

Achieving Multi-Port Memory Performance on Single-Port Memory with Coding Techniques

ABSTRACT

Many performance critical systems today must rely on performance enhancements, such as multi-port memories, to keep up with the increasing demand of memory-access capacity. However, the large area footprints and complexity of existing multi-port memory designs limit their applicability in practice. This paper explores a coding theoretic framework to address this problem. In particular, this paper introduces a framework to encode data across multiple single-port memory banks in order to *algorithmically* realize the functionality of multi-port memory.

This paper proposes three code designs with significant less storage overhead compared to the existing replication based emulations of multi-port memories. To further improve performance, we also demonstrate a memory controller design that utilizes redundancy across coded memory banks to more efficiently schedule read and write requests sent across multiple cores. Furthermore, guided by real-life traces, the paper explores two potential directions to improve the efficiency of the coding based memory design: 1) *Dynamic coding*, and 2) *Prefetching*. We then show significant performance improvements in critical word read and write latency in the proposed coded-memory design when compared to a traditional uncoded-memory design. **[Ethan: real-life, PARSEC, or both?]**

1. INTRODUCTION

Memory accesses are one of the most vital parts of any computer program. A program is intrinsically made up of loads and stores to the memory. As illustrated in Figure 1, we have witnessed an increasing difference between the performance of processors and memory systems. Even with the saturation/demise of Moore’s law [1, 2, 3], processing power is expected to grow with the increased reliance on multi-core architectures [4]. Since the end-to-end performance of a program heavily depends on both processor and memory performance, slower memory becomes a bottleneck and slows down the whole system. This has been driving motivation for computer architects and researchers to explore various ingenious ways to keep memory access latency as short as possible, including sustained efforts towards enhancing the memory hierarchy [5]. Despite these continuous efforts, long-latency memory accesses do occur when there is a

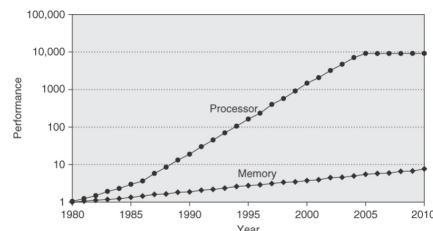


Figure 1: *The gap in performance, measured as the difference in the time between processor memory requests (for a single processor or core) and the latency of a DRAM access, is plotted over a 30 year span [6].*

miss in the last level cache (LLC). This triggers an access to shared memory, where the processor has to wait for the shared memory to return the requested information. Such waits create stall in the processors.

In a multi-core processor architecture, contention between various cores exacerbates access latency to the shared memory, resulting in large access request queues. Figure 2 illustrates a general multi-core architecture. The bank queues are served every memory clock cycle and the acknowledgement with data (in the case of a read) is sent back to the corresponding processor. In the scenario where multiple cores request access to memory locations on the same bank, the memory controller arbitrates them using bank queues. This contention between cores to access from the same bank is known as a *bank conflict*. As the number of bank conflicts increases, memory access latency also increases and the entire system slows down.

We address the issue of increased latency due to bank conflicts by introducing a coded memory design. The main principle behind our memory design is to distribute the accesses intended for the information stored in a particular bank across multiple banks in the memory by using coding theoretic techniques to create redundancy. We store the information in the memory banks such that it is possible to recover the information stored on a particular bank by utilizing the information stored in other memory banks. This allows us to simultaneously serve multiple read requests intended for a particular bank, one read request by directly accessing the bank and other requests by querying other banks in

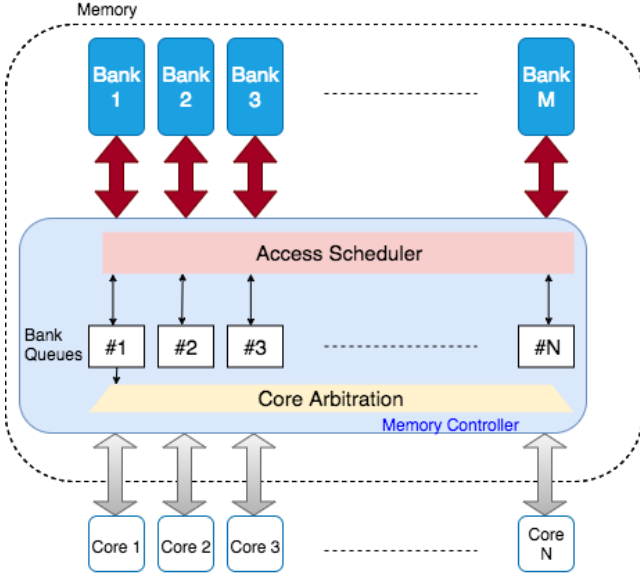


Figure 2: General multi-core architecture with a shared memory. N processor cores share a memory consisting of M banks.

the system. Figure 3 shows this with an example. Here, Bank 3 is redundant as its content is a function of the content stored in Banks 1 and 2. Such redundant banks are also referred to as *parity banks*. Assume that the information is arranged in L rows in two first two banks, represented by $[a(1), \dots, a(L)]$ and $[b(1), \dots, b(L)]$, respectively. Let $+$ denote the XOR operation, and additionally assume that the memory controller is capable of performing simple decoding operations, *i.e.* recovering $a(j)$ from $b(j)$ and $a(j) + b(j)$. Because the third bank store L rows containing $[a(1) + b(1), \dots, a(L) + b(L)]$, this design allows us to simultaneously serve any two read requests in a single memory clock cycle.

The memory design in Figure 3 also helps us recognize various other key issues that are relevant to a hybrid memory: 1) Serving write requests (with or without bank conflicts), 2) Effective utilization of storage space, and 3) Arbitration/scheduling of accesses across multiple clock cycles. A successful memory system should be able to enable efficient write accesses and maintain the consistency among various read and write requests. Therefore, a memory design should take both read and write requests into account. In the design shown in Figure 3, any write request for an information element, say $a(j)$, should be committed to both Bank 1 and Bank 3. As far as the utilization of the storage space is concerned, the design in Figure 3 uses 3 banks to store the 2 banks' worth of information. This correspond to the information rate¹ of $2/3$. Moreover, as it will become clear later, additional storage space is needed to store the pointers and queues/buffers that further increase

¹The information rate is a standard measure of redundancy of a coding scheme ranging from 0 to 1, where 1 corresponds to the most efficient utilization of storage space.

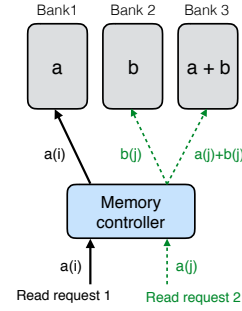


Figure 3: Enabling multiple read accesses to a bank by coding. Given two read requests $\{a(i), a(j)\}$ directed to Bank 1, we can deal with bank conflict in the following manner: 1) First request for $a(i)$ can be directly served by Bank 1 itself, and 2) The read request for $a(j)$ can be served by downloading $b(j)$ and $a(j) + b(j)$ from Bank 2 and Bank 3, respectively. Another case where two read request corresponding to two different banks, *e.g.*, $\{a(i), b(j)\}$, can be simultaneously served from their respective banks without utilizing Bank 3.

the redundancy in any memory system. Finally, in a multi-core setup where multiple cores are sending access requests to hybrid memory systems, some designs do not allow for all these requests to be met in a single memory clock cycle. This would require queueing of access requests and mapping of these requests to the memory banks in a manner such that the overall performance of the entire system is optimized. This objective is referred to as *arbitration or scheduling*.

Main contributions and organization: In this paper we systematically address all key issues pertaining to a shared memory system that can simultaneously service multiple access requests in a multi-core setup. We present all the necessary background on realization of multi-port memories using single-port memory banks along with an account of relevant prior work in Section 2. We then present the main contributions of the paper which we summarize below.

- We focus on the design of the storage space (array of memory banks) in Section 3. In particular, we employ three specific coding schemes to redundantly store the information in memory banks. These coding schemes, which are based on the literature on distributed storage systems [7, 8, 9, 10], allow us to realize the functionality of multi-port memories from a single port memories while efficiently utilizing the storage space. Moreover, these coding schemes have low complexity encoding and decoding processes that require only simple XOR operation.
- We present a memory controller architecture for the proposed coding based memory system in Section 4. Among other issues, the memory controller design involves devising scheduling schemes for both read and write requests. This includes careful utilization of the redundancy present in the memory banks while maintaining the validity of information stored in them.

- Focusing on applications where memory traces might exhibit favorable access patterns, we explore two ways to improve the efficiency of our coding based memory design in Sections 4.6 and 4.7. First, we propose a dynamic coding scheme which is based on continuous detection of heavily accessed regions on memory banks. The second solution involves predicting the patterns of memory addresses in different access requests.
- Finally, we conduct a detailed evaluation of the proposed designs of shared memory systems in Section 6. We implement our memory designs using system C and evaluation the overall performance of these designs by regressing their system C implementation through memory traces from real multi-core systems. In addition, we also analyze the performance of our purposed designs with the help of extensive simulation on Ramulator, a DRAM simulator designed by Kim et al. [11].

2. BACKGROUND AND RELATED WORK

2.1 Emulating multi-port memories

The multi-port memories are essential to provide seamless memory accesses in a multi-core setup as these memories can support simultaneous accesses to data elements (which are potentially stored on the same memory bank) by multiple cores. However, designing a true multi-port comes at a large cost. Besides complex circuit implementation for I/O, the area requirements for multi-port bit-cells is significantly higher than that for single-port bit-cells [12, 13]. This motivates the exploration of algorithmic and system level designs to emulate multi-port memories using simple and area efficient single-ported memory banks [14, 15, 16, 17, 18]. Attempts have been made to emulate multi-port memory by [19], however they use replication based design that makes the resulting architecture very large in memory. **[Ethan: Move some of this earlier?]**

Due to space limitations we focus on specific, illustrative request patterns. We invite the reader to verify that our designs indeed handle the set of all possible requests.

2.1.1 Read-only Support

Replication-based designs are the most prevalent candidates in this design space. Assuming that a memory design is required to support only read request, say r read request per memory clock cycle, one can simply store r copies of each data element on r different single-port memory banks. In every memory clock cycle, the r read requests can be served in a straightforward manner by mapping all read request to distinct memory banks (see Figure 4). This way, the r -replication-based design completely avoids bank conflicts for up to r read request in a memory clock cycle.

REMARK 1. *If we compare the memory design in Figure 4 with that of Figure 3, we notice that both designs*

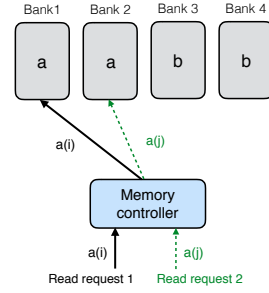


Figure 4: 2-replication based design to support multiple 2 read requests in the same memory clock cycle. The two banks' worth of data $\mathbf{a} = [a(1), \dots, a(L)]$ and $\mathbf{b} = [b(1), \dots, b(L)]$, all the data elements are stored on two distinct memory banks. Note that any 2 read requests to distinct memory banks. For example, the figure considers the scenario with 2 read requests for elements $\{a(i), a(j)\}$. Since both $a(i)$ and $a(j)$ are stored on 2 banks, one of those banks can be used to serve each request without causing any bank conflicts. It's straightforward to verify that this memory design avoids bank conflicts for any other set of 2 read requests.

can simultaneously serve 2 read requests without causing any bank conflicts. Note that the design in Figure 3 consumes smaller storage space as it needs only 3 single-port memory banks while the design in Figure 4 requires 4 single-port memory banks. However, for the design in Figure 3, the access process involves some computation. This observation indeed generalizes to the conclusion that the sophisticated coding schemes allow for better storage efficient designs as compare to the replication based design [20]. However, this comes at the expense of increased computation (XOR decoding). Therefore, it is important to employ those coding schemes that enable storage efficiency with as small computational overhead as possible.

2.1.2 Read and Write Support

[ANKIT: Mainly describing the results from the work of Auerbach, Chen, and Paul[14].] The redundancy mechanism can vary from simple replication-based strategy to more sophisticated coding schemes. However, a successful memory design necessarily need to address the issues of (potentially multiple) write requests as well. A challenge that arises in the presence of write requests is that one also need to ensure consistency across different requests. This requires managing multiple versions of the same information across all the memory banks and making sure that stale information is not supplied in response to a particular read request.

Restricting ourselves to replication-based designs, a multi-port memory that simultaneously supports r read requests and w write requests in a memory cycle can be emulated by using a $r \cdot (w + 1)$ replication scheme, where $r \cdot (w + 1)$ copies of each data element are stored on $r \cdot (w + 1)$ different single-port memory banks. We illustrate this scheme for $r = 2$ and $w = 1$ in Figure 5. According to all of our previous illustrations, we as-

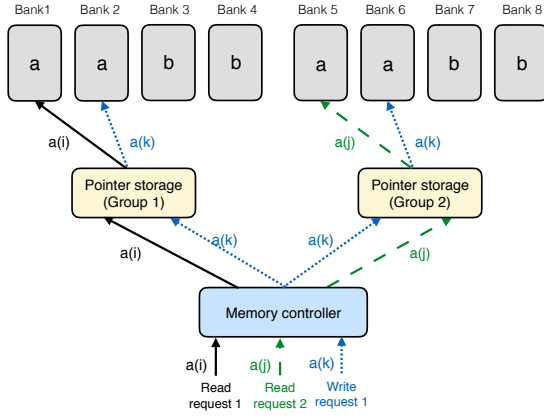


Figure 5: 4-replication based design to support $r = 2$ read requests and $w = 1$ write request in one memory clock cycle. Both collections of information elements $\mathbf{a} = [a(1), \dots, a(L)]$ and $\mathbf{b} = [b(1), \dots, b(L)]$ are replicated on $r \cdot (w + 1) = 4$ different single-port memory banks. These banks are then partitioned into $r = 2$ disjoint groups. We utilize each group to serve one read request. In a given memory clock cycle, we focus on the specific access pattern with the read requests for $\{a(i), a(j)\}$ and the write request for $\{a(k)\}$. Assuming that Bank 1 (from Group 1) and Bank 5 (from Group 2) have the updated versions of the data elements $a(i)$ and $a(j)$, respectively, we serve the read requests for $a(i)$ and $a(j)$ from Bank 1 and Bank 5, respectively. As for the write request for the data element $a(k)$, we need to perform this write request in at least one memory bank in each of the two groups. This will enable both groups to continue serving any possible set of $r = 2$ read requests during future accesses. Since we have one memory bank storing $a(k)$ in each of the groups that is not busy serving write request, we write the updated $a(k)$ in these non-busy banks (Bank 2 and Bank 3 in this case). During the writing process, we also need to modify the pointer storage accordingly to keep track of the banks in each group that are storing the most updated values of different data elements.

sume that we have two symbols' worth of information $\mathbf{a} = [a(1), \dots, a(L)]$ and $\mathbf{b} = [b(1), \dots, b(L)]$. We store 4 copies each of data elements \mathbf{a} and \mathbf{b} and partition the banks that store a data element into $r = 2$ disjoint groups with each group containing $(w + 1) = 2$ memory banks. In Figure 5, Banks 1 – 4 and Banks 5 – 8 correspond to Group 1 and Group 2, respectively. For the underlying replication-based scheme, we also require additional storage space to keep track of the versions of different copies of the information elements. This space is referred to as the pointer storage. In Figure 5, we illustrate how this design serves a particular set of 2 read requests and 1 write request.

Additional cost to support write requests: Let's look at the additional cost associated with the requirement of being able to support write requests. Recall that the r -replication enables us to serve any set of r

read requests in a memory clock cycle. Demanding that we also support w write requests, the required replication factor of the replication-based design jumps to $r \cdot (w + 1)$. This follows as we use r different groups of banks to serve r different read requests. In order to avoid bank conflicts this requires that, for every data element, there should be at least one memory bank that store the most update version of that data element at the beginning of every memory clock cycle. Thus, we should be able to perform w write requests in each of the groups of memory banks. Since we have w write and 1 read operations to perform in every group, we require at least $(w + 1)$ memory banks in each of the r groups. This amounts to the replication factor of $r \cdot (w + 1)$. Furthermore, the memory design also requires additional storage space to keep track of the locations of the updated versions of each of the data element. This storage space is referred to as pointed storage in Figure 5. [Ethan: condense the beginning of this paragraph, and move the end of this paragraph later since it's not really background] Note that in order to ensure that the pointer storage space is small, we need to continuously update all the replicas of each data element. For data elements that do not have an entry corresponding to them in the pointer storage, we assume that all of their replicas are storing their current version. This process of synchronization across the replicas of a data element is opportunistically performed on the different banks storing the replicas when these banks are not busy serving access requests from the cores. Therefore, we have two components of the additional cost for the ability to support write requests: 1) Storage space for more replicas and pointer storage and 2) Continuous background maintenance task of synchronizing all the replicas of a data element with its current version.

REMARK 2. As illustrated above, an r -replication based design to serve r read request can be modified to an $r \cdot (w + 1)$ -replication based design to support r read and w write requests. If we focus on memory design that supports multiple read requests by using sophisticated coding schemes (e.g., the design in Figure 3), we can modify it to support both read and write requests as well. A generic approach that can be used to support r read requests and w write requests is as follows². Take a coding scheme based memory design that can serve any set of r read requests. Now replicate this whole design $(r + w)$ times. These $(r + w)$ copies of the original design are considered as $(r + w)$ different groups. Now, given r read requests we look for minimum number of groups that store the most updated version of the data elements associated with these read requests and serve all the read requests. In the worst case this would require using r different groups. For the w write requests, we commit these w requests to w different groups that are not used to serve read requests. Note that there are

²We note that depending on the specific coding scheme, one can present a more storage-efficient design. Here, we present a universal scheme that works for any coding scheme.

at least w such groups. While performing a write request inside a group, we update all the memory banks of the group according to the write request. Similar to the $r \cdot (w + 1)$ -replication based design, this design also requires additional storage space to store pointers to keep track of the groups storing the most updated version of the data elements. Furthermore, In order to keep this storage space small, we again need to opportunistically synchronize all the banks with the most recent version of the data elements. **[Ethan: rewrite]**

2.2 Storage-efficient emulation of multi-port memories

As described in Section 2.1, by utilizing various ways to introduce redundancy (ranging from simple replication to more sophisticated coding schemes) it's possible to design a memory based on only single-port memory banks that emulate the behavior of a multi-port memory. In a setup where only read requests need to be served (cf. Section 2.1.1) such an emulation is less costly to achieve, both in terms of storage and computational cost. In particular, by careful selection of the underlying coding scheme, it's possible to serve multiple read requests by incurring both small storage and computational overhead (cf. Remark 1). **[Ethan: remove?]**

However, the emulation become much more costlier in the scenario when write requests also needs to be performed (cf. Section 2.1.2). Besides the increment in the number of single-port memory banks, the ability to serve write requests also requires the installation of pointer storage to keep track of the various versions of the data elements present in the memory banks. As highlighted in Section 2.1.2, it's necessary to continuously synchronize all the memory banks storing a particular data element in order to keep the pointer storage space small. **[Ethan: remove above this line, put below this line somewhere earlier?]** Furthermore, the presence of varying version in the banks also complicates the process of arbitration, i.e., mapping access requests to memory banks, as read requests need to be served by the bank storing the current version of the data element. Since most of the programs in a multi-core would involve significant amount of write requests, any design to emulate multi-port memory using single-port memory needs to take these overheads into account.

We believe that various tasks that arise in the presence of write requests and contribute to computational overhead of the memory design, including synchronization among memory banks and complicated arbitration, can be better managed at the algorithmic level. **[Ethan: good point!]** Note that these tasks are performed at memory controller. It's possible to reduce the effect of these tasks on the overall performance of memory system by relying on the increasing available computational resources while designing the memory controller. On the other hand, we believe that the storage overhead is a more fundamental issue that needs to be addressed for the emulation of the multi-port memories to be viable

and appealing. In particular, the large replication factor in a naive design (cf. Remark 2) limits the applicability of the obtained memory in practice due to large storage overhead and the associated large area requirement resulting from this.

In order to reduce the storage overhead, we avoid the two step (naive) memory design process highlighted in Remark 2: 1) First, employ a coding scheme that can serve multiple read requests, and 2) Then replicate the obtained memory bank arrangement multiple times in order to support write requests as well. We instead encode the data elements using specific coding schemes which create parity banks by encoding over a multiple data banks and have reasonably high rate. We select the underlying coding scheme to support multiple read requests in the worst case. Instead of replicating the obtained design, we exploit the fact we do not always encounter worst case pattern for read request and the obtained design can potentially serve access patterns with much larger number of read requests. In other words, for many access patterns with a given number of read requests, there are many memory banks that remain unused. These unused banks are generally available to perform (part of) pending write requests. Therefore, if one aims at performing arbitration among access requests arising over a slightly longer duration as opposed to focusing on requests arriving at each memory clock cycle, all the requests can be served without **[Ethan: with? also rewrite this paragraph]** good latency. In this way, instead of designing various components of the memory system, e.g., bank array and memory controller, independently, taking the holistic view of the entire memory system allows us to not commit unnecessary storage space in terms of large number of bank which only provide small amount of utility in terms of performance of the system. We recognize that this approach leads to increased complexity at the memory controller. *However, we show that the increment in the complexity can be kept within the acceptable level while insuring storage-efficient emulation of multi-port memories with the help of better algorithmic design.*

2.3 Related work

Coding theory is one of the well studied field which deals with mitigating the adversarial effects of the underlying medium in an information processing system [20, 21]. In particular, the developments in the field have enabled both reliable communication across noisy channel and storage over fault-prone storage units in resource efficient manners. Recently, we have witnessed intensive efforts towards the applications of coding theoretic ideas to design large scale distributed storage systems (see e.g., [22, 23, 24]). In this domain of coding for distributed storage systems, the issue of access efficiency has also received attention, especially the ability to support multiple simultaneous read accesses with small storage overhead [9, 10, 25, 26] and references therein. In this paper, we rely on the coding techniques developed under in this domain to realize emulation of multi-port memories using single-port mem-

ory banks. However, we note that the existing work on batch codes [9] only focuses on the read requests. On the other hand, the successful emulation of multi-port memory also requires handling write requests in an efficient manner. Furthermore, the design presented in this paper also needs to address the entire memory system which also involves memory controller design as opposed to just focusing on the storage array.

Here, we note that the issue of designing coding schemes that have low update complexity, i.e., that can be modified with low overhead as the information gets updated, have also received some attention in the literature (see e.g., [27, 28]). However, this treatment is extensive enough to address the update issues that arise in the context of our memory systems, where write requests may be very frequent and a large portion of the bank array needs to get updated. Again, the key issue that distinguish our work from the majority of the literature on coding for distributed storage is that we need to take the interplay among read and write requests and its effect on the overall performance (latency) into account. **[Ethan: good point]** Furthermore, we are not allowed to encode across a very large number of storage units (memory banks in our case), which is very much feasible in today’s large scale cloud storage systems.

In this paper, we also explore the idea of proactively prefetching the information from memory banks to improve the access efficiency of our memory design. The idea of prefetching in realizing fast data transfer between processors and memory has been previously explored in the literature (see [29, 30, 31, 32] and references therein). However, our work addresses the issue of data prefetching in the context of coded memory system which is not addressed earlier in the literature. This does share some similarity with the recent line of work on coded caching [33] which aims to reduce the data downloaded from servers in a communication network by utilizing the cache available at the end users. Here, we would like to point out that there are many key differences in the our setup with coded memory banks with that considered in [33]. In particular, our setup has data stored in an encoded form stored across memory banks and caching is enabled by the memory controller, which is a centralized units. Whereas the setup of coded caching have a centralized storage system (referred to as a server) and cache units which store encoded information are distributed across users.

The work which is closest to our solution for emulating a multi-port memory is by Iyer and Chuang [17, 18], where they also employ XOR-ing based coding schemes to redundantly store information in an array of single-port memory banks. However, we note that our work significantly differs from [17, 18] as we specifically rely on different coding schemes arising under the framework of batch codes [9]. Additionally, due to the employment of distinct coding techniques, the design of memory controller in our work also differs from that in [17, 18].

[ANKIT: Also cite the work by Rivest et al. [16]

and Endo, Matsumura and Yamada [15].]

3. CODES TO IMPROVE ACCESSES

As a key idea behind the memory designs proposed in this paper, we plan to utilize coding schemes to introduce the redundancy into the storage space comprising an array of single-port memory banks in order to support multiple accesses to the array. For this approach to be successful, it’s important to work with the right coding schemes which are designed by keeping the access-efficiency as the central criterion. In this section, we describe three such coding schemes that we employ for the task of emulation of multi-port memories using single-port memory banks. Before presenting these coding schemes, we first introduce some basic concepts and terminology that we use throughout the rest of this paper.

3.1 Coding for memory banks

A coding scheme is defined by its encoding process which maps a given collection of information elements to a larger and redundant collection of elements known as codeword. In the context of memory banks, we begin with *data banks* which refer to the memory bank storing the original information. The encoding process of the underlying coding scheme then utilize the content of these data banks to generate elements to be stored in the additional memory banks such the overall array of memory banks stores the information in a redundant manner. The additional memory banks are termed as *parity banks*. The encoding operations used to generate parity elements in this paper can be classified into two categories.

1. **Inter-bank encoding:** A parity element depends on at most one element for each of the data banks.
2. **Intra-bank encoding:** A parity element is generated using multiple elements from a data bank.

Furthermore, we restrict ourselves to linear coding schemes which perform only linear operations (over a finite field) during the encoding process. In fact, in order to keep the computation complexity small, we only consider coding schemes over the binary field. This implies that the linear operations are nothing but *XOR* operations. The following example further clarifies these concepts along with some necessary notation with help of a coding scheme that employs only inter-bank encoding.

EXAMPLE 1. *Let’s consider a setup with two data banks **a** and **b**. We assume that each of banks store LW binary data elements³ which are arranged in an $L \times W$ array. In particular, for $i \in [L] \triangleq \{1, \dots, L\}$, $a(i)$ and $b(i)$ denote the i -th row of the bank **a** and bank **b**, respectively. Moreover, for $i \in [L]$ and $j \in [W] \triangleq \{1, \dots, W\}$, we use $a_{i,j}$ and $b_{i,j}$ to denote the j -th element in the rows*

³It is possible to work with data elements over larger alphabets/finite fields. However, assuming data elements to be binary suffices for us as we only work with coding schemes defined over binary field in this paper.

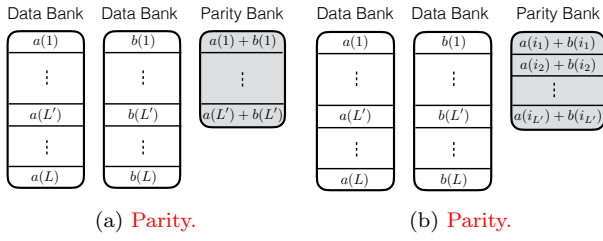


Figure 6: Design.

$a(i)$ and $b(i)$, respectively. Therefore, for $i \in [L]$, we have

$$\begin{aligned} a(i) &= (a_{i,1}, a_{i,2}, \dots, a_{i,W}) \in \{0,1\}^W \\ b(i) &= (b_{i,1}, b_{i,2}, \dots, b_{i,W}) \in \{0,1\}^W. \end{aligned}$$

Now, consider a linear coding scheme that produces a parity bank \mathbf{p} with $L'W$ bits arranged in an $L' \times W$ array such that for $i \in [L'] \triangleq \{1, \dots, L'\}$,

$$\begin{aligned} p(i) &= (p_{i,1}, \dots, p_{i,W}) \\ &= a(i) + b(i) \\ &\triangleq (a_{i,1} \oplus b_{i,1}, a_{i,1} \oplus b_{i,1}, \dots, a_{i,1} \oplus b_{i,1}). \end{aligned} \quad (1)$$

Figure 6a illustrates this coding scheme. Since the parity bank is based on those rows of the data banks that are indexed by the set $[L'] \subseteq [L]$, we also use the following concise notation to represent the encoding of the parity bank.

$$\mathbf{p} = \mathbf{a}([L']) + \mathbf{b}([L']).$$

In general, we can use any subset $\mathcal{S} = \{i_1, i_2, \dots, i_{L'}\} \subseteq [L]$ comprising L' rows of data banks to generate the parity bank \mathbf{p} . In this case, we have

$$\mathbf{p} = \mathbf{a}(\mathcal{S}) + \mathbf{b}(\mathcal{S}),$$

or

$$p(l) = a(i_l) + b(i_l) \text{ for } l \in [L'].$$

Figure 6b illustrates the case with a generic set \mathcal{S} .

REMARK 3. Note that we allow for the data banks and parity banks to have different sizes, i.e., $L \neq L'$. This freedom in memory design can be utilized to reduce the storage overhead of parity banks based on the underlying application. The case when the size of a parity bank is smaller than a data bank, i.e., $L' < L$, we say that the parity bank is a shallow bank. We note that it's perfectly reasonable to have the provisions for shallow banks, especially in proprietary designs of integrated memories in a system on a chip (SoC).

3.1.1 Degraded reads and their locality

Now let's focus on the application of redundant (encoded) data stored on an array of banks to improve the read accesses to the original data elements by avoiding bank conflicts. Let's consider the coding scheme illustrated in Figure 6a, where the parity bank stores $\mathbf{p} = \mathbf{a}([L']) + \mathbf{b}([L'])$. Now, given two read requests

Design	Max reads (per bank)	Locality	Rate	Storage overhead	Logical complexity
I	4	2	2/5	1.5α	Low
II	5	2	2/5	2.5α	Medium
III	4	3	1/2	α	Medium

Table 1: Comparison of the code designs with respect to the performance parameters and associated cost

$\{a(1), a(L)\}$, which would have led to a bank conflict (at the data bank \mathbf{a}) without the parity banks, can now be simultaneously served without any bank conflicts: 1) Serve the request $a(L)$ from the data bank \mathbf{a} , and 2) Download $b(1)$ and $p(1) = a(1) + b(1)$ from the data bank \mathbf{b} and the parity bank to serve $a(1)$ by reconstructing $a(1) = b(1) + p(1)$. A read request which is served with the help of parity banks (the request for $a(1)$ in this case) is termed as *degraded read*. Each degraded read has a parameter *locality* associated with it which corresponds to the total number of banks that need to be accessed to serve the degraded read. In this aforementioned case, the locality of the degraded read for $a(1)$ is 2 as we access two banks, the data bank \mathbf{b} and the parity bank \mathbf{p} , to perform the degraded read.

In order to further illustrate the notion of locality, let's consider a setup where we generate a parity bank \mathbf{p} by combining three data banks \mathbf{a} , \mathbf{b} , and \mathbf{c} as $\mathbf{p} = \mathbf{a} + \mathbf{b} + \mathbf{c}$. Now, a degraded read for $a(1)$ using the parity bank as

$$a(1) = b(1) + c(1) + p(1) = b(1) + c(1) + (a(1) + b(1) + c(1))$$

has locality 3 as the degraded read is served using three memory banks.

3.2 Codes to emulate multi-port memory

We will now describe the code designs proposed in this work to emulate multi-port memories. Among a large set of possible coding schemes, we focus on three specific coding schemes for this task. We believe that these three coding schemes strike a good balance among various quantitative parameters, including storage overhead, number of simultaneous read requests supported by the array of banks, and the locality associated with various degraded reads. Furthermore, these coding schemes respect the practical constraint of encoding across a small number of data banks. In particular, we focus on the setup with 8 memory banks (the design scales with larger number of banks). This is in contrast with the application of coding in communications, where encoding is performed over a much larger number (with block size > 1024) of information symbols.

In the rest of this section, we present three code designs and discuss the number of simultaneous read requests supported by these designs in the best and worst case. We also summarize all the relevant parameters associated with these designs in Table 1 which highlights the trade-offs among these parameters.

3.2.1 Code design I

This code design is motivated from the concept of batch codes [9] which enables parallel access to the content stored in a large scale distributed storage system. This design employs only inter-bank encoding across rows of data banks. The coding scheme is illustrated in Figure 7. The code design involves 8 data banks $\{\mathbf{a}, \mathbf{b}, \dots, \mathbf{h}\}$ (each of size L) and 12 shallow banks (each of size $L' = \alpha L$ for $0 < \alpha \leq 1$). We partition the 8 data banks into two disjoint groups consisting of 4 banks each. The underlying coding scheme produces (shallow) parity banks by separately encoding data banks from the two groups. Thus, as shown in Figure 7, the entire array of banks, including data banks and parity banks, can be viewed as partitioned into two disjoint code region. For a specific choice of α , the storage overhead of this design is $12\alpha L$ which amounts to the rate of the coding scheme being

$$\frac{8L}{8L + 12\alpha L} = \frac{2}{2 + 3\alpha}.$$

REMARK 4. *Note that the size of shallow banks is a design choice which is controlled by the parameter $0 < \alpha \leq 1$. A small value of α corresponds to small storage overhead. However, $\alpha < 1$ ensures multiple access for only a subset of data elements (belonging to the encoded rows) from the data banks. The identity of the $L' = \alpha L$ rows from data banks that are encoded using the shallow parity banks depend on nature of access request being served by the memory system. In particular, in Section 4.6 we discuss a dynamic coding approach that dynamically change the encoded rows based on the detection of the regions of memory banks that receive a large number of access requests. For applications, where such sustained concentration of access patterns is not present, one can employ design with $\alpha = 1$, i.e., the parity banks have the same size as the data banks and all the elements of the data banks are stored in the encoded form in the array of banks.*

We now analyze the number of simultaneous read requests that can be supported by this code design.

Best case analysis: This code design achieves maximum performance when sequential accesses to the coded regions are issued. During the best case access, we can achieve up to 10 parallel accesses to a particular coded region in one access cycle. Consider the scenario when we receive accesses to the following 10 rows:

$$\{a(1), b(1), c(1), d(1), a(2), b(2), c(2), d(2), c(3), d(3)\}.$$

Note that we can serve the read requests for the rows $\{a(1), b(1), c(1), d(1)\}$ using the data bank \mathbf{a} and the three parity banks storing $\{a(1)+b(1), b(1)+c(1), c(1)+d(1)\}$. The requests for $\{a(2), c(2), d(2)\}$ can be served by downloading $b(2)$ from the data bank \mathbf{b} and $\{a(2)+d(2), b(2)+d(2), a(2)+c(2)\}$ from the respective parity banks storing these. Lastly, in the same memory clock cycle, we can serve the requests for $\{c(3), d(3)\}$ using the data banks \mathbf{c} and \mathbf{d} .

Worst case analysis: The code design under con-

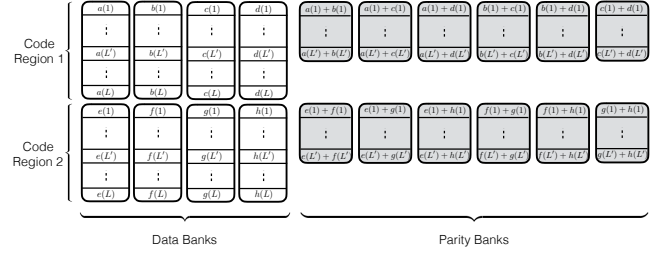


Figure 7: Code Design I

sideration (cf. Figure 7) falls off to 4 access in a single memory clock cycle when there are non-sequential and non-consecutive access to the memory banks. For example, when we receive read requests for

$$\{a(1), a(2), b(8), b(9), c(10), c(11), d(14), d(15)\}.$$

Since parity elements combining the data elements from these requested rows are not present in the parity banks, the underlying coding scheme does not provide any benefits. However, as discussed in Section 4.7, we can use the prefetching mechanism to look ahead in the queue and prefetch codes from parity banks for the subsequent access in order to exploit the otherwise unused parity banks. The worst case number of reads per cycle are equal to the number of data banks.

3.2.2 Code Design II

Figure 8 illustrates the second code design explored in this paper. Again, the 8 data banks $\{\mathbf{a}, \mathbf{b}, \dots, \mathbf{h}\}$ are partitioned into two groups containing 4 data banks each. These two groups are then associated with two code regions. This code design generates 9 parity banks for 8 data banks, where only the content stored on the data banks from the same region is combined to generate these parity elements. As evident from Figure 8, this design employs both inter-bank and intra-bank encoding in order to generate the content to be stored on the parity banks. For example, the parity element $a(1)+a(L'+1)$ results from an intra-bank encoding operation. This code design differs from the previous code design (cf. Figure 7) in terms of the size and arrangement parity banks. Even though $L' = \alpha L$ rows from each data bank are stored in a coded manner by generating parity elements, the parity banks are assumed to be storing $2\alpha L > L'$ rows. Furthermore, the parity-banks generated using intra-bank encoding from one code region are stored on the parity banks of another code region.

For a specific choice of α , the storage overhead of this design is $20\alpha L$ which amounts to the rate of the coding scheme being

$$\frac{8L}{8L + 20\alpha L} = \frac{2}{2 + 5\alpha}.$$

Note that this code design can support 5 read accesses per data bank in a single memory clock cycle as opposed to 4 read requests supported by the code design from Section 3.2.1. However, this is made possible at the

cost of extra storage overhead. Next, we discuss the performance of this code design in terms of the number of simultaneous read request that can be served in the best and worst case.

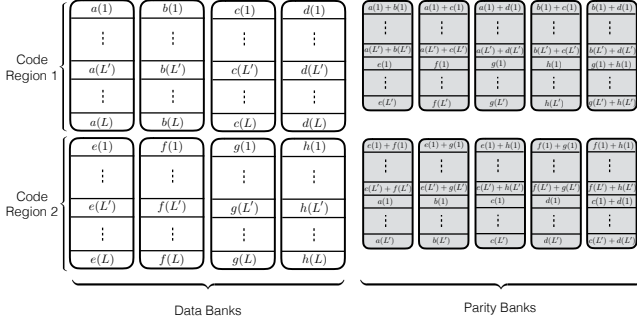


Figure 8: Code Design II

Best case analysis: This code design achieves the best access performance when sequential accesses to the data banks are issued. In particular, this design can support up to 9 read requests in a single memory clock cycle. Consider the scenario where we receive read requests for the following rows of the data banks.

$$\{a(1), b(1), c(1), d(1), a(2), b(2), c(2), d(2), a(3), b(3), c(3)\}$$

Here, we can serve the requests for the rows $\{a(1), b(1), c(1), d(1)\}$ using the data bank **a** with the parity banks storing the parity elements $\{a(1) + b(1), b(1) + c(1), c(1) + d(1)\}$. Similarly, we can serve the requests for the rows $\{a(2), b(2), c(2), d(2)\}$ using the data bank **b** with the parity banks storing the parity elements $\{a(2) + d(2), b(2) + d(2)\}$. Lastly, the request for the rows $c(2)$ and $d(3)$ is served using the data banks **c** and **d**.

Worst case analysis: The code scheme can enable 5 simultaneous accesses in a single memory clock cycle in the worst case. These are non-sequential and non-consecutive accesses to the memory banks. For example, when the access pattern corresponds to the rows $\{a(1), b(6), c(9), d(15), e(20)\}$, we can simultaneously serve these 5 read requests with the help of our coded memory. In order to better utilize the unused banks in this case, we can use the prefetching mechanisms (cf. Section 4.7) to look ahead in the queue and proactively download elements from the unused banks for future accesses.

3.2.3 Code Design III

The two code designs discussed so far have locality 2, i.e., we need to access 2 memory banks to serve a read request with the help of parity symbols. The next design that we consider has locality 3. This code design works with 9 data bank $\{\mathbf{a}, \mathbf{b}, \dots, \mathbf{h}, \mathbf{z}\}$ and generates 9 (shallow) parity banks. Figure 9 describes this design. As one can verify that this design relies on only inter-bank encoding to generate parity symbols. The storage overhead of this design is $9\alpha L$ which corresponds to the

rate of $\frac{1}{1+\alpha}$. We note that this design possesses higher logical complexity because of increased locality.

This design helps us support 4 simultaneous read access per bank per memory clock cycle. As an example, the requests for the rows $\{a(1), a(2), a(3), a(4)\}$ can be satisfied as follows. The request for $a(1)$ can be served by the data bank **a**. The request for the row **a**(2) can be supported by using the data banks **b** and **c** along with the parity bank storing $a(2) + b(2) + c(2)$. Similarly, the data banks **d** and **g** along with parity bank storing $a(3) + d(3) + g(3)$ allows us to access $a(3)$. Lastly, we can serve the request for the row $a(4)$ by using the data banks **e** and **z** with the parity element $a(4) + e(4) + z(4)$.

Best case analysis: Following the analysis similar to design I and II, the best case number of reads per cycle will be equal to sum of data bank and parity bank (18 reads per cycle in case of design III).

Worst case analysis: Similar to design I and design II, the number of reads per cycle is equal to the number of data banks (9 in case of design III).

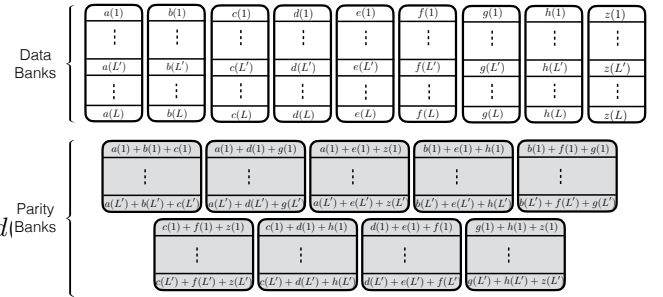


Figure 9: Code Design III

REMARK 5. Note that the coding scheme in Figure 9 describes a system with 9 data banks. However, we have set out to construct a memory system with 8 data banks. It is straightforward to modify this code design to work with 8 data banks $\{\mathbf{a}, \mathbf{b}, \dots, \mathbf{h}\}$. In particular, we can assume the data elements store in the data bank to be all 0s and discard this bank. This results into the code design described in Figure 10. Since we assume the elements of the discarded data bank **z** to be all 0s, the resulting 9 parity banks do not have any contribution from this bank. Note that the modified memory system has varying locality for degraded reads. Some degraded reads require accessing 3 banks (e.g., accessing $a(1)$ using $b(1)$, $c(1)$ and $a(1) + b(1) + c(1)$) while other degraded reads have locality 3 (e.g., accessing $g(1)$ using $h(1)$ and $g(1) + h(1)$). Note that the storage overhead of the modified design is the same as that of the design described in Figure 9.

[ANKIT: What about the best case vs worst case analysis for this design??]

4. MEMORY CONTROLLER DESIGN

[MATT: BLUE: I would not mind removing this text. RED: I will likely remove this text]

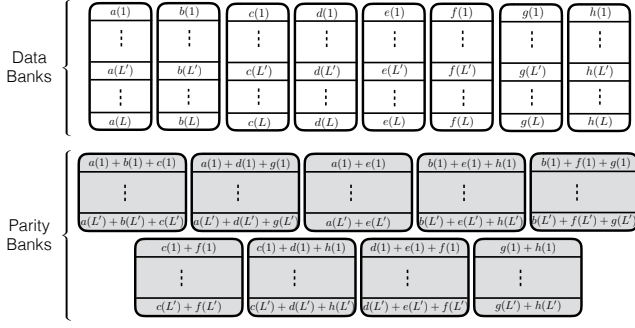


Figure 10: Code Design III with 8 data banks

In this section, we discuss the architecture of the memory controller for the proposed memory system. This memory controller is designed to make use of the coding schemes discussed in the previous section. The architecture of the memory controller is focused on exploiting the redundant storage in the coding schemes to serve memory requests faster than an uncoded scheme. This section presents the key architectural requirements of the memory controller and potential implementations of these requirements.

4.1 Memory Controller Stages

A general memory controller consists of three stages of processing illustrated in Figure 2. The first stage, the *core arbiter*, receives memory access request from the master cores. The core arbiter then routes the requests to the proper *bank queue*. The bank queues are the second stage of processing, and they are responsible for storing and tracking memory requests. A memory request seeking memory located in bank N will be sent to the N th bank queue. The *access scheduler* is the final stage of processing. It is responsible for scheduling the requests in the bank queues. Each memory cycle, the access scheduler generates an access pattern based on the requests present in the bank queues. The access pattern is a description of the reads or writes the memory controller will perform on the memory banks. Next, we discuss all of these three units and their functions in a greater detail.

- **Core arbiter:** Every clock cycle, the core arbiter receives up to one request from each core which it stores in an internal queue. The core arbiter attempts to push these request to the appropriate bank queue. If in attempting to push a request the core arbiter detects that the destination bank queue is full, the controller signals that the core is busy which stalls the core. The core arbiter is also responsible for arbitration among the access requests. It arranges the requests stored in its internal queue using a two-step priority order mechanism. It arranges the request in order of QoS priority, and it arranges requests with the same QoS priority using round-robin scheduling.
- **Bank queues:** Each data bank has a corresponding read queue and write queue. The core arbiter sends memory requests to the bank queues until the queues

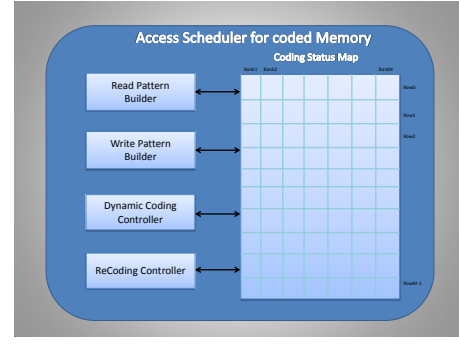


Figure 11: Access scheduler for coded memory

are full. In our simulations, we use a bank queue depth of 10.

In addition to the read and write queues, there is a single queue which holds special requests such as memory refresh requests.

- **Access scheduler:** The access scheduler is responsible for handling interactions with the memory banks. Every memory cycle, the access scheduler chooses to serve read requests or write requests and algorithmically determines which requests in the bank queues it will schedule. The scheduling algorithms the access scheduler uses are called pattern builders. Every memory cycle, the access scheduler invokes either the read pattern builder or the write pattern builder to schedule read or write requests respectively. A key design trade-off of the pattern builder algorithms is the relationship between the complexity of the algorithm and the number of requests the algorithm schedules.

We note that the core arbiter and bank queues should not differ much from those in a traditional setup with an uncoded storage space. The access scheduler directly interacts with the memory banks including the parity banks, so it must be designed with the proposed coding schemes in mind. The rest of this section is devoted to discussing the access scheduler in detail.

4.2 Code Status Table

The code status table keeps track of the validity of data stored in the data and parity banks. The access scheduler may serve a write request using either a data or parity bank. When a write is served to a row in a data bank, any parity bank which is constructed from the data bank will contain invalid data its corresponding row. Similarly, when the access scheduler serves a write to a parity bank, both the data bank which contains the memory address specified by the write request and any parity banks which utilizes that data bank will contain invalid data. The code status table keeps track of the locations of invalid data so the access scheduler does not erroneously serve read requests with stale data.

Figure 11 depicts one implementation of the code status table. This is the implementation used to generate the simulation results described in sections 5 and 6. The

implementation contains an entry for every row in each data bank. Each entry can take one of three values. The values indicate that either the data in both the data bank and parity banks is fresh, the data bank contains the most recent data, or one of the parity banks contains the most recent data. It is not necessary for the code status table to know which parity bank a write request was served, because the dynamic coding unit described later in this section keeps track of this information. We assume that the elements of the code status table are accessible at a very fast rate.

This implementation of the code status table can be improved. This code status table does not keep track of the intermediate steps the access scheduler takes when rebuilding codes after a write is served. When rebuilding the memory in two parity banks after a data bank has been written to, it is likely that elements of one parity bank will be restored before the other. The restored parity bank is ready to serve more memory requests using the rebuilt row, but the code status table will indicate that all the parity banks are unavailable until all parity banks are restored. Full knowledge of the status of all data and parity banks allows the access scheduler to serve more requests in some scenarios. **[MATT: is this example necessary? Is the tangent worth the insight?]**

4.3 Read pattern builder

A principal goal of the proposed memory system is to serve many read requests in a single memory cycle, and the redundant memory provided by the parity banks gives the memory controller the potential to fulfill this goal. The access scheduler must determine how to use the memory provided by the parity banks. When serving read requests, the access scheduler selects a set of requests to be scheduled from the bank queues. In order to select the set of requests to be scheduled, the access scheduler must determine how the memory requests will be served by the data and parity banks. Serving a memory request from a data bank is straightforward, because the symbols in the data banks are uncoded, so they are ready to be used as long as the code status table indicates that the symbols are up-to-date. Serving a memory request using a parity bank is more complex, because parity banks which contain coded symbols must use symbols downloaded from data banks in order to be decoded. The access scheduler uses the read pattern builder algorithm to determine which requests to serve using parity and data banks. **[MATT: Is this paragraph too wordy?]**

The read pattern builder selects which memory requests to serve and determines how requests served by parity banks will be decoded. The algorithm is designed to serve many read requests in a single memory cycle. Figure 12 is one possible implementation of the read pattern builder. It is important to note that the algorithm depicted will not always schedule the maximum number of read requests in a single memory cycle. We use the implementation shown here in our simulations described in sections 5 and 6.

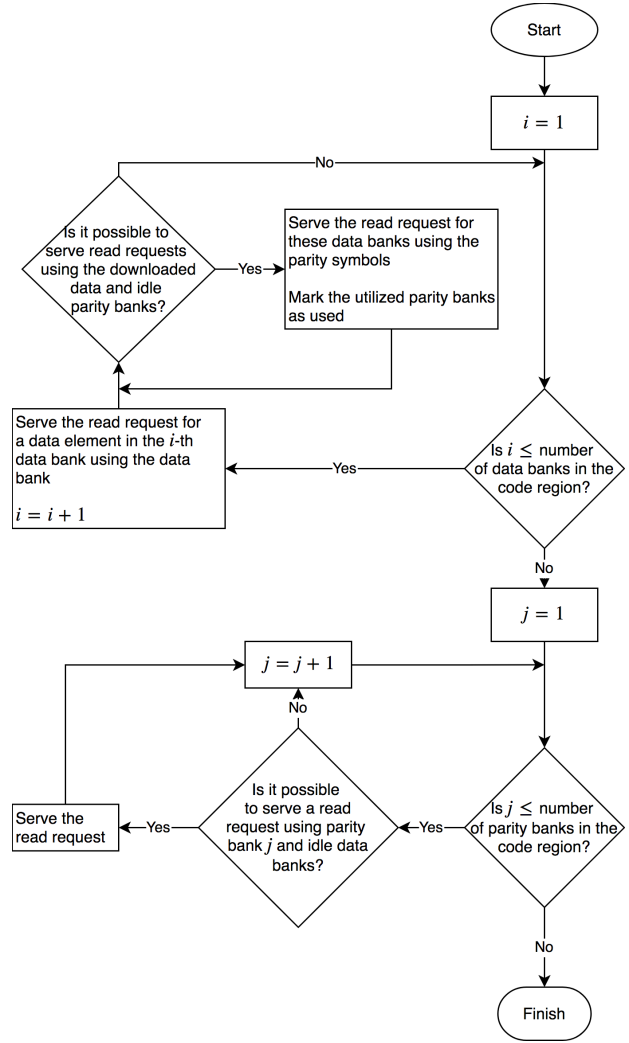


Figure 12: Description of the algorithm to build a read request pattern to be served in a given memory cycle.

Figure 13 shows the algorithm depicted in one scenario. First, the read pattern builder marks $a(1)$ to be read from data bank **a**. It then looks through banks **b**, **c**, and **d** searching for requests for rows $b(1)$, $c(1)$, or $d(1)$ because these symbols can be decoded from a parity bank using the $a(1)$ symbol. In this scenario $b(1)$, $c(1)$, and $d(1)$ are all present in the bank queues and are served using parity banks. Symbols equal to $a(1) + b(1)$, $a(1) + c(1)$, and $a(1) + d(1)$ are all downloaded from parity banks and decoded with $a(1)$. Next, $b(2)$ is read from a data bank. Similar to before, $c(2)$ and $d(2)$ are served by downloading $b(2) + c(2)$ and $b(2) + d(2)$ symbols from the parity banks. Again as before, $c(3)$ is read from data bank and $d(3)$ is decoded using $c(3)$ and $c(3) + d(3)$. Finally, $d(4)$ is read from a data bank. In this scenario, Only the top loop of the read pattern builder as pictured in Figure 12 schedules reads, but there are scenarios where the bottom loop is useful. **[MATT: I have an optimal algorithm for scheduling read requests. Should I include it in**

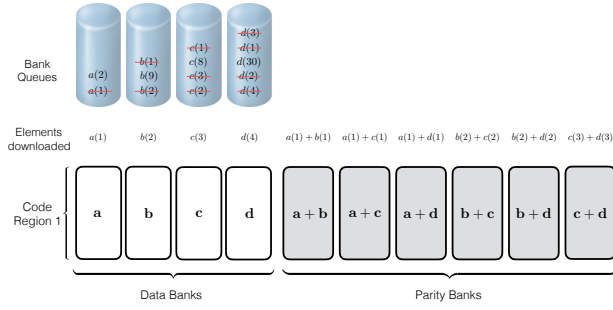


Figure 13: Illustration of the algorithm to build a read request pattern to be served in a given memory cycle. All the read requests associated with the strikethrough elements are scheduled to be served in a given memory cycle. The figure also shows the elements downloaded from all the memory banks in order to serve these read requests.

this section?]

REMARK 6. *Here we note that the aforementioned approach of maximizing the number of read request being served per cycle does come with a cost. It increases the chances of having out-of-order execution of memory access requests. This does not pose a problem in the case when the memory requests go out of order for different cores. However, in order to prevent the out-of-order execution of the access requests arising from the same core, the logic needs to take care of in-order execution of requests from each cores. We assume that the code arbiter only admits requests into the bank queues if the requests can be immediately served without the risk of out-of-order execution.*

4.4 Write pattern builder

The inclusion of parity banks allows the memory controller to serve additional write requests per cycle. The memory controller can serve multiple writes which target a single data bank by committing some of the writes to parity banks. Similar to the read pattern builder, the access scheduler implements a write pattern builder algorithm which determines which write requests to schedule in a single memory cycle.

Figure 14 illustrates a potential implementation of the write pattern builder. The implementation of the write pattern builder discussed here is used in the simulations described in sections 5 and 6. Only when the write bank queues are nearly full does the access scheduler execute the write pattern builder algorithm.

Figure 15 shows how the write pattern builder described in Figure 14 performs in one scenario. Without the parity banks only one write request can be scheduled for each of the four data banks. The inclusion of

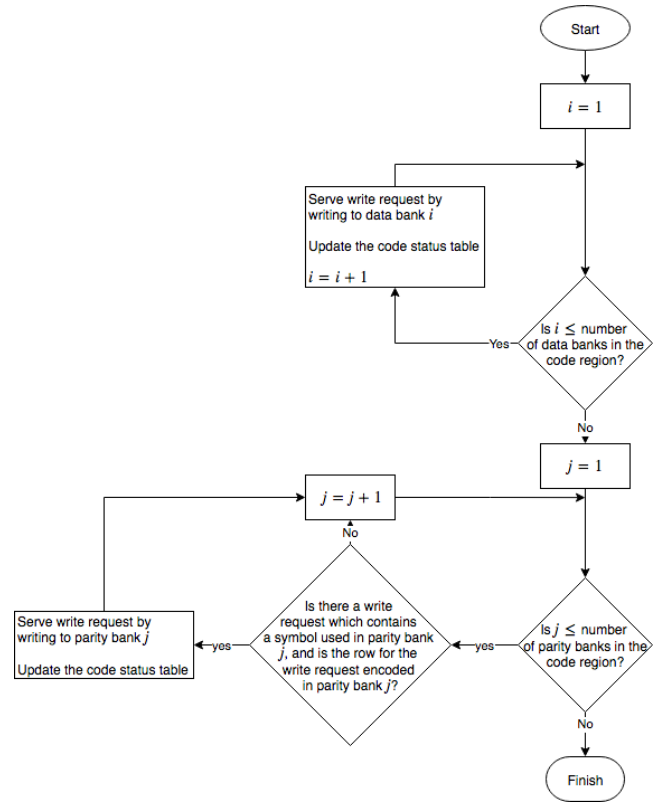


Figure 14: Flowchart of write pattern builder

parity banks allows for 10 write requests to be scheduled. Note that an element which is addressed to row n in a data bank can only be written to the corresponding row n in the parity banks. In this scenario, the write queues for each data bank are full. The controller takes 2 write requests from each queue and schedules one to be written to their target data bank the other to a parity bank. The controller also updates the code status table. **[MATT: The figure figure here contains an error - 10 write requests should be served]**

Figure 15 also demonstrates how the code status table changes to reflect the freshness of the elements in the data and parity banks. Here, the 00 status indicates that all elements are updated. The 01 status indicates that the data banks contain fresh elements and the elements in the parity banks must be recoded. The 10 status indicates that the parity banks contain fresh elements, and that the data bank must be updated and the elements in the parity banks must be updated.

4.5 ReCoding unit

After a write request has been served, the stale data in the parity or data banks must be replaced. The ReCoding Unit is responsible for updating the elements of data and parity banks after a write is served. The ReCoding Unit contains a queue of *recoding requests*. Every time a write is served, recoding requests are pushed on to the queue. Recoding requests indicate which data and parity banks contain stale elements, and they indi-

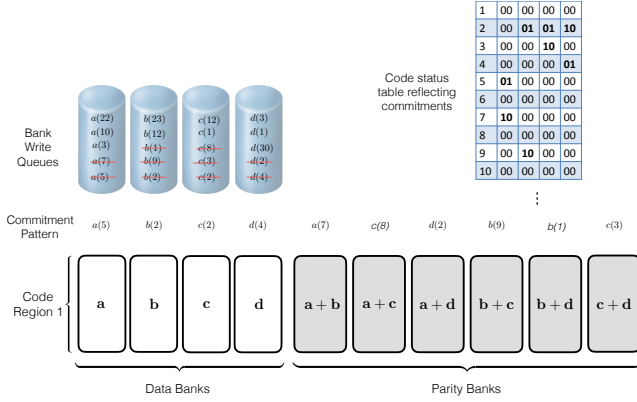


Figure 15: Figure describing write algorithm access pattern

cate the bank the write was served to which generated the recoding request. The recoding requests also contain the cycle number the request was created so the ReCoding Unit may prioritize older requests.

4.6 Dynamic Coding

To reduce memory overhead, the size of the parity banks is designed to be only a fraction of the size of the data banks. Ideally, the most heavily accessed portions of memory are stored in the parity banks. The dynamic coding block is responsible for maintaining codes for the most heavily accessed memory sub regions.

4.6.1 Motivation

Bank conflicts are most likely to occur when regions of shared-memory are localized to certain memory regions. Multi-core systems often generate memory access requests to overlapping memory regions. By dynamically coding certain memory locales, the proposed memory system aim to resolve the bank conflicts which occur during periods of heavy memory access in multi-core systems.

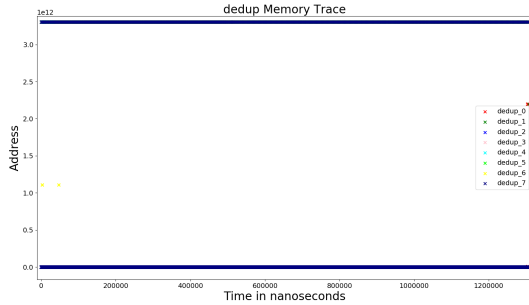


Figure 16: Memory Access from the Dedup PARSEC benchmark. This trace was generated using 8 cores.

An examination of the memory trace from one of the

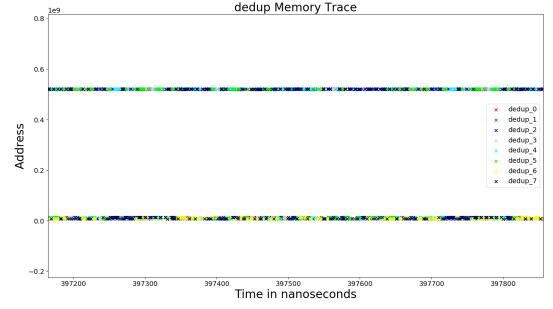


Figure 17: Memory Access from the Dedup PARSEC benchmark demonstrating the density of memory accesses

PARSEC benchmarks illustrates a scenario where dynamic coding works well. Figure 16 shows the memory trace of a simulation of an 8-core system running the dedup PARSEC benchmark. The y-axis shows the address accessed by the cores. The x-axis shows the access time in nanoseconds. This plot shows that most of the accesses from various cores are primarily located in the lower memory band. Greater than 95% of all memory accesses are in this band. Figure 17 magnifies this band and reveals that the lower band is composed of two sub-bands of roughly equal density. In a scenario where the dynamic coder can choose to encode two memory blocks it would detect that nearly all memory access are localized to the primary memory bands, so only those regions would be encoded.

4.6.2 Encoder Design

There are many possible implementations of the dynamic coding unit. The design described here is used in the simulator used to generate the results described in sections 5 and 6.

The *dynamic coding* block splits the each memory bank according to the memory partition coefficient r . Each bank is split into $\lceil \frac{1}{r} \rceil$ partitions. Recall that α is the maximum memory overhead of the proposed memory system. The block can select up to $\frac{\alpha}{r} - 1$ regions to be encoded in the parity banks. A single region is reserved to allow the dynamic coding block to encode a new region.

Every T ticks, the *dynamic coding* unit chooses the $\frac{\alpha}{r} - 1$ regions with the greatest number of memory accesses. The dynamic coding unit will then encode these regions in the parity banks. If all the selected regions are already encoded, the unit does nothing. Otherwise, the unit begins encoding the most accessed region. Once the dynamic coding unit is finished encoding a new region, the region becomes available for use by the rest of the memory controller. If the memory ceiling $\alpha - r$ is reached when a new memory region is encoded, the unit evicts the least frequently used encoded region.

4.7 Prefetching Codes

Dynamic coding works best when the most heavily

accessed regions of memory do not change over time. Though dynamic coding can still be effective when the memory access trend is not static, the proposed memory system can benefit from a system which anticipates sequential memory accesses. The prefetcher attempts to detect sequential memory accesses and exploit idle memory banks to potentially serve future memory requests. The prefetcher analyzes the pattern of memory accesses over a fixed number of memory cycles and detects sequential memory accesses. The prefetcher prioritizes long sequential memory accesses as motivation for performing an anticipatory read. Because of the speculative nature of the prefetcher, it is given the lowest priority of all the components in the access scheduler, and it will only schedule a memory access to a memory bank if all the other units do not do so first.

5. EXPERIMENTAL METHODOLOGY

In this section, we discuss our method for evaluating the performance of the proposed memory system. We utilize the PARSEC v2.1 and v3.0 benchmark suites with the gem5 simulator to generate memory traces. Next, we run the Ramulator DRAM simulator to measure the performance of the proposed memory system. We compare the baseline performance of the Ramulator simulators against a modified version of the Ramulator simulator which implements the proposed memory system.

5.1 Memory Trace Generation

We use the PARSEC benchmark suite to evaluate the performance of the proposed memory system. The PARSEC benchmark suite was developed for chip multiprocessors and is composed of a diverse set of multi-threaded applications [34]. The benchmarks allow us to observe how the proposed memory system performs in dense memory access scenarios. A number of input sets are provided alongside the PARSEC benchmarks. To run the PARSEC applications, we use the gem5 simulator [35].

The gem5 simulator allows us to select the number of processors and their attributes we use to generate the memory traces. We used 8 processors for the PARSEC benchmarks we evaluated. The PARSEC applications can be divided into different regions based on the nature of regions' computation. The most computationally interesting region is the one which features parallel processing. We extract the parallel processing region because the parallel processing creates the greatest probability of bank conflicts. The Ramulator simulations are run only on this parallel processing region of the PARSEC benchmarks.

5.2 PARSEC Trace Attributes

The most important attributes of the memory traces as it relates to the proposed memory system is the density of the traces, the overlap of the memory accesses between the processors, and how stationary the heavily utilized regions of memory are. The PARSEC benchmarks are sufficiently dense as illustrated by Figure 17.

It is clear from this image that there is heavily memory utilization during this section of the Dedup benchmark. On average across all processors, there is an average of 1.11 nanoseconds between memory accesses per core. This equates to an average of 2.22 cycles between memory access requests per 2 Ghz processor.

The location of the most heavily used memory region is stationary with respect to time for all PARSEC benchmarks. Figure 16 shows the whole of a dedup memory trace. There are two major bands clearly visible in this image, and the bands stay in the same memory regions for the entirety of the trace. Figure 17 is a magnified view of the bottom band. This figure reveals that the bottom band is composed of two sub-bands which are also stationary with respect to time. The structure of the dedup memory trace is representative for all the PARSEC benchmarks. It is also clear from this image that the memory regions utilized by all of the processors overlap sufficiently to create bank conflicts.

5.3 Ramulator

We use the Ramulator DRAM simulator to compare the number of CPU cycles required to execute the PARSEC memory traces. We use the vanilla Ramulator simulator to acquire the baseline number of CPU cycles. We extended the memory controller in Ramulator in order to simulate the proposed memory system, and we use the modified Ramulator to calculate the improvement the proposed memory system has over the baseline. We use a consistent Ramulator configuration file so that the improvements we observe over baseline are purely a result of the memory system resolving bank conflicts. We test across the memory overhead α .

6. SIMULATION RESULTS

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The simulation results are consistent across all the PARSEC benchmarks. The reason for this consistency is due to the similarity of the memory traces across the benchmarks. Given sufficient memory overhead, we see that we consistently achieve a roughly 25% improvement over the baseline simulation. We find that the Coding Scheme I generally performs the best out of the proposed schemes.

6.1 PARSEC Results

The proposed memory system performs consistently across the PARSEC benchmarks, and the three proposed schemes yield similar results. Figure 18 shows the simulation results for the dedup benchmark. The plot shows that the number of CPU cycles is reduced by between 83% and 73% once a sufficient amount of memory is provided to the memory system. The lines on this figure and others show the number of CPU cycles needed for the Ramulator simulation to finish executing. The bars on these graphs show the number of times the dynamic encoder chooses to encode a new memory region due to the number of memory requests coming

from that region. We note that when $\alpha = 1$, the number of switches is always zero because the dynamic encoder never needs to switch regions.

These results were simulated using a memory partition coefficient $r = .05$. We observe that the performance remains consistent for $\alpha > .1$. The reason for this is that there are two heavily accessed memory bands in each of the PARSEC benchmarks. Once the memory system is able to encode both of these regions, the benefits of the memory system are fully realized. At an $\alpha = .1$, the memory system finds and encodes the two heavily accessed memory bands. $\alpha = .1$ is sufficient to encode the two heavily accessed memory bands because $\lfloor \frac{\alpha}{r} \rfloor = 2$, so the memory system can select 2 regions to encode. The number of coded region switches is evidence that at $\alpha = .05$ more memory is needed to see maximum benefits from the memory system. When $\alpha = .05$, the number of switches is very high because the memory system vacillates between the two most heavily accessed bands. When $\alpha = .1$, the number of switches is nearly zero because the memory system can only select two memory regions to encode, and it seldom has a reason to switch away from the two heavily accessed bands. We see small numbers of switches when $\alpha = .2, .25, .5$ because the memory system is encoding less heavily accesses memory bands.

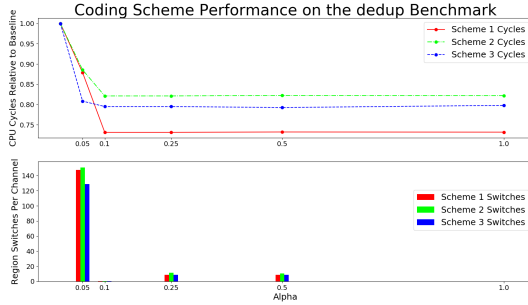


Figure 18: The simulation results for the dedup PARSEC benchmark. The line plot represents the number of CPU cycles needed and the bar plot represents the number of tiems the dynamic coding unit chooses to encode a new memory region. The results from the other PARSEC benchmarks are very similar to those seen here.

The heavily accesses memory bands are narrow, so decreasing the memory bank partition to allows us to lower α and see no decrease in performance. This is demonstrated by Figure 19. Here, it is shown that we can reduce 5 times more than the previous simulation. This is achieved by decreasing the memory partition coefficient r from .05 to .01.

6.2 PARSEC Augmentation

Because the PARSEC benchmarks are homogenous in structure, we chose to augment them in order to observe how the proposed memory system performs in more scenarios. The PARSEC benchmarks were augmented in

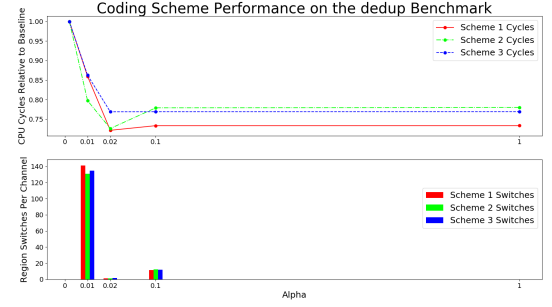


Figure 19: The simulation results for the same trace simulated in Figure 18 but with a memory partition coefficient $r = .01$

two ways. The first augmentation is to split the memory bands observed in Figure 16 and Figure 17 into a greater number of bands. The second augmentation was to ramp the memory bands over time. A visualization of the augmented traces can be seen in Figure 20 and 21

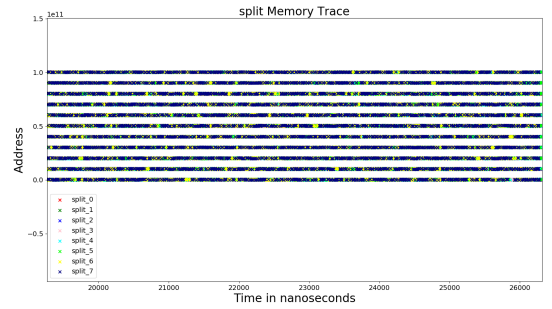


Figure 20: The vips benchmark after the major memory access bands were split into a greater number of bands

6.3 Augmented PARSEC Results

The augmented PARSEC results significantly impact the Ramulator simulation results. Increasing the number of memory bands by splitting the dense bands results in an increased memory requirement to see improved performance. Introducing a ramp to the memory bands decreases the efficacy of the proposed memory system across all values of α .

Figure 22 shows the results from the split augmentation. When there are large number of memory bands, the proposed memory system can achieve the same performance as when there are fewer memory bands if the memory overhead of the system is increased. Note that the simulation results in Figure 22 can be achieved using less memory by decreasing the memory partition coefficient. The memory partition coefficient used here is $r = .05$, but as shown in Figures 18 and 19 lowering the memory partition coefficient allows a lowering of α while achieving the same performance.

Figure 23 shows the results of the ramp augmentation. The proposed memory system performace worse

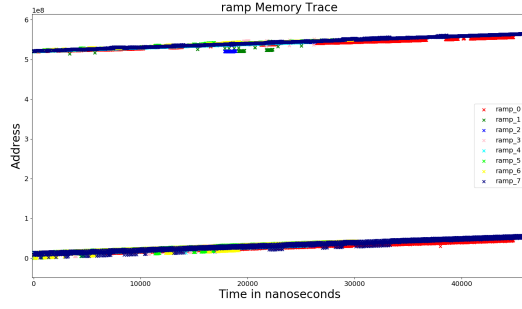


Figure 21: The vips benchmark after a ramp was added to the major memory bands

in this scenario. The number of memory region switches shows that the memory system struggles to handle the constantly changing location of the heavily accessed memory regions. In the other simulator results, we see that the number of memory region switches decreases as a function of α . The reason for this is that the memory system locates the heavily accessed memory regions and rarely switches away from them. Here, the memory system is constantly attempting to catch up with the heavily accessed memory region. We note that the ramp covers a very large number of memory addresses, so the decrease in performance we observe would only effect programs which use very large portions of memory.

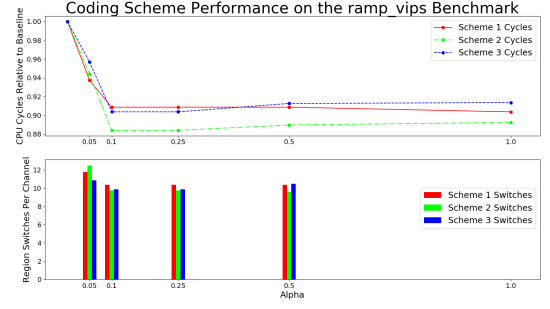


Figure 23: The simulation results of the augmented vips trace pictured in Figure 21

- Memory overhead : 15%
- Parity banks : 5 or 6 shallow banks for code storage

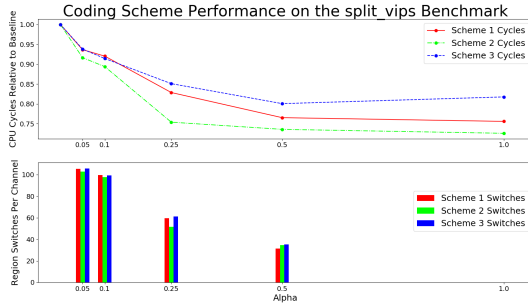


Figure 22: The simulation results of the augmented vips trace pictured in Figure 20

7. ACKNOWLEDGEMENTS

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Following are the objectives used in code design:

- Read access : 4 per bank in one cycle
- Write access : 2 per bank in one cycle
- Shared Memory size 8 kB - 256 kB
- Number of Banks : 8

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