Writeback-Aware LLC Management for PCM-Based Main Memory Systems

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With the increase in the number of data-intensive applications on today's workloads, DRAM-based main memories are struggling to satisfy the growing data demand capacity. Phase Change Memory (PCM) is a type of non-volatile memory technology that has been explored as a promising alternative for DRAM-based main memories due to its better scalability and lower leakage energy. Despite its many advantages, PCM also has shortcomings such as long write latency, high write energy consumption, and limited write endurance, which are all related to the write operations.

In this article, we propose a novel writeback-aware Last Level Cache (LLC) management scheme named WALL to reduce the number of LLC writebacks and consequently improve performance, energy efficiency, and lifetime of a PCM-based main memory system. First, we investigate the writeback behavior of LLC sets and show that writebacks are not uniformly distributed among sets; some sets observe much higher writeback rates than others. We then propose a writeback-aware set-balancing mechanism, which employs the underutilized LLC sets with few writebacks as an auxiliary storage for the evicted dirty lines from sets with frequent writebacks. We also propose a simple and effective writeback-aware replacement policy to avoid the eviction of the dirty blocks that are highly reused after being evicted from the cache.

Our experimental results show that WALL achieves an average of 30.9% reduction in the total number of LLC writebacks, compared to the baseline scheme, which uses the LRU replacement policy. As a result, WALL can reduce the memory energy consumption by 23.1% and enhance PCM lifetime by 1.29×, on average, on an 8-core system with a 4GB PCM main memory, running memory-intensive applications.

CCS Concepts: • **Computer systems organization** → **Processors and memory architectures**; • **Hardware** → **Emerging technologies**;

Additional Key Words and Phrases: Phase change memory, write endurance, energy consumption, performance, last level cache

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1 INTRODUCTION

DRAM can no longer satisfy the memory capacity demands of the modern-day applications due to its scalability limit; it is difficult to scale DRAM cells down to feature sizes smaller than 16nm [34]. Moreover, DRAM consumes considerable amount of static and refresh power. It is estimated that DRAM power constitutes 20% to 40% of the total system's energy in today servers [16]. Phase Change Memory (PCM) is a promising technology that is gaining interest as a DRAM replacement for building future main memories [2, 21, 20, 23, 26]. PCM is a random-access memory that is about 2 to 4 times denser than DRAM [14]. In addition to its scalability, zero standby power, low read latencies, and resiliency to soft errors are some of the intriguing features of a PCM-based main memory [26]. However, PCM suffers from some major shortcomings including long write latency, high write energy consumption, and limited write endurance, which are all related to write operations. The impact of write operations on PCM will be discussed in detail in Section 2.2.

To deal with the above-mentioned overheads of write operations in PCM, there are two common types of solutions. First, category is the optimizations on the PCM architecture to minimize the impact of writes. For example, modifying the request scheduling policy in the PCM main memory to alleviate the performance overheads of writes on reads [1, 24, 32, 38]; or modifying the PCM main memory architecture to reduce or balance the write loads on PCM cells and enhance their lifetime [37]. Second, category is reducing the total number of writes sent to the PCM main memory by modifying the Last Level Cache (LLC)'s management policies [28]. Our work falls into the latter category.

We propose *WALL*, a novel dynamic writeback-aware LLC management scheme to improve performance, energy efficiency, and lifetime of a PCM-based main memory system by reducing the number of writebacks from LLC to PCM. In general, *WALL* consists of a writeback-aware set balancing mechanism and a writeback-aware replacement policy. Writebacks of the last level cache are not uniformly distributed among its sets; some sets have far more writebacks than others, while some sets rarely see writebacks (please see Section 3.1 for detailed results). The proposed set balancing mechanism reduces the number of writebacks by employing the underutilized sets with infrequent writebacks as auxiliary storage units (inside LLC) for the evicted dirty lines from sets with many writebacks. Moreover, the proposed writeback-aware replacement policy tries to keep the dirty blocks that are frequently accessed after eviction in LLC. To do so, it allows the dirty eviction victims (i.e., dirty LRU block) to stay in the cache and be re-accessed; if the block becomes LRU block again without being accessed, then it will be evicted from LLC then.

To implement the set balancing mechanism of *WALL*, we first proposed a simple partner assignment strategy [22]. The simple partner assignment strategy classifies sets into three categories: (1) *writer*, or sets with frequent writebacks; (2) *non-writer*, or sets with infrequent writebacks; and (3) *neutral*, sets that are neither *writer* nor *non-writer*. Each *writer* set is partnered with a *non-writer* set until no *non-writer* sets are left un-partnered. Although this partner assignment strategy has simple implementation and works effectively for many workloads, it also has two limitations. First, it cannot always balance the number of *writer* and *non-writer* sets; thereby some *writer* or *non-writer* sets may remain without partners. Second, it does not guarantee the inclusion of *writer* sets with the largest number of writebacks or *non-writer* sets with the smallest number

Fig. 1. A schematic showing how PCM cells can be addressed, and a close-up view of the phase-change element [11].

Fig. 2. The impact of reducing write traffic on PCM lifetime.

of writebacks in the partner assignment process. We further propose three novel partner assignment strategies called *contraction*, *expansion* and *ConExp* to alleviate the limitations of the simple partner assignment strategy. Specifically, when the number of *writer* and *non-writer* sets are imbalanced, the *expansion* strategy includes some of the *neutral* sets, which are the most eligible to be considered *writer* or *non-writer*, in the partner assignment process. However, the *contraction* strategy addresses the second limitation of the simple partner assignment strategy by first assigning partners to *writer* sets with the largest number of writebacks and *non-writer* sets with the smallest number of writebacks. The *ConExp* strategy is a combination of the two *contraction* and *expansion* strategies to deal with both limitations of the simple partner assignment strategy.

We evaluate our proposed schemes by running SPEC CPU2006, NAS and PARSEC workloads on gem5 [10] integrated with modified NVMAIN [19], which simulates the PCM-based main memory system. The experimental results indicate that our scheme can reduce the total number of LLC writebacks by 30.9%, on average, compared to a baseline scheme, which uses the LRU replacement policy. As a result, for a system with eight cores and a 4GB PCM main memory, it can enhance PCM lifetime by 1.29 $\times$, on average, and reduce the memory energy consumption by 23.1%, on average.

The rest of this article is organized as follows. Section 2 discusses background. Section 3 describes the proposed scheme. Section 4 presents the experimental results. The related work is discussed in Section 5. Finally, Section 6 summarizes the work.

2 BACKGROUND

2.1 Phase Change Memory (PCM)

Phase Change Memory (PCM) is a type of non-volatile memory technology that has been extensively explored as a DRAM alternative. Figure 1 illustrates the structure of a PCM cell. To store bit information, a PCM cell uses the phase change property of a material known as chalcogenide that can be in two physical states: amorphous state that has high resistance and represents bit “0” and crystalline state that has low resistance and represents bit “1” [26, 30]. Writing on a PCM cell is performed by heating the storage material via applying a short but high voltage pulse and then cooling it down. The rate at which the material is cooled down determines the stored bit; slow cooling stores bit “1” and fast cooling stores bit “0” on the cell. To later read a PCM cell, the state of the material is detected by applying a low voltage to it [33]. The resistive characteristic of PCM cells allows them to retain their data for a long time with no need for periodic refreshes.

2.2 Impact of Write Operations On PCM

The main advantages of PCM over DRAM are its scalability and non-volatility. However, PCM has higher write access energy and latency than DRAM (2 to 8 times [14]) and limited write endurance.

Fig. 3. Cumulative distribution of writebacks over LLC sets. (NOTE: sets are sorted in a descending order based on their total number of writebacks.)

A previous study [1] has shown that the long-latency write operations can increase the effective latency of read requests by 1.2 to 1.8 times. In addition, the number of write operations to PCM affects its lifetime. The PCM-based memory system lifetime can be estimated as [23]:

$$\text{System Lifetime} = Y(\text{years}) \approx \frac{w_{\max} \cdot S}{B} \cdot 2^{-25}$$

In this formula, B is the write traffic (or write rate, GBps), Y is the maximum number of years that a PCM with size S and cell endurance of $w_{\max}$ can last. The impact of reducing the write traffic on the expected PCM lifetime is shown in Figure 2. It should be noted that the results of the figure are independent of S and $w_{\max}$. We also assume that the writes are distributed uniformly across the entire PCM memory.

3 WALL SCHEME

Our proposed scheme, WALL [22], consists of a writeback-aware set balancing mechanism and a writeback-aware replacement policy. The WALL set balancing mechanism classifies LLC sets into three categories, **writers** (i.e., *frequent writeback sets*), **non-writers** (i.e., *infrequent writeback sets*), and **neutral**. To reduce the number of write requests to PCM, the *non-writer* sets are used to store the evicted dirty lines from the *writer* sets. Specifically, each *writer* set is partnered with a *non-writer* set (until there is no *non-writer* set left) and upon eviction of a LRU dirty line from the *writer* set, the line will be inserted into the set's partner instead of being written back to the main memory. Besides, our writeback-aware replacement policy further reduces the number of LLC writebacks by keeping the *frequent writeback blocks* in the cache.

3.1 Motivation

In this section, we explain the motivation of our work by investigating LLC sets' writeback behavior. To this end, we have run three workloads, selected from different benchmark suites (*sp* from NAS [18], *gcc* from SPEC CPU2006, and *streamcluster* from PARSEC [4]) on our simulated system (please see Section 4.1 for more details). Figure 3 shows the cumulative distribution of writebacks over LLC sets.

The results reveal that majority of the writebacks from the LLC to main memory are generated by less than half of the LLC sets. For *sp*, 25% of the LLC sets, with the largest number of writebacks (i.e., *frequent writeback sets*), are responsible for 41.1% of the total number of writebacks. However, 12.5% of the sets, with the smallest number of writebacks (i.e., *infrequent writeback sets*), are accountable for only 5.3% of the total number of writebacks. In general, some sets tend to write back much more frequently than others. For example, since 22.9% of the writebacks for *sp* are performed by 12.5% of the *frequent writeback sets*, a *frequent writeback set* writes to main memory about four times more frequently than an *infrequent writeback set*, on average. Similarly, for *gcc*, 25% of the *frequent writeback sets* perform 49.6% of the writebacks while the same percentage of the

infrequent writeback sets are responsible for only 10.8% of the total number of writebacks. Finally, for *streamcluster*, 20.7% of the writebacks are sourced from 6.3% of the *frequent writeback sets*.

Based on this observation, we propose a set balancing mechanism to reduce the number of writes to a PCM-based main memory system. More specifically, WALL aims to prevent a noticeable percentage of write traffic from reaching the PCM main memory by taking the non-uniform distribution of LLC set writebacks into account. The idea of avoiding the eviction of LLC sets' highly reused dirty blocks, which are likely to become eviction victims soon after being re-inserted in the cache (i.e., *frequent writeback blocks*), has been discussed in a recent study called WADE [28]. WADE partitions the blocks of each LLC set into two groups, *frequent writeback blocks* and *non-frequent writeback blocks* and tries to keep the *frequent writeback blocks* in the set to reduce the number of writes to the main memory. However, one major shortcoming of WADE is that for every set, irrespective of its characteristics, it considers the *nonfrequent writeback blocks* of the set as the only replacement candidates; while other sets might have clean, underutilized lines. Moreover, WADE is rather complex. In our study, a simple but effective writeback-aware replacement policy is also proposed to keep the *frequent writeback blocks* in the cache. Overall, WALL can reduce the number of LLC writebacks by considering the writeback behavior of sets and their blocks at the same time.

3.2 Writeback-Aware Set Balancing Scheme

To decide whether a set is a *writer* or *non-writer*, WALL monitors the number of writebacks and accesses of each LLC set for a time window. Generally, a set is “*writer*” if the number of writebacks from it exceeds a certain threshold (i.e., τ_{high_wb}), but a set with relatively small number of writebacks is not necessarily a good partner set. A *non-writer* set must have enough space to store the evicted dirty blocks of its *writer* partner without noticeable performance penalty. To measure the degree to which a set can hold its working set, we employ a saturating arithmetic miss counter (i.e., saturation counter) like that in a previous study [27]. For a K-way set associative cache, the working range of the saturation miss counter is from 0 to $2K-1$ [27]. Upon every access, the saturation counter is incremented if the access results in a miss, and it is decremented otherwise. To count the number of writebacks, we also use a saturating writeback frequency counter for each set that is incremented upon every writeback from the set. At the end of a monitoring period, we divide the writeback values by two (i.e., shift the counters right one bit). This reduces the impact of set's writeback behavior in the past on the type of the set in the current time period.

WALL considers a set “*non-writer*” if both of saturation and writeback counters are smaller than specific thresholds (i.e., τ_{sat} , τ_{low_wb}). For a set with writeback frequency counter of W and saturation counter of M , the set is considered *writer* if $(W \geq \tau_{high_wb})$, *non-writer* if $(M \leq \tau_{sat} \ \& \ W \leq \tau_{low_wb})$ and *neutral* otherwise. We divide the total execution time of programs into epochs of 10^7 accesses to the LLC. On entering an epoch, the partnership between two sets can be easily broken if the *writer* set has no blocks in its *non-writer* partner. The thresholds are re-calculated and if there is a pair of *writer* and *non-writer* sets with no partners, they will be assigned to each other. Note that for a set with partner (i.e., a *writer* set with blocks in its partner or a *non-writer* set that holds some of its partners' blocks), we do not change the set type. Our experiments show that set types rarely change after an initial set type identification epoch and most partnerships remain intact. However, to avoid overfill a *non-writer* set, if the saturation counter of a *non-writer* set reaches $\alpha \times \tau_{sat}$, where α is 2 in our experiments, then the insertion of blocks from its *writer* partner will be suspended until the set's saturation counter retrieves to values smaller than τ_{sat} . To reduce implementation complexities, we assume each *writer* set is partnered with only one *non-writer* set. In other words, the number of the paired *writer* and *non-writer* sets is equal to the size

Fig. 4. Distribution of LLC sets based on the thresholds (wb: writebacks; sat: saturation; *NOTE: sat bars are only for the sets with $wb < \tau_{low_wb}$*).

of the smaller group of *writer* and *non-writer* sets. We later discuss how accesses to sets and their partners are handled in Section 3.4.

To determine the writeback thresholds, three simple steps are followed. First, the arithmetic mean of all the writeback values is computed and referred to as the overall average. Then, τ_{low_wb} is computed as the arithmetic mean of the writeback values smaller than the overall average. Finally, τ_{high_wb} is computed as the arithmetic mean of the writeback values larger than the overall average. Note that since these thresholds cannot guarantee an equal number of *writer* and *non-writer* sets, some *writer* sets may remain without a partner at the end. Moreover, we assume $\tau_{sat} = K/4$ (i.e., K is the set associativity). Figure 4 depicts the distribution of sets based on the discussed thresholds for the workloads shown in Table 3 (see Section 4.1). The results are based on the values obtained after the initial epoch of 10^7 accesses to the LLC. It should be noted that the saturation bars (i.e., bars with horizontal axis title of *sat*) in the figure are only for the sets with writeback counters smaller than τ_{low_wb} . Our results show that the selected thresholds can distinguish different types of sets from each other effectively.

3.3 Writeback-Aware Replacement Policy

In addition to assigning partners to the *writer* sets, WALL enables a writeback-aware replacement policy inside the LLC sets to further reduce the number of writebacks to the PCM. To keep the *frequent writeback blocks* in the cache, such blocks need to be identified first. We propose a much simpler, yet effective method compared to the prediction scheme discussed in WADE [28], because such prediction schemes are usually complex and costly in terms of area, energy, and/or performance overheads.

The intrinsic definition of a *frequent writeback block* is a block that is frequently reused each time after being evicted from the cache. Generally, our scheme avoids the eviction of such blocks by giving the dirty victims a second chance to stay in the cache and be accessed again. To keep track of the dirty blocks that have been given a second chance, a one-bit flag called *FV* (i.e., Former Victim) is considered for each block. We assume the baseline replacement policy is LRU. When a replacement is needed in a LLC set, the dirty status bit of the LRU line (i.e., the eviction victim) is checked; if the LRU block is clean, then it will be evicted from the cache, but if the block is dirty, then two scenarios are possible. First, the block is not a former victim ($FV = 0$). In this case, the line will be moved to the MRU position of the access stack and will be marked as a former victim (i.e., its *FV* flag will be set to “1”), this process will be repeated until finding an eviction victim. Second, the block is a former victim ($FV = 1$) and has become the eviction victim for the second time without being accessed. In this case, the block will be evicted from the cache. If a cache line with $FV = 1$ is accessed, then its *FV* bit will be reset to “0.” The reason is that such block is likely

Fig. 5. WALL design.

to be a *frequent writeback block*. It should be noted that all these steps happen in parallel with the resolution of the miss, thereby there is no performance penalty.

We use the proposed replacement policy for the *non-writer* and *neutral* sets. Since *writer* sets usually have high miss rate values and often choose dirty blocks as eviction victims, for those sets, we use the baseline LRU replacement policy. However, on eviction of a LRU dirty block from a *writer* set with a partner, the block will be inserted into the set's partner.

3.4 Set Balancing Simple Partner Assignment and Access Management

For *writer* sets with large number of writebacks, changing the replacement policy may cause a non-trivial increase in the sets' miss rates. Hence, the writeback-aware replacement policy is applied to those sets that are not *writer* (i.e., *neutral* and *non-writer* sets). Instead, WALL virtually increases the associativity of a *writer* set by assigning a *non-writer* partner to it. We first propose a simple partner assignment strategy and access management for set-balancing LLC. The reason that we have excluded the neutral sets from the partnering process is that it is not beneficial to write from one set to another set with similar writeback or miss frequencies.

The partner of a *writer* set is selected randomly from the *non-writer* sets. To keep tracking the partners, a small direct-access *remap table* is introduced. The indices of the sets' partners are saved in the remap table, which is indexed by set indices. For a set with no partner, its own index is stored. When a LRU dirty line is evicted from a *writer* set with a partner, it will be inserted into the set's partner. To show whether a block in a *non-writer* set is repositioned from the set's *writer* partner or not, a one-bit flag called **RB** (i.e., Repositioned Block) is considered for each block. The *remap table* is also augmented with one-bit flag **P** (i.e., Partnered) for each set to show whether a *writer* set has any blocks in its partner or not. Upon an access to a *writer* set, if the access results in a miss, then the remap table is checked; if **P** is "1," then the set's partner will be accessed for the block; otherwise, main memory will be accessed as usual. If the access also misses in the set's partner, then main memory must be accessed. If all the repositioned blocks of a *writer* set get evicted from its partner, then **P** flag of the *writer* set will be reset to "0."

The design of WALL is depicted in Figure 5. On an eviction of a block from a LLC set, we first decide whether the block needs to be written back to the PCM or not. If not, then depending on the set type, the block either remains in the set as MRU or will be written back into the set's partner.

Fig. 6. Distribution of LLC sets after applying the expansion strategy.

Fig. 7. Distribution of LLC sets after applying the contraction strategy.

To specify the type of each set, a 2-bit register called ST is considered per set (i.e., the set is *writer* if ST = “11,” *non-writer* if ST = “10,” and *neutral* if ST = “00” or “01”).

3.5 Extended Partner Assignment Strategies

The simple partner assignment strategy of WALL (explained in Section 3.4) cannot guarantee an equal number of *writer* and *non-writer* sets. In other words, some *writer* sets may remain without partners at the end of the partner assignment process. In this section, to efficiently exploit the available storage space of the *non-writer* sets and to further reduce the number of writebacks from the *writer* sets, we propose three more partner assignment strategies called *expansion*, *contraction* and *ConExp*, which is a combination of *contraction* and *expansion* strategies.

3.5.1 Expansion Partner Assignment Strategy. The expansion strategy modifies the writeback thresholds to balance the number of *writer* and *non-writer* sets. Specifically, when the number of *non-writer* sets is considerably smaller than the *writer* sets, the expansion strategy finds the most eligible *neutral* sets to be added to the *non-writer* sets. However, when the number of *writer* sets is smaller, the expansion strategy assigns the remaining (without partners) *non-writer* sets, to the *neutral* sets that can benefit the most from the partnership.

To avoid enlarging the group of *writer* or *non-writer* sets unreasonably (i.e., causing more imbalance in the sizes of the two groups), we define an *expansion condition*; the expansion strategy is applicable only when the size of the larger group is at least $\beta \times$ the size of the smaller group. Our evaluations show that $\beta = 1.5$ provides the best balance between the number of *writer* and *non-writer* sets. The writeback thresholds of the expansion strategy are represented as $\tau_{\text{exp_low_wb}}$ and $\tau_{\text{exp_high_wb}}$. When the expansion condition is true, considering a *neutral* set with writeback frequency counter of W and saturation counter of M , the two possible scenarios are as follows: (1) If *non-writer* sets are fewer, then the *neutral* set is considered *semi non-writer* if $M \leq \tau_{\text{sat}}$ and $W \geq \tau_{\text{exp_high_wb}}$. To determine $\tau_{\text{exp_low_wb}}$, the arithmetic mean of the writeback values between $\tau_{\text{low_wb}}$ and the overall average is computed. (2) If *writer* sets are fewer, then the *neutral* set is considered *semi writer* if $W \leq \tau_{\text{exp_low_wb}}$. $\tau_{\text{exp_high_wb}}$ is also computed as the arithmetic mean of the writeback values between the $\tau_{\text{high_wb}}$ and the overall average. Figure 6 shows the distribution of sets with the expansion strategy after the initial monitoring epoch.

The expansion strategy starts by assigning the original *writer* and *non-writer* sets as partners. Then, it continues by assigning the remaining *writer/non-writer* sets to the *semi non-writer/semi writer* sets until no *semi non-writer/non-writer* set remains without a partner.

3.5.2 Contraction Partner Assignment Strategy. Since the number of *writer* and *non-writer* sets are usually not the same, some sets remain without a partner. However, it is beneficial to always keep the *writer* sets with the largest number of writebacks, or “*super writer* sets,” and *non-writer* sets with the smallest number of writebacks, or “*super non-writer*” sets, included in the partner assignment process. The contraction strategy distinguishes the *super writer* and *super*

Table 1. Total Storage Overhead

Type	Storage	Type	Storage
<i>FV</i> per block	16KB	Saturation counter (6-bit) per set	3KB
<i>RB</i> per block	16KB	Writeback counter (8-bit) per set	4KB
<i>P</i> per set	0.5KB	Remap table	6KB
<i>ST</i> per set	1KB	TOTAL	46.5KB

non-writer sets from the rest of the sets using two writeback thresholds called $\tau_{con_high_wb}$ and $\tau_{con_low_wb}$. Specifically, a *non-writer* set with writeback counter of W is considered *super non-writer* if $W \leq \tau_{con_low_wb}$ and a *writer* set with writeback counter of W is considered *super writer* if $W \geq \tau_{con_high_wb}$. To determine the $\tau_{con_low_wb}$, the arithmetic mean of the writeback values smaller than the τ_{low_wb} is computed. Also, $\tau_{con_high_wb}$ is computed as the arithmetic mean of the writeback values larger than the τ_{high_wb} . Figure 7 illustrates the distribution of sets with the contraction strategy after the initial monitoring epoch.

The contraction strategy starts from assigning partners to *super writer* and *super non-writer* sets and then continues by assigning partners to the remaining *writer* and *non-writer* sets.

3.5.3 Contraction-Expansion (ConExp) Strategy. There are two main shortcomings with the expansion strategy. First, since the *semi non-writer* sets are less effective than the *non-writer* sets in reducing the number of writebacks, assigning them as partners to the *super writer* sets should be avoided. Second, although the expansion strategy tries to balance the number of *writer* and *non-writer* sets, the *super writer* or *super non-writer* sets may still be excluded from the partner assignment process. To alleviate these problems, we propose the ConExp strategy, which is a combination of the contraction and expansion strategies. ConExp assigns partners, in order, to the *super* sets, then to the original *writer* and *non-writer* sets, and finally to the *semi* sets, until no *non-writer* or *semi non-writer* set remains without a partner.

It is worth mentioning that the *semi* and *super writer* sets are represented (treated the same) as the *writer* sets and the *semi* and *super non-writer* sets as the *non-writer* sets. Hence, these strategies do not require any additional hardware overheads.

3.6 Overhead Analysis

Table 1 summarizes the storage overhead of WALL. The total storage overhead of WALL is less than 0.6% of the LLC capacity. It is worth mentioning that this overhead is about half of that of WADE [28].

Calculating the writeback thresholds and updating the remap table (i.e., pairing *writer* and *non-writer* sets) are only performed once at the end of each epoch. Hence, their performance impacts are negligible.

4 RESULTS

4.1 Methodology

In this work, we model an 8-core processor using the gem5 full-system simulator integrated with NVMAIN. The system configuration of our experiments is shown in Table 2. The PCM configurations are generated by NVSIM [9] and CACTI [5], the cell parameters used in NVSIM are based on the projections by Reference [7]. The benchmarks used in this study are chosen from NAS [18], SPEC CPU2006, and PARSEC [4] as depicted in Table 3. The selected benchmarks are some of the memory-intensive workloads from the three benchmark suites. For all the workloads, we use either

Table 2. System Configuration

Processor and On-chip Caches	
Cores	8 cores, out-of-order, 2.0GHz
L1-I/D	Split 32KB I/D-cache/core, 4-way, 8-MSHR, 2-cycle hit
L2	256KB/core, 8-way, 12-MSHR, 12-cycle hit
L3 (LLC)	SRAM: Shared, 8MB, 32-way, 32-MSHR, 35-cycle hit
Coherency	MOESI directory, 2×4 grid packet NoC, XY routing
Main Memory	
PCM	4GB, 4 Channel, 1 rank/channel, 4 banks/rank, 400MHz $t_{SET} = 150\text{ns}$, $t_{RESET} = 100\text{ns}$, $t_{RCD} = 120\text{ns}$ Cell endurance = 32×10^6 writes
MC	Four controllers, Open page, 32-entry queues (one read and one write queue), Write drain threshold: high = 80%, low = 50%, Address mapping: page interleaving

Table 3. Evaluated Workloads Characteristics

Workload	RPKI	WPKI	Workload	RPKI	WPKI
from the NAS benchmarks (8-Thread)					
sp	4.98	2.55	ua	3.12	2.67
from the PARSEC benchmarks (8-Thread)					
stream	24.4	0.21	dedup	11.5	8.32
from the SPEC CPU2006 benchmarks					
$8 \times \text{gcc}$	7.42	1.59	$8 \times \text{mcf}$	43.5	9.02
mix1	2.91	1.90	mix2	12.7	4.21
mix1: $4 \times \text{lbn}$, $4 \times \text{bzip}$			mix2: $4 \times \text{cactusADM}$, $4 \times \text{leslie3D}$		

RPKI/WPKI: main memory reads/writes per 1,000 instructions.

sampled reference or native input sets to represent a real-world execution scenario and run the applications for two billion instructions, after two billion instructions for cache warm-up phase. In this article, we compare WALL with (1) *Baseline* that uses the LRU replacement policy, (2) *Baseline double-way*, a baseline cache of the same size with double the associativity, and (3) *WADE*, which is the scheme proposed in Reference [28]. In PCM, we always prioritize reads over writes if write queue is less than 80% full.

4.2 LLC Writeback Reduction

Figure 8 shows the writeback reduction of WALL for the different types of LLC sets. The results are normalized to the baseline scheme. It is worth mentioning that any writeback of a *writer* set's lines from its partner is considered for the original *writer* set.

WALL when using the simple partner assignment strategy achieves an average of 26.6% writeback reduction, compared to the *Baseline* scheme. The three main reasons for this reduction are: (1) The efficacy of the set type identification process. (2) The capability of the writeback-aware set balancing scheme in reducing the *writer* sets' writebacks; the number of writebacks originated from *writer* sets is reduced by 39.5%, on average (i.e., from 33.4% to 20.1% of the *Baseline* total writebacks), while the writebacks originated from *non-writer* sets are increased slightly from 10.4% to 13.1% of the *Baseline* total number of writebacks. (3) The proposed writeback-aware replacement

Fig. 8. WALL's normalized LLC writebacks reduction.

Fig. 9. Writebacks reduction of evaluated schemes.

Fig. 10. Writebacks reduction of WALL with different partner assignment strategies.

policy has been able to reduce the writebacks originated from the *neutral* sets by 28.6%, on average (i.e., from 56.2% to 40.1% of the *Baseline* total writebacks). It is worth noting that for some of the benchmarks, the proposed replacement policy has also been able to reduce the number of writebacks originated from the *non-writer* sets. Figure 9 compares the normalized writebacks reduction of the evaluated schemes. Compared with *Baseline double-way* and *WADE*, WALL reduces the number of writebacks by 23.3% and 16.4%, on average, respectively. Based on the results, duplicating the set associativity is not very helpful in reducing the number of LLC writebacks; our baseline implementation is 32-way and increasing the associativity beyond that does not cause a significant improvement.

Figure 10 compares the writeback reduction of the extended partner assignment strategies proposed in Section 3.5. The results are normalized to the simple partner assignment strategy. The expansion strategy can reduce the number of writebacks by 3.6%, on average (by up to 9.2% for *gcc*). This reduction is caused by including more *writer* (or *semi writer*) sets in the partner assignment process. The contraction strategy can reduce the number of writebacks by 3.4%, on average (by up to 4.6% for *ua*). The reason for this reduction is the fact that sets with highest write frequency (*super writer* sets) are always assigned a partner, which is in the *super non-writer* sets (i.e., one that has the smallest write frequency). ConExp, which uses the benefits of both strategies, can reduce the number of writebacks by 5.9%, on average, compared to the simple partner assignment strategy. In other words, ConExp strategy can reduce the number of writebacks by 30.9% compared to the *Baseline* scheme.

Fig. 11. WALL's normalized MPKI.

Fig. 12. MPKI of evaluated schemes.

4.3 LLC Miss Rate

Figure 11 shows the normalized MPKI (Misses Per Kilo Instructions) of WALL for different types of LLC sets. The accesses that result in a hit in a *writer* set's partner are considered for the original *writer* set. Figure 12 shows the normalized MPKI of the evaluated schemes.

Results reveal that WALL when using the simple partner assignment strategy reduces the MPKI by 2.4%, on average, compared to the *Baseline*. This reduction is mainly because WALL stores the frequently reused dirty blocks of *writer* sets in the *non-writer* partners and performs similarly to doubling the associativity of those cache sets. More specifically, the MPKI of *writer* sets is reduced by 27.8%, on average (i.e., from 30.7% to 22.1% of the *Baseline* total MPKI). However, the MPKI is increased from 12.0% to 16.2% for the *non-writer* sets and from 57.3% to 59.1% of the *Baseline* total MPKI for the *neutral* sets, on average, respectively. For some cases, the writeback-aware replacement policy has incurred miss penalties by evicting the clean lines that are later reused more frequently than the saved dirty blocks (i.e., those that have been given a second chance). For other cases, the dirty lines kept in LLC by the writeback-aware replacement policy are re-referenced more than the lines evicted by them instead. It should be noted that the penalty is small, because we give only a second chance to the dirty victims of the sets. The set-balancing scheme reduces the MPKI of *writer* sets at the cost of increasing the MPKI of *non-writer* sets. However, since the *non-writer* sets are usually underutilized, the increase is small. Compared with the LRU replacement policy (used for both *Baseline* and *Baseline double-way*), our scheme has higher management cost and increases the MPKI for some benchmarks. However, our evaluations reveal that it does not have a noticeable negative impact on the cache miss rate. Compared with *Baseline double-way*, WALL increases the MPKI by 1.0%, on average. But WALL reduces the MPKI by 0.3%, on average, compared to *WADE*, because *WADE* does not distinguish different set types.

4.4 Energy Comparison

Figure 13 shows the normalized energy of the PCM main memory for the evaluated schemes. WALL when using the simple partner assignment strategy can save main memory's energy by 19.2%, on average, compared to the *Baseline*. Compared with *Baseline double-way* and *WADE*, WALL reduces

Fig. 13. Normalized main memory energy.

Fig. 14. Main memory energy of WALL with different partner assignment strategies.

Fig. 15. Normalized IPC.

the energy consumption of the PCM main memory by 16.5% and 11.3%, on average, respectively. The energy consumption of writing to PCM is much higher than that of reads. Hence, the energy saving is mainly due to the reduction in the number of write requests issued to PCM by WALL. That is also the reason that *Baseline double-way* exhibits a higher power consumption compared to WALL; *Baseline double-way* experiences a smaller MPKI, but a higher rate of writebacks. As discussed in Section 3.1, unlike *WADE*, which uses complex prediction schemes, the energy consumption of the logic components added to LLC by WALL is negligible.

Figure 14 shows the normalized energy of the main memory for the extended partner assignment strategies. Compared to the simple partner assignment strategy, the expansion and the contraction strategies can save main memory's energy consumption by 2.7% and 3.0%, on average, respectively. ConExp can reduce the main memory's energy by 4.8%, on average, compared to the simple partner assignment strategy. In other words, ConExp strategy can reduce the energy consumption of the PCM main memory by 23.1%, on average, compared to the *Baseline* scheme.

4.5 Performance Comparison

Figure 15 compares the normalized system IPC of the evaluated schemes. The overhead of the second searches in partners of the *writer* sets is considered in our experiments.

WALL when using the simple partner assignment strategy improves performance by 6.7%, on average, compared to the *Baseline* scheme. Compared with *Baseline double-way* and *WADE*, WALL improves system performance by 4.9% and 3.2%, on average, respectively. The latency of writing to PCM is much higher than that of reads. Hence, the reduced average access latency of the PCM main memory is the major reason for the performance improvement. The results indicate that WALL can reduce the PCM average access latency by 12.6%, on average, compared to the *Baseline*.

Fig. 16. Normalized IPC of WALL with different partner assignment strategies.

Fig. 17. Lifetime enhancement (years, log scale).

Fig. 18. Lifetime enhancement of WALL with different partner assignment strategies.

The reduction is due to reducing the PCM write traffic and thus the queuing delay of the PCM read requests.

Figure 16 illustrates the normalized system IPC of WALL with the extended partner assignment strategies. Compared to the simple partner assignment strategy, the expansion and contraction strategies can improve the system performance by 0.7% and 1.5%, on average, respectively. ConExp, which uses the benefits of the both strategies, can improve performance by 2.1%, on average, compared to the simple partner assignment strategy. Compared to *Baseline*, ConExp strategy can improve performance by 8.7%, on average.

4.6 PCM Lifetime Enhancement

Figure 17 compares the PCM lifetime enhancement of the evaluated schemes. The lifetime is calculated based on the analytical model explained in Section 2.2. It should be noted that PCM lifetime is inversely proportional to the writes per cycle or write rate (GBps). WALL when using the simple partner assignment strategy can enhance PCM lifetime by 1.25 $\times$, on average, compared to the *Baseline*. Compared with *Baseline double-way* and *WADE*, WALL enhances the PCM lifetime by 1.21 $\times$ and 1.17 $\times$, on average, respectively. Alleviating the write traffic sent out to the PCM main memory by WALL is the reason for the lifetime enhancement.

Figure 18 shows the PCM lifetime enhancement of the extended partner assignment strategies. ConExp can enhance PCM lifetime by 1.04 $\times$, on average, compared to the simple partner assignment strategy. In other words, ConExp strategy can enhance PCM lifetime by 1.29 $\times$ compared to the *Baseline* scheme.

Fig. 19. Writeback reduction of WALL for three different time window sizes.

Fig. 20. MPKI of WALL for three different time window sizes.

4.7 Impact of Time Window Size

For experimental results presented so far, the set types are checked and adjusted with an epoch of 10^7 LLC accesses, because our experiments indicate that this provides the best balance between the writeback reduction and storage overhead. Next, we discuss the impact of time window size. We choose to use the number of LLC accesses instead of the number of cycles, because WALL works based on the number of writebacks/accesses of the sets and epochs with the same number of cycles may have very different number of writebacks/accesses. In other words, to obtain a consistent approach among the epochs, we choose the number of LLC accesses rather than cycles.

Figures 19 and 20 compare the average writeback and miss rate values of WALL + ConExp for three different time window sizes. The results are normalized to 10^7 LLC access time windows. Our goal is to reduce the number of writebacks while keeping the storage overhead at minimum. The evaluations show that using time windows of 0.5×10^7 accesses results in 10.3% more writebacks and 6.3% higher miss rate compared to time windows of 10^7 accesses. The reason is that time windows of 0.5×10^7 accesses are not long enough, resulting in incorrect identification of some set types. Identifying a *neutral* set as *non-writer* and assigning a *writer* partner to it can increase its writeback and miss rate values, because the set will not have enough space for its *writer* partner's blocks. Moreover, identifying a *writer* set as *neutral* can also increase its writeback and miss rate values, because *writer* sets need to be managed differently, as we explained in Section 3.2. Finally, identifying a *neutral* set as *writer* or a *non-writer* set as *neutral* may prevent us from using the set-balancing scheme efficiently.

Our results also show that for time windows of 2×10^7 accesses, larger writeback counters are required; otherwise, counters will saturate, causing inaccurate identification of set types. Using larger writeback counters improves the accuracy of the set type identification. However, based on our evaluations, even with the higher storage overhead, the writeback reduction is small (only 1.2%) compared to 10^7 access time windows. So, overall, the selected time windows of 10^7 accesses to the LLC gives us the best balance between the writeback reduction and storage overhead. It is also worth mentioning that there is no benefit in using even larger time window sizes (e.g., 10^8 accesses), because not only the storage overhead would be much higher but also any required updates on the set types would be postponed to later times in the program execution, which in turn can reduce the benefits of WALL.

5 RELATED WORK

Many recent studies have focused on mitigating the overheads of write operations in PCM-based main memories. Lee et al. [15] proposed a scheme called *eager writeback*, which writes the LRU dirty cache lines back into the main memory before their eviction to improve system performance. A variation of eager writeback is proposed in Reference [25] to improve PCM performance by early and eagerly writing back the long latency SET operations. In Reference [24], the concept of *write cancellation* is proposed to prioritize reads over writes; to immediately service the incoming reads,

this scheme cancels the conflict writes. The performance overhead of write operations is alleviated by parallelizing read or write accesses with an ongoing write in Reference [1]. Moreover, Zhou et al. [38] developed a non-blocking PCM bank design that aims to service subsequent reads or writes in parallel with an on-going write. Xia et al. [32] explored the possibility of removing the unmodified data from a single write and then, merging modified data of multiple writes to be sent within one write request to improve PCM write bandwidth. In addition, Zhang et al. [37] has shown that only a small portion of the main memory is frequently accessed in a given time period. Based on that observation, their scheme records and predicts the memory regions' write frequencies to select a proper write latency (i.e., the number of SET iterations) for every incoming memory write operation to improve system performance and memory lifetime. In this work, we focus on reducing the number of write requests issued to PCM. Since our design only reduces the number of writebacks from the last-level cache and does not change the main memory's architecture, it can be used along with other techniques that optimize the PCM architecture to minimize the impact of writes.

There have also been other studies proposed to reduce the write overheads of other types of non-volatile memory technologies such as STT-RAM and ReRAM. Zhang et al. [36] proposed a scheme called *Mellow Writes* that extends memory controllers to selectively perform slow writes to reduce the impact of writes on endurance and performance of the ReRAM-based memories. In Reference [3], a temperature aware scheme is proposed to enhance the lifetime and performance of ReRAM-based memories by reducing the number of write accesses to the hot ReRAM banks. Kultursay et al. [13], investigated the possibility of replacing DRAM with STT-RAM for main memories. In that work, STT-RAM write overheads are reduced by bypassing the row buffer writes and tracking dirty blocks to perform partial writes within a row. STT-RAM is typically considered as an alternative to SRAM caches or used in SRAM-NVM hybrid caches. To alleviate the write overheads of STT-RAM in a hybrid cache, Wang et al. [29] presented an adaptive placement and migration policy based on the access pattern of different classes of write operations in LLC. Wu et al. [31] partitioned hybrid cache into read and write regions and migrated cache blocks within the cache to mitigate the write overheads of STT-RAM. In this work, we have focused on PCM as one of the most extensively studied alternatives for DRAM-based main memories due to its high density and low cost. However, WALL can also be used for other types of non-volatile main memory technologies (e.g. ReRAM) with similar shortcomings related to the write operations.

Some studies have proposed techniques for reducing the number of LLC writebacks to the non-volatile component of a hybrid main memory consisting of NVM and DRAM [6, 35]. In Reference [6], a miss penalty-aware LRU-based cache replacement policy, called MALRU is proposed to consider the asymmetry of cache miss penalty on DRAM and NVM. MALRU keeps the high-latency NVM blocks as well as the low-latency DRAM blocks with good temporal locality in a reserved area to protect them from being evicted. Similarly, Zhang et al. [35] proposed a write-back aware LLC management scheme for the hybrid main memory systems to reduce the number of writebacks to NVM by improving the hit ratio of the NVM memory blocks in the cache. However, those techniques are only applicable for the hybrid main memories.

The set balancing cache (i.e., SBC) proposed in Reference [27] tries to balance the pressure on cache sets by associating sets with maximum saturation counters with sets with small saturation counters. Though SBC reduces cache miss rate, it is not always able to reduce the number of writebacks. Our experiments show that, not every set with a maximum saturation counter has large number of writebacks (e.g., a set may evict clean lines mostly). However, there are some sets with saturation counters smaller than the maximum value, which write back more frequently than those with maximum saturation counter values. However, SBC shares resources between two sets only when a set's saturation counter reaches its maximum.

Writebacks may also be caused by cache flushes required for ensuring PCM crash consistency. In case cache flushes are required for the consistency of data in the persistent memory, to avoid causing consistency problems, the flushed dirty blocks need to be written back to the main memory. In other words, WALL cannot interfere with crash consistency flushes, and needs to treat normal writebacks and flush operations differently. The impact of flush operations on WALL depends on how often and when the flushes are required. With *buffered epoch persistency* [8], a set of write operations called an epoch are persisted together to allow write coalescing. In other words, data is persisted (i.e., or buffered to be persisted later) at specific points of the program execution specified by persist barriers. To implement epoch persistency, cache tags are extended with core and epoch ID fields to allow delaying or reordering of the writebacks. WALL can utilize the buffered epoch persistency model and still reduce the number of writebacks within the epochs. Using larger persistency epochs reduces the number of consistency writebacks; however, though, if a crash happens, then the program will need to be restarted from a relatively earlier state; so, there is basically a trade-off here for WALL. It is also worth noting that recent designs use non-invalidating flush operations (i.e., *clwb* instead of the *cflush* operations) to avoid the eviction of applications' working sets from the cache [12]. This enables WALL to continue keeping the blocks in the cache after persisting them in the main memory. Moreover, loose ordering consistency scheme proposed in Reference [17] relaxes the write ordering requirements with two mechanisms called eager commit and speculative persistence. So, such scheme can also be used with WALL, which basically delays the write back of some cache blocks to the main memory. Considering crash consistency when reducing the number of writebacks was not the focus of this study, and we leave it for the future work.

6 CONCLUSION

In this article, a novel writeback-aware LLC management scheme is proposed to reduce the number of LLC writebacks to a PCM based main memory. We first investigate the non-uniformity of the LLC sets writebacks and based on that propose a writeback-aware set-balancing mechanism. To implement the set-balancing mechanism, we propose three novel partner assignment strategies, called contraction, expansion, and ConExp to pair sets with different behaviors more efficiently compared to the simple partner assignment strategy of WALL. In addition, we propose a simple but effective writeback-aware replacement policy to keep the frequently reused dirty lines of the sets in the cache. Our evaluation results show that our scheme can achieve a significant reduction in the total number of writebacks to PCM, thereby improving the system performance, energy efficiency, and PCM lifetime.

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