

---

# Contents

---

<b>Acknowledgments</b> . . . . .	xi
<b>Foreword 1</b> . . . . .	xiii
Pierre FICHEUX	
<b>Foreword 2</b> . . . . .	xv
Maryline CHETTO	
<b>Part 1. Introduction</b> . . . . .	1
<b>Chapter 1. General Introduction</b> . . . . .	3
1.1. The outburst of digital data . . . . .	3
1.2. Performance and power consumption of storage systems . . . . .	4
1.3. Memory hierarchy and storage technology . . . . .	6
1.4. Introduction to flash memory integration . . . . .	8
1.5. Scope of the book . . . . .	11
1.6. Target audience . . . . .	11
1.7. Outline of the book . . . . .	12
1.8. How to read this book . . . . .	13
<b>Chapter 2. Flash Memories: Structure and Constraints</b> . . . . .	15
2.1. General presentation of flash memory . . . . .	16
2.1.1. The different types of flash memory . . . . .	16
2.1.2. Operating physical principles . . . . .	16

2.1.3. Simplified hierarchical architecture of a NAND flash memory chip . . . . .	18
2.1.4. Operations on flash memory . . . . .	21
2.2. Constraints and limitations . . . . .	24
2.2.1. Erase-before-write constraint . . . . .	24
2.2.2. Wear constraint . . . . .	25
2.2.3. Reliability limitation . . . . .	26
2.3. Flash memory constraint management systems: general concepts . . . . .	26
2.3.1. Management of erase-before-write constraint . . . . .	27
2.3.2. Wear leveling . . . . .	31
2.3.3. Reliability management . . . . .	32
2.3.4. Constraint management systems . . . . .	32
2.4. Conclusion . . . . .	33
<b>Chapter 3. Evaluation of Performance and Power Consumption of Storage Systems . . . . .</b>	<b>35</b>
3.1. Benchmarking storage systems based on flash memory . . . . .	36
3.1.1. Micro-benchmarks . . . . .	37
3.1.2. Macro-benchmarks . . . . .	39
3.1.3. I/O traces . . . . .	41
3.2. Performance and power consumption metrics of storage systems . . . . .	42
3.2.1. Performance metrics . . . . .	42
3.2.2. Power consumption metrics . . . . .	44
3.3. Performance and power consumption measurements for flash memory based storage systems . . . . .	44
3.3.1. Performance exploration through measurements . . . . .	45
3.3.2. Exploration of the power consumption of storage systems based on NAND flash memory through measurements . . . . .	47
3.4. Evaluation of performance and power consumption through simulation . . . . .	48
3.4.1. General concepts . . . . .	48
3.4.2. FlashSim . . . . .	50
3.4.3. NandFlashSim . . . . .	52
3.4.4. Other simulators and general comparison . . . . .	52
3.5. Conclusion . . . . .	52

---

<b>Part 2. Embedded Domain and File Systems for Flash Memory: Flash File Systems</b> . . . . .	55
<b>Chapter 4. Flash File Systems</b> . . . . .	57
4.1. General presentation of FFSs . . . . .	57
4.1.1. Storage management and flash memory constraints . . . . .	58
4.1.2. Embedded constraints and scalability of FFSs . . . . .	59
4.2. Integration of FFS storage systems in computer systems: the Linux example . . . . .	60
4.2.1. Linux Virtual File System <i>VFS</i> . . . . .	61
4.2.2. NAND driver <i>MTD</i> . . . . .	62
4.3. Presentation of the most popular FFSs: JFFS2, YAFFS2 and UBIFS . . . . .	63
4.3.1. JFFS2 . . . . .	64
4.3.2. YAFFS2 . . . . .	66
4.3.3. UBI and UBIFS . . . . .	69
4.4. Other state-of-the-art FFSs . . . . .	71
4.5. Conclusion . . . . .	73
<b>Chapter 5. Methodology for Performance and Power Consumption Exploration of Flash File Systems</b> . . . . .	75
5.1. General presentation of exploration methodology . . . . .	76
5.1.1. Methods and tools . . . . .	76
5.1.2. Hardware platform . . . . .	77
5.2. A toolset for performance exploration of FFS-based systems on Linux . . . . .	78
5.2.1. Flashmon . . . . .	80
5.2.2. VFSSMon and FuncMon . . . . .	84
5.3. Exploration of power consumption: Open-PEOPLE platform . . . . .	87
5.4. Conclusion . . . . .	91
<b>Chapter 6. Performance and Power Consumption of Dedicated File Systems: Experimental Results</b> . . . . .	93
6.1. Hardware and driver levels . . . . .	93
6.1.1. Performance and power consumption of basic flash operations . . . . .	94
6.1.2. Impact of the MTD read buffer . . . . .	96
6.1.3. Conclusion . . . . .	99

6.2. FFS level – focus on JFFS2 . . . . .	99
6.2.1. Read at the FFS level . . . . .	99
6.2.2. Write at the FFS level . . . . .	108
6.2.3. Conclusion . . . . .	116
6.3. VFS level . . . . .	117
6.3.1. Page cache . . . . .	117
6.3.2. Read-ahead mechanism . . . . .	120
6.3.3. The write-back mechanism . . . . .	122
6.3.4. Conclusion . . . . .	123
6.4. Conclusion . . . . .	123
<b>Part 3 . Flash Translation Layers . . . . .</b>	<b>127</b>
<b>Chapter 7. Flash Translation Layer . . . . .</b>	<b>129</b>
7.1. Introduction . . . . .	129
7.2. Basic mapping schemes . . . . .	130
7.2.1. Page-level mapping scheme . . . . .	131
7.2.2. Block-level mapping scheme . . . . .	131
7.2.3. Hybrid mapping scheme . . . . .	132
7.3. Complex mapping schemes . . . . .	133
7.3.1. Log block FTL . . . . .	134
7.3.2. Page-level mapping FTL . . . . .	138
7.3.3. FTL with partitioned flash memory . . . . .	139
7.4. Wear leveling . . . . .	140
7.4.1. Wear leveling based on the number of erase operations . . . . .	141
7.4.2. Wear leveling based on the number of write cycles . . . . .	142
7.5. Garbage collection algorithms . . . . .	142
7.6. Cache mechanisms for flash memory . . . . .	144
7.7. Conclusion . . . . .	146
<b>Chapter 8. Methodology for the Evaluation of SSD Performance and Power Consumption . . . . .</b>	<b>149</b>
8.1. Introduction . . . . .	150
8.1.1. Method and tools . . . . .	150
8.1.2. Hardware platform . . . . .	151
8.2. I/O software stack in Linux . . . . .	151
8.2.1. The generic block layer . . . . .	153

---

8.2.2. The I/O scheduler . . . . .	154
8.2.3. The device driver . . . . .	156
8.3. Context: the Cloud . . . . .	156
8.4. I/O monitoring tools for performance exploration . . . . .	157
8.4.1. Level 1: the hypervisor . . . . .	158
8.4.2. Level 2: host VFS . . . . .	160
8.4.3. Level 3: file system . . . . .	162
8.4.4. Level 4: block layer . . . . .	162
8.5. Performance and energy consumption analysis . . . . .	166
8.5.1. Measurement of the overall system (PDU) . . . . .	166
8.5.2. Measurement of the storage system (sensors) . . . . .	168
8.6. Conclusion . . . . .	169
<b>Chapter 9. Performance and Power Consumption of SSD Based Systems: Experimental Results . . . . .</b>	<b>171</b>
9.1. Introduction . . . . .	171
9.2. Impact of I/Os on performance and energy consumption . . . . .	172
9.3. A macroscopic view of performance and power consumption of storage systems . . . . .	174
9.3.1. Hardware/software configuration for experiments . . . . .	175
9.3.2. Measurement results . . . . .	176
9.4. A microscopic view of performance and power consumption of storage systems . . . . .	185
9.4.1. The use of micro-benchmarks . . . . .	185
9.4.2. Video application case study . . . . .	190
9.5. Conclusions . . . . .	198
<b>Part 4. Emerging Non-volatile Memories . . . . .</b>	<b>201</b>
<b>Chapter 10. Emerging Non-volatile Memories . . . . .</b>	<b>203</b>
10.1. Introduction . . . . .	203
10.2. NVM integration . . . . .	204
10.2.1. Integration as a storage system . . . . .	204
10.2.2. Integration as a main memory . . . . .	206
10.2.3. Integration in CPU caches . . . . .	206
10.3. PCM or phase-change memory . . . . .	207
10.3.1. Basic concepts . . . . .	207

10.3.2. PCM integration . . . . .	208
10.3.3. PCM as a main memory . . . . .	208
10.3.4. PCM as a storage system . . . . .	209
10.3.5. Open questions . . . . .	210
10.4. MRAM or magneto-resistive memory . . . . .	211
10.4.1. Basic concepts . . . . .	212
10.4.2. MRAM integration . . . . .	213
10.4.3. Open questions . . . . .	215
10.5. FeRAM or ferroelectric memory . . . . .	215
10.5.1. Basic concepts . . . . .	216
10.5.2. FeRAM integration . . . . .	217
10.6. ReRAM or resistive memory . . . . .	218
10.6.1. Basic concepts . . . . .	219
10.6.2. ReRAM integration . . . . .	221
10.6.3. Open questions . . . . .	222
10.7. Conclusion . . . . .	223
<b>Conclusion . . . . .</b>	<b>225</b>
<b>Bibliography . . . . .</b>	<b>229</b>
<b>Index . . . . .</b>	<b>249</b>