Journal of Network and Computer Applications 63 (2016) 125–139

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

journal homepage: www.elsevier.com/locate/jnca

A page-granularity wear-leveling (PGWL) strategy for NAND flash memory-based sink nodes in wireless sensor networks

Debao Wei [a], Libao Deng [b,*], Peng Zhang [a], Liyan Qiao [a], Xiyuan Peng [a]

[a] *School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin 150080, China*
[b] *School of Information and Electrical Engineering, Harbin Institute of Technology at Weihai, Weihai 264209, China*

ARTICLE INFO

Article history:
Received 8 June 2015
Received in revised form
5 December 2015
Accepted 14 December 2015
Available online 11 February 2016

Keywords:
Wireless sensor networks
Sink nodes
Massive storage management
Flash memory
Page-granularity wear leveling
Bit error rate prediction

ABSTRACT

Sink nodes are the data centers of wireless sensor networks (WSNs), and the storage management scheme for such nodes is vital, particularly in applications such as wireless multimedia sensor networks that involve the collection of massive amounts of data. NAND flash memory is often employed in sink nodes because of its excellent characteristics. Because the lifetime of NAND flash memory is highly restricted by the bit error rate (*BER*), we present a novel page-granularity wear-leveling (PGWL) strategy to extend the lifetime of NAND flash memory. The concept of PGWL is motivated by two main experimental observations obtained from our own experimental platform for NAND flash memory: first, the raw bit error rate (*RBER*) distribution exhibits a distinct variance in endurance among different pages, and this variance is more significant than that among different blocks; second, programming relief operations (consisting of only erasing, not programming) can clearly reduce both program-disturb and retention errors. In this study, we first present a practical average *RBER* prediction model to evaluate the reliability of flash pages using the system clock of the sink node. Thus, the PGWL strategy enables self-adaptive leveling of the *RBER* growths of different pages in real time by introducing page-granularity wear leveling instead of block-granularity wear leveling to exploit the lifetime potency of each page in a block. Experimental results show that PGWL can extend the lifetime of 2 × -nm NAND flash memory by 88.3% compared with traditional bad block management (BBM), while experiencing at most a 0.85% degradation in data throughput speed compared with the conventional sector mapping scheme.

1. Introduction

In the past decade, wireless sensor networks (WSNs) have been applied in environmental monitoring, seismic and structural monitoring, medical care services and a large number of other applications (Yang, 2014). In WSNs, monitoring can be implemented using one of three techniques. First, each sensor node may transmit its generated data directly to a sink node. This approach is referred to as sense and send (Wang et al., 2010). Second, every sensor node may aggregate its own generated data and data received from its children nodes and then send these aggregated data to its parent node. This scheme is called sense, merge and send (Wang et al., 2012). Third, each sensor node may store its own generated data in its local memory. The data are aggregated and sent to the sink node when it is queried. This approach is called sense, store, merge and send (Zeinalipour-Yazti et al., 2005). Conventional approaches in WSNs require that data be transferred from sensor nodes to a centralized sink node because the storage capability in sensor nodes is limited. On the one hand, WSNs usually consist of a large number of sensor nodes. Thus, although the amount of data in each sensor node is small, the amount of gathered data in the sink node is high. In an application scenario that requires periods of data collection, the writing frequency is high for a short duration of time after data collection. In this case, the storage processing of sink node is faced with a reliability challenge. On the other hand, the availability of inexpensive hardware such as CMOS cameras and microphones that are able to capture multimedia content from the environment has fostered the development of Wireless Multimedia Sensor Networks (WMSNs) (Akyildiz et al., 2007). In WMSNs, the amount of multimedia data in the sink node is large. Above all, optimizing the storage management of the sink node is important when massive amounts of data are stored over time. In this paper, we focus on the storage reliability of sink nodes.

NAND flash memory is extensively employed in sink nodes because of its small size, low power consumption and resistance to shocks (Jiang et al., 2015). NAND flash memory is continuously

---

[*] Corresponding author.
E-mail address: denglibao_paper@163.com (L. Deng).

http://dx.doi.org/10.1016/j.jnca.2015.12.010
1084-8045/

being scaled down to achieve high storage capacities and low costs. Thus, the gap between two adjacent threshold voltages (V_{th}) decreases (Cai et al., 2013). This aggressive scaling causes reliability degradation Park et al., 2014, which results in low endurance because each flash memory cell can tolerate only a limited number of program/erase (P/E) cycles (Pon et al., 2014). Wear leveling (Chang, 2007) is a vital technique for improving the effective endurance of NAND flash memory. Over time, an increasing number of blocks are marked as bad (Chung et al., 2009) and made unavailable for storage use. The entire chip will be considered defective when the number of bad blocks reaches a certain threshold defined by the manufacturer (typically 2% Micron Technology Inc.).

Chang et al. reviewed existing wear-leveling schemes and proposed a dual-pool algorithm (Chang, 2007), which separates blocks into a hot pool and a cold pool depending on their erase counts. On occasion, blocks may exchange data and be moved to the opposite pool. Murugan et al. proposed a static wear-leveling algorithm named Rejuvenator for large-scale NAND flash memory. Rejuvenator adapts to changes in workload and minimizes the cost of expensive data migration (Murugan and Du, 2011). Wang et al. proposed a technique to extend the lifetime of NAND flash memory by salvaging bad blocks (Wang and Wong, 2012). They combined the healthy pages from multiple bad blocks to form a smaller set of virtual healthy blocks. Nevertheless, this technique functions until entire blocks have turned bad. It somewhat limits the release of lifetime potential (1.17 × lifetime extension at best). Pan et al. studied the variance in block endurance and suggested an adaptation of the classical wear-leveling algorithm to apply to blocks based on their *BERs* rather than their P/E cycle counts (Pan et al., 2013). The authors assumed homogeneous page endurance and negligible faulty bit count variance among P/E cycles.

As mentioned above, the wear-leveling schemes both belong to the flash translation layers (FTLs) of the block granularity (Ban, 1999). Generally, a flash memory contains millions of pages. For instance, one 32 Gb flash memory with 4096 blocks of 256 pages requires 4096 kB of storage for a page-mapping table, while a block-mapping table requires only 16 kB. However, a block-mapping table translates the most significant bits of a logical address to a physical block number, while the offset of a physical address is fixed to the least significant bits of the logical address (Hu et al., 2010). In addition, block-granularity FTLs perform poorly with higher erasure counts, particularly under random write workloads. On the contrary, the page-granularity FTL scheme is arguably the best FTL scheme, as it facilitates the page-mapping table and usually yields better performance and a longer lifetime (Thontirawong et al., 2014). In addition, with the increase in RAM size, the problem of occupying larger RAM in the page-granularity FTLs is gradually weakened. Thus, Jimenez et al. discovered a larger endurance variance at the page level than at the block level (Jimenez et al., 2014), and as a consequence, they were the first to propose a wear-unbalancing technique. This approach allows the strongest cells to relieve the weaker ones to lengthen the overall lifetime of the flash memory. However, this technique encounters several problems. First, the wear-unleveling technique focuses only on program-disturb errors rather than data retention errors, although many researchers and our own observations have indicated that the latter is the more significant type of error (Mielke et al., 2008). Second, the wear-unleveling technique can only manage hot blocks, which are a minority among all blocks, and is even subject to a maximum threshold value of the relieved page percentage. This will strongly limit the lifetime extension that can be achieved for a NAND flash storage system in which this technique is deployed. Third, in the wear-unleveling technique, weak pages are defined as those whose *RBERs* exceed a specified threshold. When weak pages are found, they should be relieved to increase the number of P/E cycles that the error correction code (ECC) can tolerate. This type of operation can have a effect on the weak pages only after a relatively long retention time; it is not as effective when the system is operating in real time. Thus, the effect of wear unleveling is limited.

In this paper, we first study the page endurance variance of flash memory given a long retention time. Then, by virtue of other experimental observations, we propose a novel page-granularity wear-leveling (PGWL) algorithm that can be adopted in any FTL mapping scheme at the page level to extend the lifetime of the flash memory. Because there is a significantly larger endurance variance on the page level than on the block level, giving up the entire block because of the failure of the weakest-performing page is a serious waste. Thus, by applying the wear-leveling algorithm to page endurance, there is more opportunity to expand the lifetime of the flash memory. This paper contributes to the research in the following ways.

- We obtain large amounts of data regarding the *RBER* growth of different pages in different blocks from our experimental platform, and we determine the distinct *RBER* growth variance among the different pages within a block.
- We present the first proposal of an *RBER* growth estimation model, which describes the average increases in the *RBER* with an increasing number of P/E cycles and with increasing retention time.
- We present the first proposal of a PGWL strategy based on the formulated average *RBER* growth estimation model to dynamically relieve weak pages in real time.
- We present a new lifetime definition for NAND flash memory. Based on real experimental data obtained from our test platform, the evaluation shows that PGWL can extend the lifetime of 2 × -nm flash memory by 88.3%.
- We use a real workload to test the I/O performance effect of an FTL that incorporates our PGWL strategy. The experimental results demonstrate that the effect on the I/O performance caused by PGWL can be ignored.

The remainder of this paper is organized as follows. Section 2 provides an overview of WSNs and NAND flash memory. Section 3 presents the motivations for this study, including many vital observational results obtained using our experimental platform. Section 4 presents the average *RBER* growth estimation model and the proposed PGWL strategy for NAND flash memory. Section 5 introduces our experimental platform and presents a performance evaluation of PGWL, including an assessment of the lifetime extension and the effect on I/O performance when our PGWL strategy is applied. Finally, the conclusions are presented in Section 6.

2. Background

2.1. An overview of wireless sensor networks

Figure 1 shows the basic architecture of a WSN, which consists of sensor nodes, relay nodes and a sink node. The sensor nodes are sources of information; they may also forward messages in the network. The sink node is the data convergence node; all sensor nodes ultimately send their data to the sink node. A relay node is used to transfer sensor data when the distance to the sink node exceeds the communication capability of the sensor node. Compared with those of the sensor nodes, the sink node's computing power, storage capacity and communication capability are relatively strong. The sink connects the sensor network to an external network (such as Ethernet or General Packet Radio Service