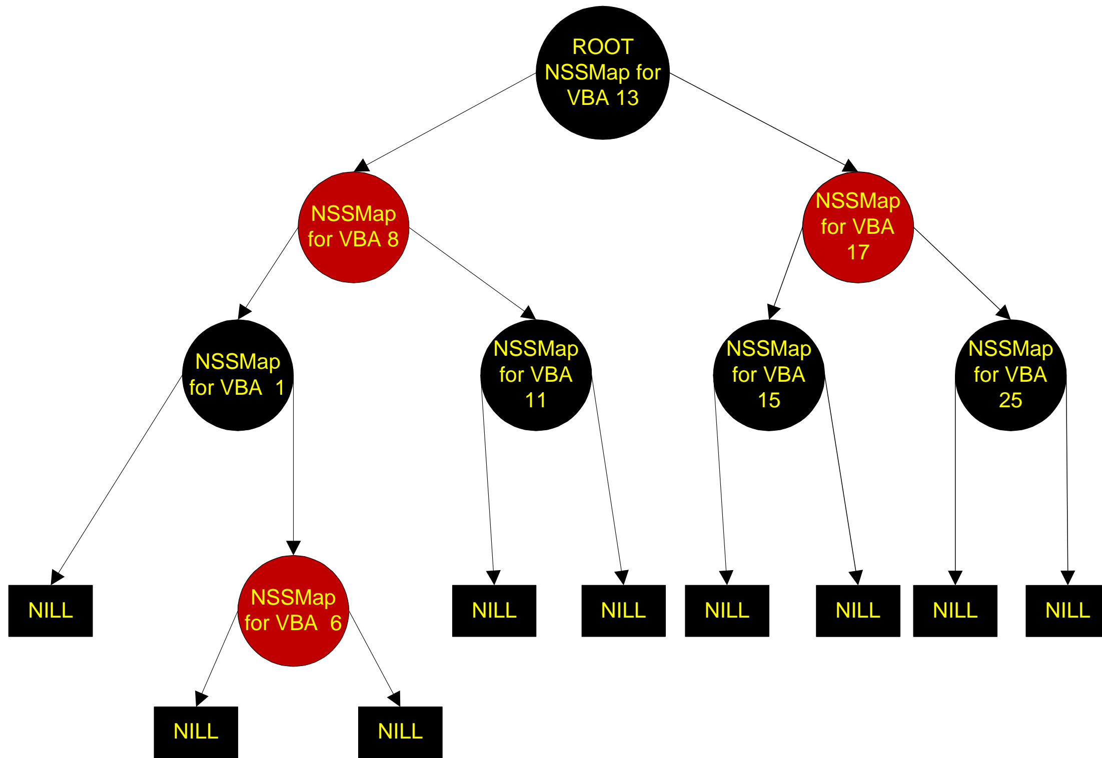


Figure 6-14. Non-sequential Map in Red Black Tree Structure

6.5.3.1 Prevent thrashing when switching from primary block to backup block

Since NSSM uses a backup block that contains the previous contents of the block (primary one), when the primary block becomes full, the primary and backup are merged into a new block. There are a few existing merge strategies as described below:

- shortCircuitMerge: When the primary block is full, WL requests a new free physical block from the PhyMap and assigns it as a new primary block. The backup block is erased and freed. At this time, the backup block points to the previous primary block.

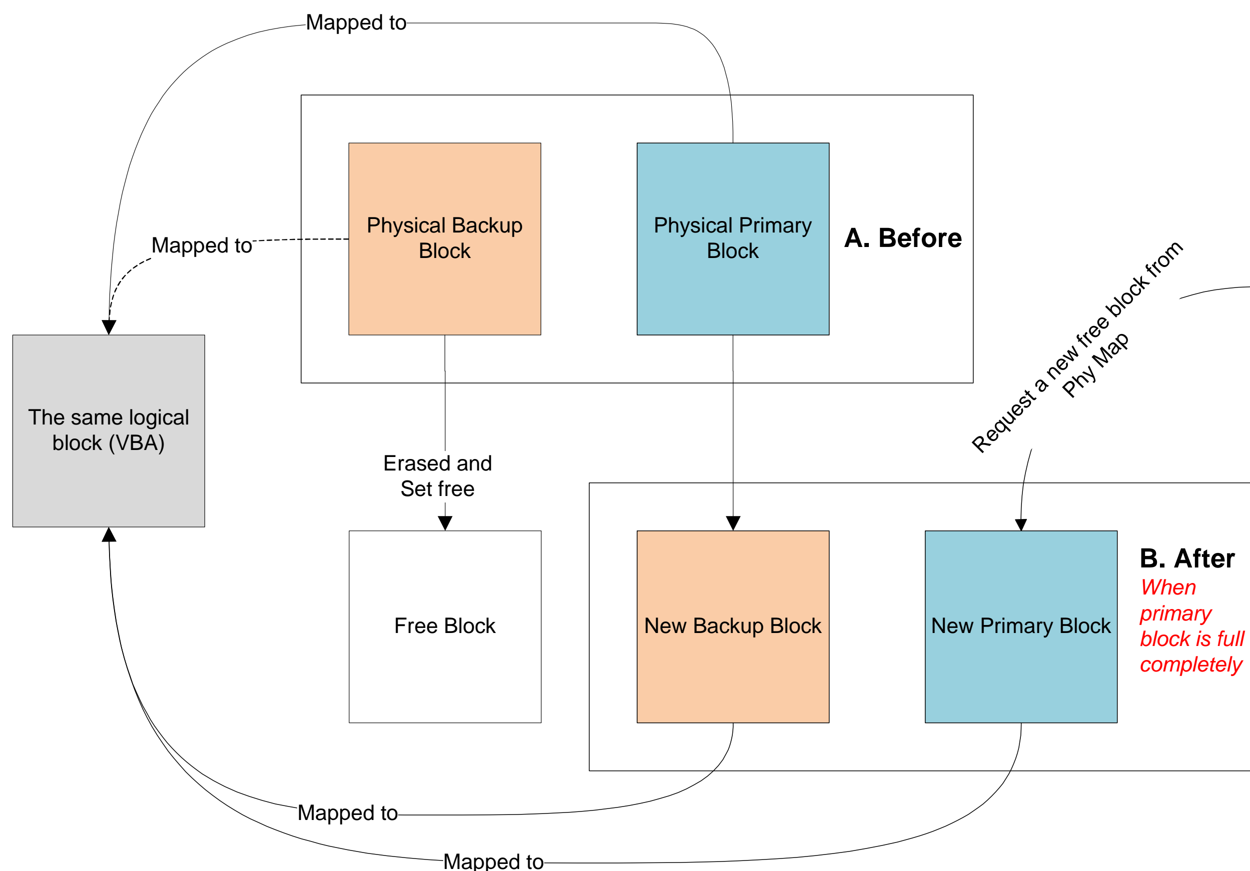


Figure 6-15. ShortCircuitMerge for Non-sequential Sector Map

- quickMerge: occurs if the system requests WL to flush all data to memory. Merge happens when the primary block is not yet full, but the number of sectors in backup is fitted to the primary only. In this case, WL will copy all remaining sectors in the backup block to the primary block. After that, the backup block is erased and freed.

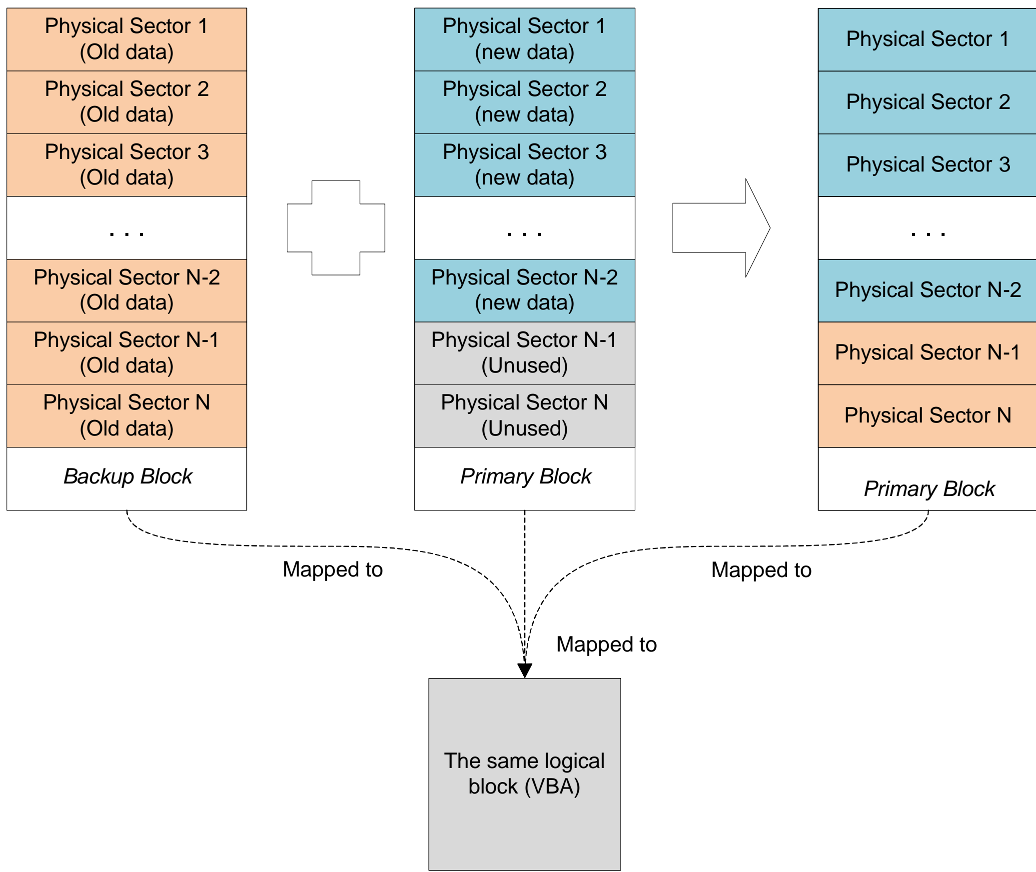


Figure 6-16. QuickMerge for Non-sequential Sector Map

- mergeBlocksCore: When the upper layer is writing to a sector, if any error occurs, that means that the block, to which the sector belongs, is bad, so WL has to merge the backup block and primary block into a new block. Finally, the backup block is erased and the previous primary block is marked as bad.

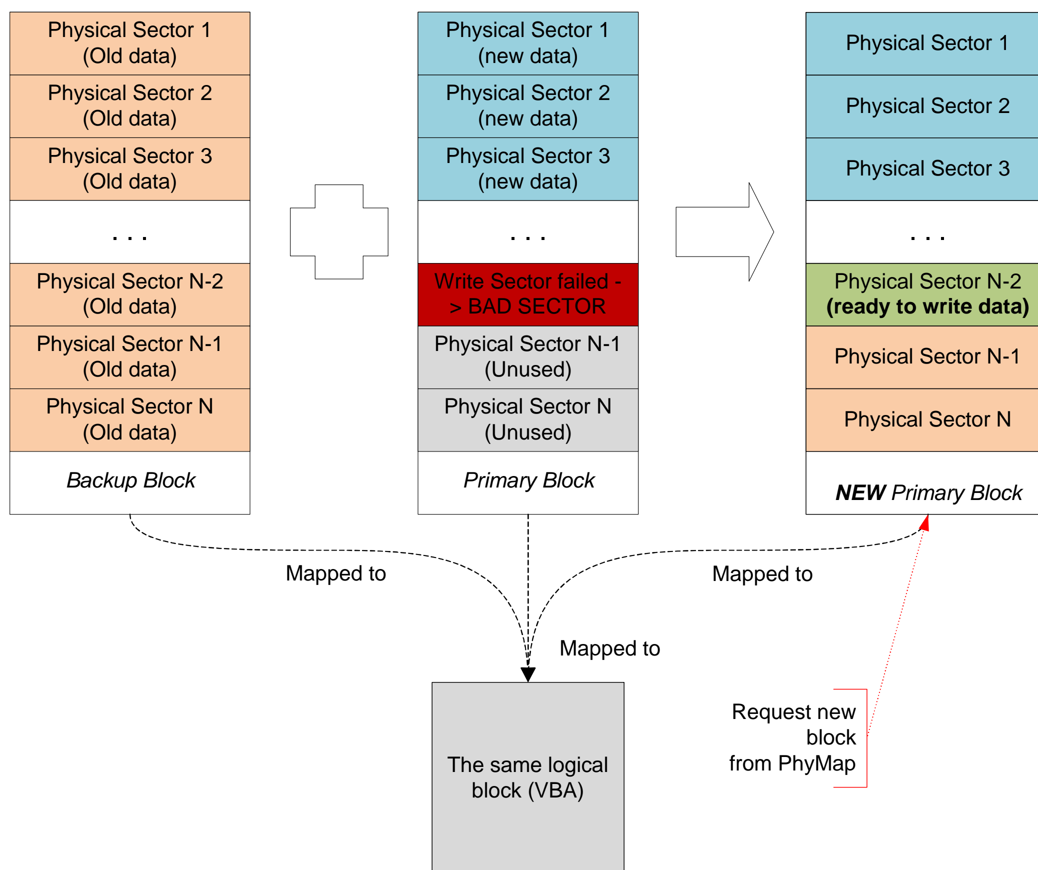


Figure 6-17. MergeBlocksCore for Non-sequential Sector

NOTE

Occasionally, because of power-loss, the backup block and the primary block are not merged together. In this situation, two physical blocks are assigned to only one logical block. When the conflict occurs, WL needs to re-merge the blocks.

Revision History

To provide the most up-to-date information, the revision of our documents on the World Wide Web will be the most current. Your printed copy may be an earlier revision. To verify you have the latest information available, see freescale.com/mqx.

The following revision history table summarizes changes contained in this document.

Revision Number	Revision Date	Description of Changes
Rev. 1.0	04/2012	Initial Release coming with MQX 3.8.0.
Rev. 1.1	07/2012	Update document for MQX 3.8.1.
Rev. 1.2	12/2012	Update document for MQX 4.0.0.
Rev. 1.3	06/2013	Update documents for MQX 4.0.2. Language improvements.
Rev. 1.4	12/2013	Updates specific to MQX 4.1.0-beta release.